HYDROLOGY OF SOIL TYPES

A HYDROLOGICALLY-BASED CLASSIFICATION OF THE SOILS OF ENGLAND AND WALES

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INTRODUCTION

Soil type has a major influence on hydrological processes and on the overall response of a catchment. However, to determine this influence from maps showing the distribution of soils calls for an expertise that few possess and some interpretation is therefore required.

One attempt to classify soils according to their hydrological response was the Winter Rainfall Acceptance Potential (WRAP) scheme used in the Flood Studies Report (NERC, 1975) and described in more detail by Farquaharson *et al.* (1978). A 1:1,000,000 scale map of the British Isles was produced showing the distribution of the 5 WRAP classes. This map was enlarged to 1:625,000 for inclusion in Flood Studies Report (FSR) Volume 5. Although the WRAP system has few classes and limited resolution it has been at the core of the FSR rainfall-runoff method of design flood estimation contained in the FSR and used in many design studies over the last 15 years. It is also engrained in other design procedures (eg. WASSP, Department of the Environment, 1981).

A value of standard percentage runoff (SPR) is attached to each WRAP class. This presents the usual response of a catchment to a moderate rainfall and provides a yardstick for comparisons between catchments. For the five WRAP classes the standard percentage runoff, SPR, values published in the FSR were 15, 30, 40, 45 and 50%.

Near the boundary between WRAP classes there is clearly a problem using this scheme as SPR can change by a factor of 2 or 3 between classes. Clearly mapping at a larger scale would remove some of the uncertainty, but users have also commented on the poor discrimination and limited range of the WRAP classification scheme. Downland chalk catchments have typical responses of just a few percent and some small, upland catchments may have a standard response of over 60% (see, for example, Boorman 1985). These deficiencies were recognised from the start and users were advised to refine estimates by reference to local data, or to commission a more detailed soil survey of the study catchment. It is interesting to note that the WRAP scheme originated from a theoretical consideration of runoff processes by hydrologists and soil scientists, and was not based on the widespread analysis of hydrological data, although minor revisions to the WRAP map have used the latter approach.

An opportunity to revise the scale of the WRAP map came in 1983 when the Soil Survey and Land Research Centre, SSLRC, completed mapping of soils in England and Wales at 1:250,000. (Macaulay Land Use Research Institute, MLURI, produced similar maps for Scotland in 1984 but based on a different soil classification scheme) However, rather than merely producing a WRAP map at a more detailed scale it was considered worthwhile to use the large hydrological databases held by the Institute of Hydrology to assist in the definition of the classes. Thus the Hydrology Of Soil Types (HOST) project was born as a joint research project involving IH, SSLRC, MLURI and the Department of Agriculture for Northern Ireland. It was anticipated from the outset that HOST would be used in applications beyond design flood estimation; low flow estimation and susceptibility to pollution were seen as other key uses.

SOIL DATA

The soil maps of England and Wales show the distribution of 295 soil associations. Each association comprises a limited number of soil series that occur together in the landscape. Soil series are distinguished by precise definitions of soil and substrate properties that can be assessed by soil survey and are the key soil unit within the HOST project.

In addition to the properties that are used to characterize soil series, physical properties, such as average soil water release, porosity and density, can be calculated by reference to the SSLRC soil physical property database. This holds measured values from about 4,000 soil layers that represent over 1,000 soil profiles. For each of the 417 soil series contained in the associations found on the national soil maps the following hydrologically important properties were abstracted.

Soil hydrogeology. This is used a way of differentiating between mechanisms of vertical water movement (eg. intergranular or fissure flow), and to distinguish between permeable, slowly permeable and impermeable substrates. The classification was derived specially for the HOST project using soil parent material definitions and the 1:625,000 scale Hydrogeological Map of England and Wales (Institute of Geological Sciences, 1977).

Definitions of permeability are based on Bell (1985). Permeable substrates have a vertical saturated conductivity >10cm/day and an aquifer or shallow water table, slowly permeable substrates have a vertical saturated conductivity of 10-0.1cm/day and may contain a local or concealed aquifer, and impermeable substrates have a vertical saturated conductivity of <0.1cm/day and contain no aquifers.

Depth to aquifer or groundwater. This gives and indication of the time taken for excess water to reach the water table.

Presence of a peaty top soil. A raw peaty topsoil indicates saturated surface conditions for most of the year. Such a layer limits infiltration and provides a lateral pathway for rapid response in the uppermost parts of the soil. A raw peaty topsoil has specific characteristics of thickness, consistency and fibre composition (Avery, 1980).

Depth to a slowly permeable layer. A slowly permeably layer (ie. a layer with a lateral saturated conducitivity of <10cm/day, Avery, 1980) impedes the downward percolation of excess soil water and causes periodic saturation in the overlying layer. Soil water storage is reduced under such conditions and there is an increased rapid response to heavy rainfall.

Depth to gleyed layer. Gleying, the presence of grey and ochreous mottles within the soil, is caused by intermittent waterlogging. The particular definition of gleying used identifies soil layers wet for at least 30 days each year, or soils that are artificially drained (Hollis, 1989).

Integrated air capacity. The air capacity, or 'drainable' pore space, of a soil layer, is defined as its volumetric air content at a tension of 5KPa (roughly field capacity). Integrated air capacity (IAC) is the average percentage air volume over a depth of 1m. This provides a surrogate for permeability in permeable soils and substrates (Hollis and Woods, 1989). In slowly permeable or impermeable soils and substrates, IAC indicates the capacity of a soil to store excess water.

HYDROLOGICAL DATA

Standard Percentage Runoff data for the HOST project comprise the 174 values of catchment average SPR derived for the FSR and follow-up research. These data represent only a small fraction of the catchments for which flow data are available in the UK Surface Water Archive (see, for example, Institute of Hydrology, 1988). Whereas the calculation of SPR requires detailed event-based data describing both the flow and rainfall, an alternative index of catchment response may be derived using only daily mean flow data. This is the base flow index (BFI) developed in the Low Flow Studies (Institute of Hydrology, 1980).

BFI is the long term average proportion of flow that comes from baseflow. Observed values are close to unity on catchments dominated by baseflow but as low as 0.15 on the most flashy catchments. Approximately 1100 values of BFI were available to the HOST project, but rigorous quality control reduced the number to 826. Rejection of catchments with more than 5% urbanization or substantial lake effects led to a usable data set of 633 catchments. Although BFI is derived from flow data alone, it is reasonably well correlated with SPR, the correlation coefficient being 0.75 on a set of 166 catchments used by Boorman (1985). These data provided the main hydrological feedback to the development of a HOST classification but limited use was made of flow duration curve and flood peak statistics.

For each catchment a digitised boundary has been overlain on a 1 km gridded version of the national soil maps and the total percentage of each soil association abstracted. From this the proportion of each component soil series was derived and hence the link established between the catchment response descriptors and soil properties.

THE HOST CLASSIFICATION

The HOST classification is based on a number of conceptual models that describe dominant pathways of water movement through the soil and, where appropriate, substrate. Within each of the models there may be a subdivision according to flow rate and water storage. Whereas the soil properties could differentiate many thousand classes, the model definitions recognise that some properties have no relevance in particular siutations and a manageable number of valid combinations of models and properties results. Of these combinations, some can be expected to give a similar hydrological response and indeed cannot be distinguished using the available hydrological data; in such situations they may be combined in a single HOST class. Other model/property combinations are also indistinguishable using the hydrological data but represent different mechansims of runoff production or situations in which some differentiation may be required for certain applications; in such cases the soils are assigned to different HOST classes. Various classification schemes were assessed by studying individual catchments and by multiple regression analysis of the response descriptors for the catchment data set.

The final system contains 29 soil-hydrological (HOST) classes and is shown in Table 1. This table indicates the percentage of England, Wales and Scotland covered by each class. The HOST scheme explains over 80% of the observed variation of BFI and 60% of the variation in SPR; comparable figures for WRAP are 52% and 47%. It is anticipated, however, that HOST will be used in conjunction with other mapped data (eg. describing climate or slopes) and indeed it has already been used in this way to help model the susceptibility of groundwaters to pollution.

Three of the conceptual response models are now described to illustrate how the HOST classification works.

Example 1 (HOST classes 1-5)

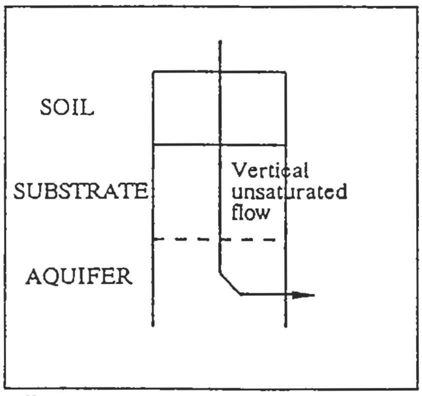

Figure 1

Permeable well drained soils on permeable substrates in which the dominant water movement is downwards through the unsaturated zone to an aquifer at least 2m below ground level. Lateral movement is confined to the saturated zone, (see Figure 1). The response of the model will depend on the time taken for the water to follow this pathway which is determined by the flow mechanism in the substrate. Five variations of this model are distinguished (HOST classes 1-5).

HOST 1. Weakly consolidated microporous substrates with composite matrix and fissure flow (eg. chalk, oolitic & brashy limestone). (BFI=1.00, SPR=0%)

HOST 2. Weakly consolidated macroporous substrates with intergranular flow predominant (eg. soft sandstone (Triassic)). (BFI=0.90, SPR=10%)

HOST 3. Hard consolidated substrates with by-pass fissure flow. (eg. Carboniferous limestones & sandstones, fissured/weathered igneous rock) (BFI=0.75, SPR=30%)

HOST 4. Unconsolidated macroporous substrates with intergranular flow (eg. sandy drift, gravel). (BFI=0.95, SPR=10%)

HOST 5. Unconsolidated microporous structured substrates with composite matrix and fissure flow (eg. loamy drift, coverloam). (BFI=0.65, SPR=30%)

Example 2 (HOST classes 8 and 9)

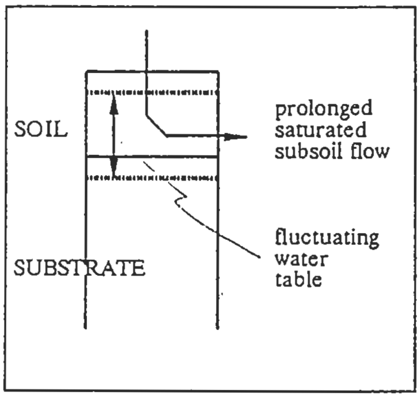

Figure 2

Permeable soils with prolonged saturated lateral subsoil flow caused by a shallow, fluctuating groundwater table. As the water table is close to the surface vertical water movements are short and water reaches the water table more quickly than in the previous model (compare Figures 1 and 2). Response within the model varies according to the saturated hydraulic conductivity of the soil as indexed by IAC.

HOST 8. IAC<12.5% (K_{sat} <1m/day) (BFI=0.85, SPR=10%)

HOST 9. IAC>12.5% (K_{sat} >1m/day) (BFI=0.35, SPR=50%)

Example 3 (HOST classes 17-22)

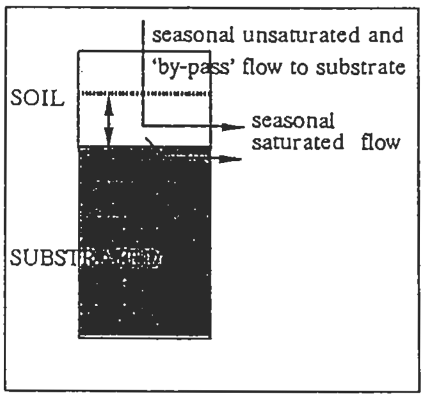

Figure 3

Soils with short seasonal saturation on slowly permeable or impermeable substrates. Soils within this model will always show some response to rainfall as water movement is predominantly lateral and the underlying strata prevent deep percolation (see Figure 3). The response within this model is broken down by Impermeability of the substrate and capacity of the soil to store water as indexed by IAC.

HOST 17. Higher soil water storage (IAC>7.5%), slowly permeable substrate (BFI≈0.50, SPR≈50%)

HOST 18. Higher soil water storage (IAC>7.5%), impermeable hard substrate (BFI≈0.50, SPR≈55%)

HOST 19. Higher soil water storage (IAC>7.5%), impermeable soft substrate. (BFI≈0.40, SPR≈55%)

HOST 20. Lower soil water storage (IAC≤7.5%), slowly permeable substrate. (BFI≈0.35, SPR≈55%)

HOST 21. Lower soil water storage (IAC≤7.5%), impermeable hard substrate. (BFI≈0.30, SPR≈50%)

HOST 22. Lower soil water storage (IAC≤7.5%), impermeable soft substrate. (BFI≈0.20, SPR≈50%)

CONCLUSION

A new soil classification that uses physical property data to define soil classes has been developed for hydrological purposes. It has been calibrated using catchment scale hydrological indices. The scheme can be applied at any site in England and Wales via the national 1:250,000 soil maps, but the same classification scheme can be applied with greater accuracy using larger scale soil series maps (where available) or soil survey data. The efficacy of the HOST classification has been demonstrated in estimating important flood and low flow indices and it has also been used in assessing the susceptibility of groundwater to pollution. It is hoped that many more areas of application are developed when details of how the classification may be used are published later this year.

ACKNOWLEDGEMENTS

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Table 1 The HOST Classification

<table>
<tr><td colspan="7">MINERAL SOILS</td><td colspan="2" rowspan="2">PEAT SOILS</td></tr>
<tr><td>GROUNDWATER OR AQUIFER</td><td>SOIL-HYDROGEOLOGY</td><td>No impermeable or gley layer with 100cm</td><td colspan="2">Impermeable layer within 100cm but no gleying
or
Gleyed layer between 40 and 100cm</td><td colspan="2">Depth to gleyed layer <40cm</td></tr>
<tr><td rowspan="3">>10 m</td><td>Weakly consolidated, Microporous, By-pass flow uncommon</td><td>1 (6.44)</td><td colspan="2" rowspan="5">12 (0.95)</td><td colspan="2" rowspan="5">13 (0.61)</td><td colspan="2" rowspan="5">14 (9.85)</td></tr>
<tr><td>Weakly consolidated Macroporous By-pass flow common</td><td>2 (1.56)</td></tr>
<tr><td>Strongly consolidated Non or slightly porous By-pass flow common</td><td>3 (3.23)</td></tr>
<tr><td rowspan="2">2 - 10 m</td><td>Unconsolidated Macroporous By-pass flow v. uncommon</td><td>4 (5.11)</td></tr>
<tr><td>Unconsolidated Microporous By-pass flow common</td><td>5 (7.28)</td></tr>
<tr><td rowspan="2"><2 m</td><td>Unconsolidated Macroporous By-pass flow v. uncommon</td><td colspan="3">6 (0.78)</td><td>Lateral Saturated Hydraulic Conductivity</td><td>IAC≥12.5% >1m day^{-1}</td><td>Drained</td><td>Undrained</td></tr>
<tr><td>Unconsolidated Microporous By-pass flow common</td><td colspan="3">7 (1.51)</td><td>IAC<12.5% <1m day^{-1}</td><td>9 (2.74)
8 (3.61)</td><td>10 (0.55)</td><td>11 (0.19)</td></tr>
<tr><td rowspan="6">NO GROUNDWATER OR AQUIFER</td><td>Permeable</td><td>15 (4.64)</td><td colspan="2">Soil water storage capacity
IAC >7.5% IAC ≤7.5%</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Slowly permeable</td><td>16 (0.86)</td><td>17 (4.88)</td><td>20 (4.02)</td><td colspan="2">23 (13.87)</td><td colspan="2">26 (2.52)</td></tr>
<tr><td>Impermeable (hard)</td><td></td><td>18 (2.22)</td><td>21 (1.12)</td><td colspan="2">24 (0.02)</td><td colspan="2">27 (0.87)</td></tr>
<tr><td>Impermeable (soft)</td><td></td><td>19 (0.69)</td><td>22 (1.31)</td><td colspan="2">25 (3.64)</td><td colspan="2"></td></tr>
<tr><td>Eroded peat</td><td colspan="5"></td><td colspan="2">28 (0.59)</td></tr>
<tr><td>Raw peat</td><td colspan="5"></td><td colspan="2">29 (8.37)</td></tr>
</table>

Numbers outside brackets are HOST classes, numbers inside brackets are percentage of England, Wales and Scotland covered by class.

THE HOST FRAMEWORK

	Depth to S.P.L. >100cm Depth to GL. hor. >100cm	GL. hor. @ 40–100cm OR GL. hor >100cm+S.P.L.<100cm	GL. hor. @ < 40cm	'Raw' peaty topsoil present
Aquifer at least 2m below the surface	SOIL SUBSTRATE AQUIFER Vertical unsaturated flow BFI 0.67–1.0	short seasonal saturated flow Mainly vertical unsaturated flow BFI 0.74	prolonged seasonal saturated flow some 'leakage' to substrate BFI 0.28	surface run-off + saturated soil flow some 'leakage' to substrate BFI 0.39
Aquifer/G'water within 2m of the surface	SOIL SUBSTRATE Mainly vertical unsaturated flow saturated flow fluctuating water table BFI 0.64–0.9	Model same as on left	prolonged saturated subsoil flow BFI 0.36–0.85	surface run-off + saturated soil flow BFI 0.25
No Aquifer or G'water present	SOIL SUBSTRATE vertical unsaturated and 'by-pass' flow BFI 0.5–0.55	seasonal unsaturated and 'by-pass' flow to substrate seasonal saturated flow BFI 0.21–0.51	prolonged seasonal saturated flow short seasonal unsaturated and 'by-pass' flow to subsrate BFI 0.21–0.32	surface run-off + saturated soil flow BFI 0.26