

Estimating recharge in UK catchments

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Abstract A review of the methods of estimating recharge in the UK is being carried out by the Environment Agency. This paper deals with two aspects of estimating recharge which occur in British conditions: (a) potential recharge, and (b) recharge when drift (rock material deposited by glacial activity) is present. Potential recharge is estimated using an approach which takes into account crop water requirements, soil type and evapotranspiration from bare soil. Recharge when drift is present is much less well understood. The key to its adequate estimation is the development of realistic conceptual models for the different processes which can occur. In order to develop and test our understanding, we need to be in full control of the mathematical representation hence this paper presents a method for estimating potential recharge which is readily updated as understanding increases.

Key words drift; groundwater resources; modelling; recharge; UK

INTRODUCTION

The UK Environment Agency is reviewing its methods of recharge estimation because it is increasingly developing total catchment models rather than concentrating on the aquifer system alone. The Agency needs a coherent method of estimating all forms of recharge including potential recharge, vertical flow through drift, runoff recharge, summer bypass flow and river–aquifer interaction. This paper considers: (a) potential recharge, and (b) recharge when drift is present (vertical flow through drift and runoff recharge).

CONCEPTUAL MODEL FOR POTENTIAL RECHARGE

Potential recharge is the water that leaves the bottom of the soil zone. If the material in the unsaturated zone does not restrict the vertical movement of water, the actual recharge (the water reaching the water table) equals potential recharge.

The processes within the soil zone leading to an estimation of potential recharge are illustrated in Fig. 1. Precipitation, P_r , reaches the ground surface and depending upon the rainfall intensity and the state of the soil, some rainfall runs away as surface runoff, RO , and some infiltrates into the soil zone. The infiltration, I_n , is then available to supply the potential evapotranspiration, PE , or increase the amount of water stored in the soil. Once the potential evapotranspiration demand has been met, any remaining infiltration will be stored in the soil. The soil continues to store more water until it reaches *field capacity*, which is the point at which the soil begins to drain, and recharge can occur.

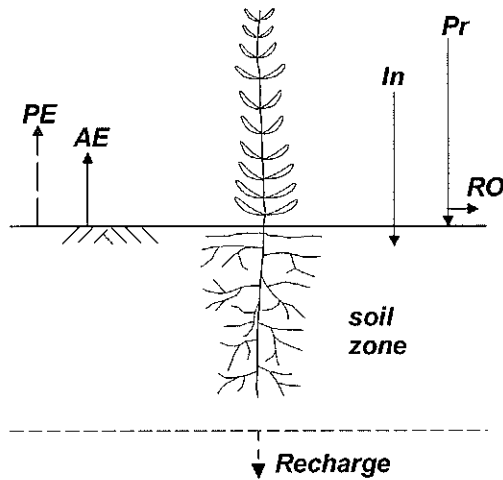


Fig. 1 Conceptual model showing processes within the soil zone leading to an estimation of potential recharge.

When there is no rain the soil dries as a result of water uptake by the crop. The depletion below field capacity is called the *soil moisture deficit*, *SMD*. It is the equivalent depth of water required to bring the soil back to field capacity. Since it is an equivalent depth, the *SMD* should be divided by porosity to get an indication of the actual depth of dry soil. The actual evapotranspiration, *AE*, will be at the potential rate if there is sufficient water available (from infiltration or from soil moisture). If not the *AE* will be less than the *PE*.

ESTIMATION OF POTENTIAL RECHARGE

The current methodology for estimating potential recharge in the UK is based on work by Penman and Grindley and is summarized by Rushton & Ward (1979). Estimates are obtained of (a) the potential evapotranspiration from climatic conditions, and (b) the actual evapotranspiration when the water available is limited by using a daily water balance to estimate the soil moisture deficit, *SMD*. Critical values of the *SMD*, known as the root constants *C* and *D*, were identified to indicate when water was freely available to the crop and when it was limited. These were first used in the 1970s; values for the Lower Mersey and Liverpool aquifer studies (Rushton *et al.*, 1988) are quoted by Lerner (1990).

Whereas the existing method relates the root constants *C* and *D* to crop types and agricultural practice, the modified technique uses actual information about crop water requirements and different soils from the Food and Agriculture Organization of the United Nations (FAO) approach to estimating crop evapotranspiration (1998). It also allows a more realistic consideration of bare soil conditions in winter and the effect of autumn sown crops by taking account of both the *evapotranspiration* from the crop and the *evaporation* from the soil.

Evapotranspiration of the crop

The potential evapotranspiration for the crop, PE_{crop} , is calculated by factoring the potential evapotranspiration for the reference crop, PE_0 , with the crop coefficient K_c :

$$PE_{crop} = K_c PE_0 \quad (1)$$

The crop coefficient, K_c , represents the differences between the actual crop and the reference crop (hypothetical grass). The variation of K_c for a spring-sown crop is shown in the sketch of crop and root growth (Fig. 2); FAO (1998) gives other crop types.

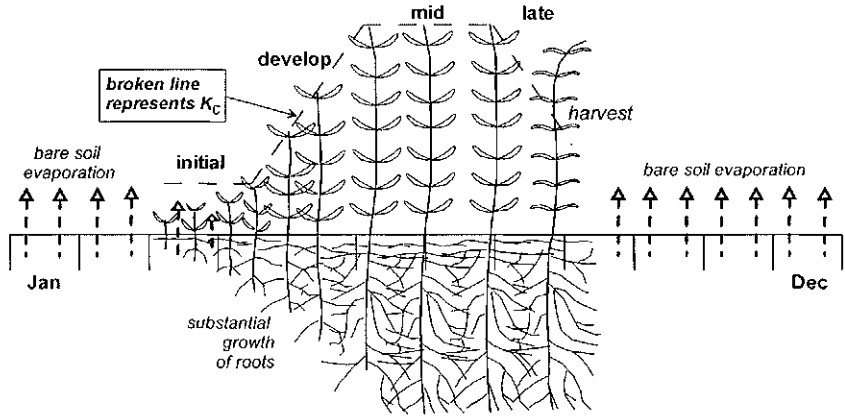


Fig. 2 Growth of crop and roots for a representative spring sown crop; the diagram also shows bare soil evaporation.

The reference crop and the crop coefficient, K_c , assume an ample supply of water; the actual evapotranspiration of the crop, AE_{crop} , is less than the potential rate when the water supply is limited and the crop is stressed. A stress coefficient, K_s , is introduced so that, in the absence of precipitation (or irrigation), the actual evapotranspiration is:

$$AE_{crop} = K_s K_c PE_0 \quad (2)$$

The stress coefficient, K_s , for a given crop is estimated by considering: (a) the moisture holding properties of the soil, (b) the depth of the roots, (c) the behaviour of the crop under water stress, and (d) the soil moisture deficit.

Different soils have different water holding capacities. For example, it is well known that plants in clay soils can withstand water shortages more readily than those in sandy soils. As the crop takes up water, the remaining water is held by the soil particles with greater force, making it more difficult for the plant to extract moisture. Eventually a point is reached where the plant can no longer extract the remaining water from the soil. This wilting point, θ_{WP} , is a characteristic of a particular soil but independent of the crop.

The total water available to the plant depends upon the rooting depth of the crop, Z_r , and the difference between the water content of the soil at field capacity, θ_{FC} , and at the wilting point, θ_{WP} . The total available water, TAW , is defined as:

$$TAW = 1000(\theta_{FC} - \theta_{WP})Z_r \quad (3)$$

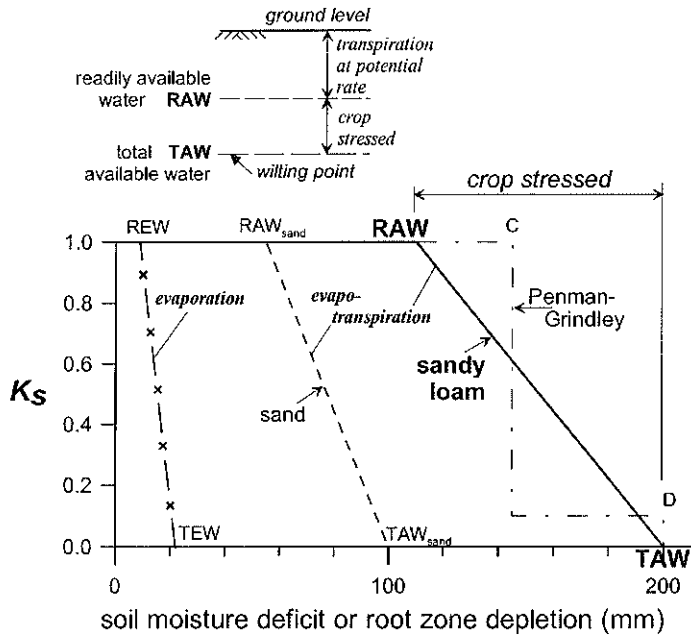


Fig. 3 Illustration of readily available water, RAW , and total available water, TAW concepts (top); variation of soil stress coefficient, K_s , with soil moisture deficit (bottom).

where TAW is in mm, θ_{FC} and θ_{WP} in $m^3 m^{-3}$ and Z_r in m. If the SMD reaches the TAW the plant wilts (top part of Fig. 3).

A second parameter, the readily available water, RAW , is required to represent the condition when the crop can obtain all the water it requires from the soil. Once the SMD is larger than the RAW , the crop is stressed and will transpire at a reduced rate (top diagram of Fig. 3). The RAW (in mm) is the fraction of the TAW that the crop can extract without suffering water stress.

The crop stress coefficient plotted in Fig. 3 is defined as:

$$K_s = (TAW - SMD)/(TAW - RAW) \quad (4)$$

When the SMD is less than the RAW , the stress coefficient, K_s , is unity and the crop transpires at the potential rate ($AE_{crop} = PE_{crop}$). As the SMD increases beyond RAW , K_s decreases linearly, reaching zero when the SMD equals the TAW (and the crop wilts). The plot also shows typical values of the Penman-Grindley C and D constants; when the SMD exceeds C , K_s reduces abruptly to 0.1 (Rushton & Ward, 1979).

Evaporation from bare soil

When the crop does not cover the whole of the soil surface, for example between harvest and the period of full growth the following year, soil evaporation becomes important. Evaporation is calculated in a similar manner to potential evapotranspiration, equation (1), but with much lower total available water:

$$PE_{soil} = K_e PE_0 \quad (5)$$

Two parameters analogous to those for the crop evapotranspiration are introduced for soil evaporation: the total evaporable water, TEW , and the readily evaporable water, REW , where:

$$TEW = 1000(\theta_{FC} - 0.5\theta_{WP})Z_e \quad (6)$$

and Z_e is the depth of the surface soil layer that is subject to drying by evaporation (between 0.1 and 0.15 m).

A soil stress coefficient K_s' is used to calculate actual evaporation:

$$AE_{soil} = K_s' K_e PE_0 \quad (7)$$

K_s' is calculated in a similar manner to the crop stress coefficient, K_s , but using TEW and REW instead of TAW and RAW in equation (4). The variation of K_s' with SMD is shown in Fig. 3.

Combined evapotranspiration from crop and soil

When using a soil moisture balance to estimate recharge in the UK it is essential to consider both crop evapotranspiration and bare soil evaporation because most recharge occurs in the winter when either the soil is bare or the crop covers only part of the area. By weighting the crop coefficient, K_c , and the evaporation coefficient, K_e , according to the percentage area of bare soil and crop, a combined crop coefficient can be calculated. Typical values of this combined coefficient for a spring wheat are plotted in Fig. 4. In the winter all the evapotranspiration is due to soil evaporation and the combined coefficient equals the bare soil value of 1.10. As the crop sprouts in the spring, the area of the crop increases until in the full-growth period of the summer, the crop dominates and the combined coefficient is the crop value of 1.15. As the crop ripens, the combined crop coefficient falls to its lowest value of 0.35 at harvest. After ploughing the coefficient returns to the bare soil value.

The TAW/TEW and RAW/REW lines in Fig. 4 also reflect this influence of both soil evaporation and crop evapotranspiration. In the winter, the lines indicate the TEW and REW values because the soil is dominant. Later, once the crop becomes dominant, they indicate the TAW and RAW values.

MATHEMATICAL REPRESENTATION

Water balance

A daily soil moisture balance calculation is required to track the changes in the SMD . This is because the estimation of the crop stress coefficient, K_s , and soil stress coefficient, K_s' , and hence the actual evapotranspiration depend upon the current soil moisture deficit.

The process for obtaining the actual evapotranspiration is illustrated in the three examples in Fig. 5. The parameters included in the diagrams are: daily infiltration values ($In = Pr - RO$) where Pr is daily precipitation and RO daily runoff. The volume

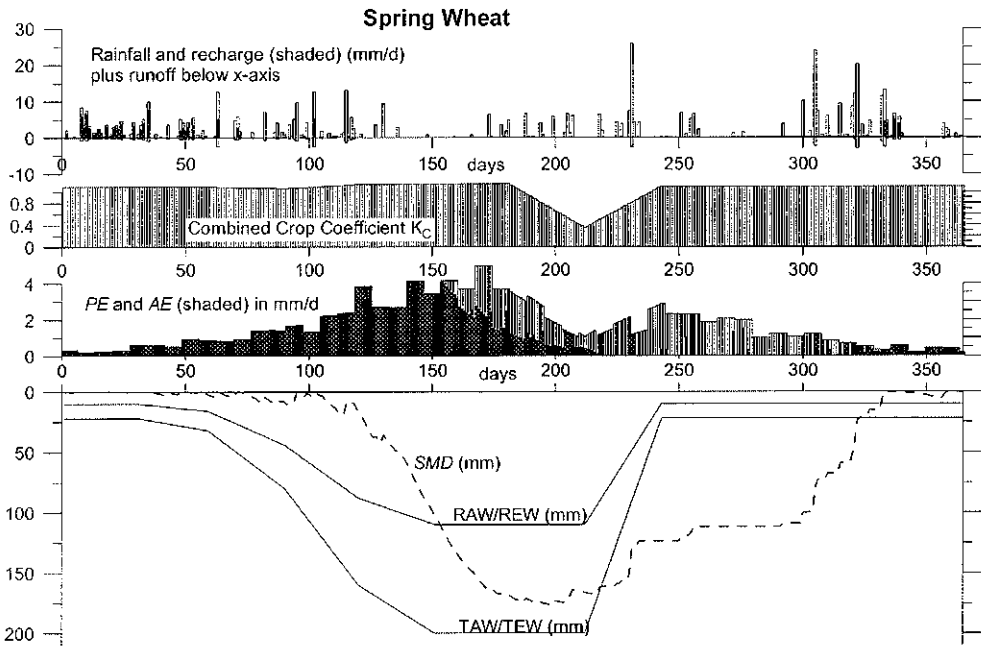
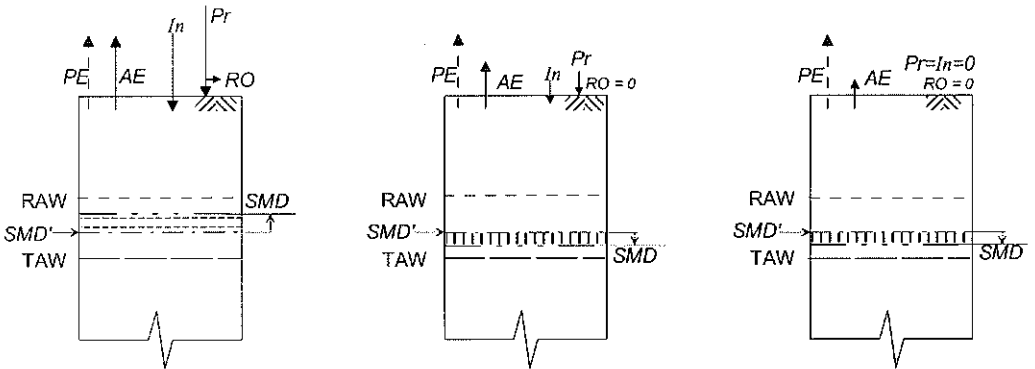


Fig. 4 Representative results of potential recharge estimation for part of the Southern Lincolnshire Limestone catchment for a year when potential evapotranspiration is slightly less than rainfall.



SMD' is greater than RAW but less than TAW hence AE may be less than PE

Example (a)
 Infiltration ($Pr - RO$) is greater than PE , hence $AE = PE$ and SMD reduces

Example (b)
 Infiltration is less than PE , $AE < PE$ and SMD increases slightly

Example (c)
 Infiltration is zero hence less than PE ; AE is a fraction of PE and SMD increases

Fig. 5 Illustration of the components of the water balance calculations when the soil moisture deficit at the start of the day, SMD' , is greater than the readily available water, RAW .

of runoff can be estimated as a function of daily rainfall intensity and SMD from field observations. PE and AE are the potential and actual evapotranspiration. RAW and TAW are the readily and total available water. SMD' and SMD are the soil moisture deficits at the start and end of the day.

In Example (a) (Fig. 5) the infiltration is larger than the potential evapotranspiration; $AE = PE$ since the shallow roots collect the infiltration. The soil moisture deficit decreases as shown by the upward arrow. If the infiltration is less than potential evapotranspiration, Example (b), the crop draws upon the soil moisture to meet the potential evapotranspiration but since the soil moisture deficit is larger than RAW , it can only supply part of the demand. Hence $AE < PE$ and the soil moisture deficit increases during the day (downward arrow). In Example (c) there is no rainfall so the actual evapotranspiration is determined by equations (2) or (7).

A representative example for these water balance calculations is shown in Fig. 4 for a spring wheat crop with precipitation and potential evapotranspiration values taken from part of the Southern Lincolnshire Limestone catchment. The results from the water balance calculations highlight that:

- (a) The RAW/REW and TAW/TEW are low during the winter but increase from March to July to represent the deeper roots as the crop develops; values then fall following harvest.
- (b) The SMD is small from January to April; when it falls below the RAW in the summer, AE is less than PE unless there is high rainfall.
- (c) After harvest the RAW/REW and TAW/TEW suddenly fall so the SMD is larger than the TAW/TEW and only decreases on days when infiltration ($Pr - RO$) $> PE$.
- (d) Recharge (the shaded part of the upper plot) does not begin until late autumn when the SMD reaches zero; even then not every rainfall event produces recharge because after several days without rainfall the SMD has risen above zero.

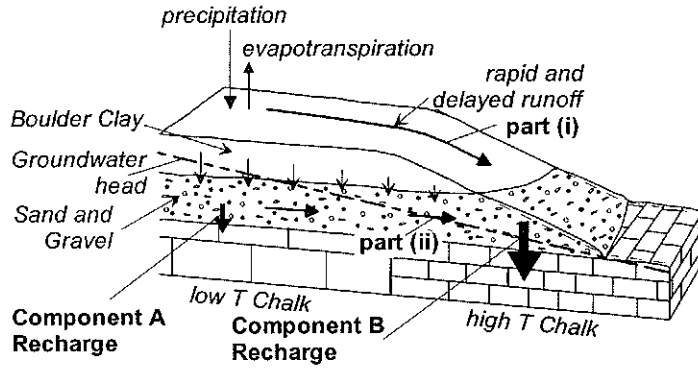
RECHARGE MECHANISMS WHEN DRIFT IS PRESENT

In many British aquifers, there are drift deposits containing low permeability material between the base of the soil zone and the permanent water table. Three alternative approaches are described below. They are required either because of the differing nature of the drift or to be consistent with the field data.

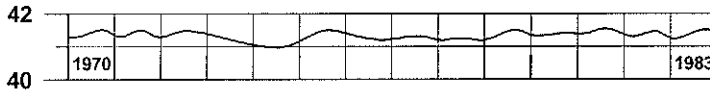
The Gipping catchment in eastern England (Fig. 6) illustrates two major influences of drift on recharge: (a) it may restrict the actual recharge; (b) it may lead to runoff recharge which subsequently enters the aquifer elsewhere. The vertical flow of water through the low permeability drift is labelled as Component A recharge in Fig. 6 and runoff recharge as Component B recharge.

Vertical flow through low permeability drift

In the interfluvial of the Gipping catchment, where the Chalk is overlain by a sand and gravel layer and then by Boulder Clay, there is slow vertical movement through low permeability layers in the Boulder Clay (Component A in Fig. 6). Flow down through the Boulder Clay is strongly influenced by low permeability layers within it. In this



Groundwater head in Chalk, Component A Recharge through Boulder Clay



Groundwater head (m) in Chalk for Component B Runoff Recharge

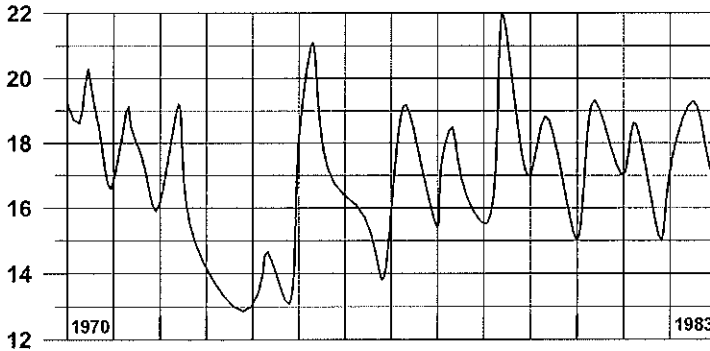


Fig. 6 Conceptual diagram from the Gipping catchment showing the various routes which water can take when low permeability strata overlie the main aquifer.

instance, the quantity of water entering the Chalk in the interfluves is restricted by the low transmissivity of the underlying Chalk hence the hydrograph of groundwater head in the Chalk is subdued and water flows horizontally through the sands and gravels.

One way of representing the actual recharge is to estimate a constant flow into the low transmissivity Chalk. The basis of this approach is that the vertical hydraulic gradient in the unsaturated zone is close to unity (predominantly the effect of gravity) hence the recharge is constant throughout the year. In the Gipping study a value of 24 mm year^{-1} was used (Jackson & Rushton, 1987). It was based on estimates of vertical hydraulic conductivity and modified during groundwater modelling.

Another approach is to assume that the actual recharge moving through the unsaturated zone is a certain percentage of the potential recharge. The percentage is a function of the drift properties. This is a convenient method when there is information about the thickness of the drift and the percentage of the more permeable sandy clays. It was used for the Lower Mersey study (Rushton *et al.*, 1988). In order to take account of the location of the water table in the drift another factor is introduced which reduces

as the groundwater head in the aquifer rises. When the groundwater head is at the same elevation as the water table in the drift, the actual recharge is zero.

A third method is to use a classical “leaky” approach with a regional groundwater model. An effective vertical hydraulic conductivity (which will be dominated by the low permeability layers) and the thickness of the drift must be specified to give a vertical conductance term. The flow is proportional to the difference between the perched water table in the drift and the groundwater head in the underlying aquifer. The perched water table may be a specified head or a head which can fall below but not rise above a specified level.

This approach was used in an area to the east of Doncaster where historically water from the underlying Sherwood Sandstone aquifer flowed upwards due to the higher head in the aquifer. Extensive agricultural drainage was constructed and surface pumps removed the water (Fig. 7(a)). As abstraction from the Sandstone aquifer increased, head gradients were reversed so that water is now drawn from the drainage channels into the aquifer (Fig. 7(b)). In some locations the water table has been drawn below the bottom of the drift (Fig. 7(c)).

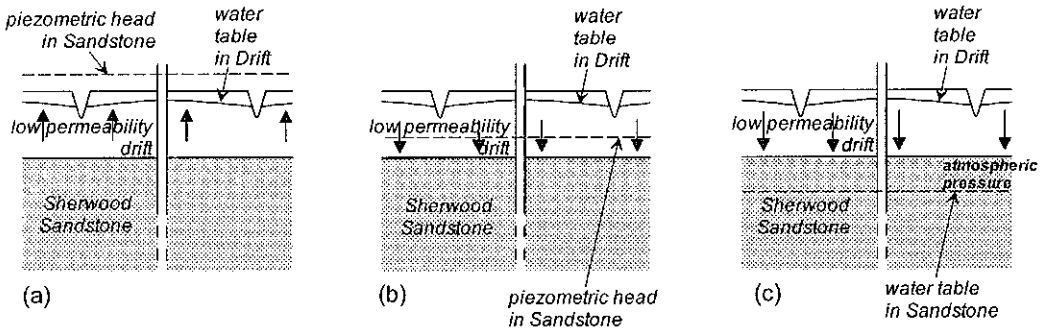


Fig. 7 Conditions near Doncaster where flows through the drained areas of the low-lying land have been reversed; (a) water seeping up vertically when there was no abstraction, (b) reversal of flows as abstraction increased, (c) water table sometimes below low permeability drift.

However, the “leaky” aquifer approach has several shortcomings which can result in flows being calculated which are inconsistent with field evidence. Hence it is essential to check that the vertical leakage does not exceed the potential recharge; the vertical gradient does not exceed unity if the low permeability layer has become “disconnected”; the vertical hydraulic conductivity reflects the saturated or unsaturated nature of any sandy lenses in the drift; and, that the assumption that there is an instantaneous response through the full depth of the drift layer is valid.

Runoff recharge

Recharge does not always occur at the same location as the rainfall inducing it. Surface runoff may flow across low permeability drift before recharging aquifer outcrop. Hence we need to consider runoff recharge. Significant amounts of water may be involved.

Both rapid and delayed runoff can contribute to runoff recharge (Component B recharge in Fig. 6). *Rapid runoff* occurs when there is heavy rainfall and water flows across the surface into drains and streams. *Delayed runoff* occurs when water passes through the soil zone into deposits of head, alluvium or sands which act as minor aquifers. This water is subsequently released as seepages and springs over a period of several weeks. If the streams which collect the water from either of these mechanisms then run onto the aquifer, runoff recharge occurs.

In the Gipping catchment, runoff part (i) in Fig. 6 indicates rapid runoff flowing across the Boulder Clay into drains and streams which first enter the sands and gravels then the Chalk. Runoff part (ii) indicates delayed runoff. This is some of the potential recharge that passes through the Boulder Clay, enters the sand and gravels and flows laterally through the underlying sands and gravels. Once it reaches the margins of the Boulder Clay where the transmissivity of the Chalk is much higher, it can enter the Chalk aquifer.

DISCUSSION

The key to obtaining a satisfactory representation is to strive to understand the physical processes via carefully tested conceptual models, to keep the approach as simple as possible and to make sure that the parameters and calculations are physically meaningful and faithfully represent the concepts.

Preliminary water balance calculations are essential in testing the conceptual models on a coarse scale and it is important to consider the whole catchment not just the groundwater catchment. For example, surface runoff from outside the groundwater catchment may enter the aquifer as runoff recharge.

The inclusion of soil and crop type information improves estimations of potential recharge. However, actual recharge is often less than potential recharge when low permeability drift is present. Three examples from the UK are included to illustrate the approaches which may be used. Runoff recharge is often very important and is briefly mentioned.

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