# Single-tree influence on soil permeability: The influence of mature English oaks (*Quercus robur*) on the permeability of a dystric gleysol in northwest England

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# Single-tree influence on soil permeability: The influence of mature English oaks (*Quercus robur*) on the permeability of a dystric gleysol in northwest England

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**The influence of single trees on soil permeability was investigated for six isolated oak trees (*Quercus* robur) growing on a dystric gleysol in an area of parkland in northwest England. Soil permeability was measured within the A horizon of the soil at fixed depths of 0.1 to 0.2 m using a borehole permeameter. Detailed study was initially undertaken around a single tree. Mean permeability was determined for distances from 1 to 13 m from the tree at 2 m intervals and compared with the mean permeability of the surrounding grassland soil. T-tests showed a significant difference between the soil permeability 1, 3, 5, 7 and 11 m from the trunk of the tree and in the surrounding grassland. There was no significant difference 9 and 11 m from the tree. Mean permeability 1 m from the tree was 5.05 x $10^{-6}$ m $s^{-1}$, a factor of 3.1 higher than the surrounding grassland soil. Mean permeability decreases with distance from the tree up to 9 m from it. Further measurements were then taken from around the five other trees and grouped with the data collected for the first tree in order to test if the pattern evident around the first tree was evident for all isolated oak trees at the site. A general pattern was confirmed and it was concluded that a circle of influence affecting the mean permeability of the soil around isolated oak trees on a dystric gleysol has been confirmed.**

***Keywords — borehole permeameter, constant head well permeameter method, English oak, hydraulic conductivity, Quercus robur, soil permeability***

## INTRODUCTION

Soil permeability (or hydraulic conductivity) is one of the main factors determining hydrologic flow pathways through a catchment. Consequently it exerts a strong influence on the shape of the catchment hydrograph (*i.e.* the rate at which water is discharged from the catchment) as well as the quality of water entering streams. Where soil permeability is low in relation to rainfall intensity, surface flow can cause soil erosion and localised flooding.

It has been widely accepted that forest soils have higher permeabilities than soils under other types of vegetation (Pritchett and Fisher, 1987; McCulloch and Robinson, 1993). This concept is typically supported by studies comparing infiltration capacity or surface saturated hydraulic conductivity (*e.g.* Wood, 1977; Berglund *et al.*, 1980; Burt *et al.*, 1983). While significantly fewer studies have compared permeability deeper in the soil profile (Chappell *et al.*, 1996), soils under forest cover have been shown to also have higher sub-surface permeabilities than under other vegetation types (*e.g.* Auten, 1933; Burch *et al.*, 1987, Lorimer and Douglas, 1995).

The perception that trees always enhance soil permeability has had important implications for land management decisions. The benefits associated with higher soil permeability has led to the use of forest cover often being advocated as a means to reduce flooding (*e.g.* Gregory *et al.*, 2003), protect soils (*e.g.* DEFRA, 2006) and improve water resources (Calder, 1999). The planting or retention of trees to act as buffer zones is also increasingly being recommended by guidelines for agriculture (Long and Nair, 1999; Syversen, 2003) and forestry (*e.g.* Sist *et al.*, 1998; Forestry Commission, 2003) to reduce the transport of sediment and pollutants by overland flow to watercourses by creating areas of increased infiltration. In the UK it has been suggested that buffer zones have an important role to play in tackling the objectives of the Water Framework Directive (Fogg *et al.*, 2005).

The results of some studies, however, suggest that the presence of trees does not always increase soil permeability. A study by Jaiyeoba (2001), which investigated the effect of reforestation on degraded land in Nigeria, found that there was no significant increase in the infiltration capacity of soils under any of the pine plantations studied. A significant increase was found under a 27-year old eucalyptus stand, but not under younger stands of the same species. Another study by Giertz *et al.* (2005) compared the surface saturated hydraulic conductivities of soils supporting three different agricultural crops in West Africa with those under uncultivated land. The uncultivated land, which comprised a mix of forest and savannah, was further subdivided according to the percentage of canopy cover. While the uncultivated soils exhibited higher permeabilities than the agricultural soils, among the uncultivated soils it was the land with the lowest percentage of canopy cover that had the highest mean saturated hydraulic conductivity and the forest, with the densest canopy cover, that had the least. This may suggest that the large differences in permeability between agricultural land and forest are more the result of the negative impact of agricultural practices, rather than the effects of tree cover.

Some studies even suggest that, in some instances, trees can have a negative impact on soil permeability. For example, Ranger and Nys (1994) found reduced structural stability in soils under spruce compared to soils under deciduous trees, which can, in turn, reduce saturated hydraulic conductivity as aggregates collapse (Baumgartl and Horn, 1991). A localised reduction in soil permeability beneath Sitka spruce was also reported by Chappell *et al.* (1996), with a factor of 5.4 reduction in permeability directly beneath individual conifers compared with soil 2 m away from each tree.

The assumption that the planting of trees will always provide the benefits of enhanced soil permeability is therefore questionable and it may be argued that our understanding of the extent to which trees influence permeability has been affected by the way that the research has generally been carried out. The problem lies in the fact that long term studies following afforestation are often not possible because funding is rarely available to cover the duration of such a project. Instead, comparisons are usually made between locations with different vegetation cover. However, differences in soil permeability between locations may be affected by other factors that differ between the sites. Soils suitable for agricultural purposes, for example, often differ from those able to sustain forest growth (Wilde, 1958; Pritchett and Fisher, 1987). The presence of large stones is one such factor that makes a site more suited to forestry rather than agriculture (Pritchett and Fisher, 1987) and stony soils have also been shown to exhibit higher values of saturated hydraulic conductivity (Talsma and Hallam, 1980; Ternan *et al.*, 1987). This tendency for forests to be found on the stonier soils was demonstrated by Sauer and Logsdon (2002) who found that forest soils in a catchment in Arkansas, USA contained a greater percentage of rock fragments compared with soils under pasture.

An alternative approach to the investigation of the influence of trees on soil permeability was undertaken by this study. The concept of ‘single-tree influence circles’, first introduced by Zinke (1962), is already well established for soil properties such as exchangeable cations and pH (*e.g.* Boettcher and Kalisz, 1990; Amiotti *et al.*, 2000). The influence of single trees has also been investigated for soil moisture depletion (Ziemer, 1968), rainfall interception (David *et al.*, 2005) and earthworm abundance (Boettcher and Kalisz, 1991). This work now seeks to determine the influence of individual trees on soil permeability, using isolated trees for study. The benefits of studying isolated trees are that the permeability of soil under an individual tree may be compared with the soil in the surrounding area and therefore the only factor influencing any differences in permeability should be the tree itself. The study of isolated trees allows us to investigate the spatial variability of permeability around the tree and therefore determine if any pattern exists and how the tree may be affecting that pattern. Finally, it allows us to determine the influence of a single species on a single soil type.

The trees chosen for study are English oaks (*Quercus robur*), also known as pedunculate or common oaks, growing in a parkland setting. Oaks are considered to be the most important tree in British forestry, comprising approximately 30% of the total broadleaved forest area (Hibberd, 1991).

The objectives of this study are to

(1) investigate the spatial variability of soil permeability around a single tree and compare this with the permeability of the soil in the surrounding grassland in order to determine if a significant difference exists and if a pattern can be detected;

(2) investigate other soil properties that may be influenced by the tree, which may, in turn, affect the soil permeability;

(3) compare observations from around the single tree with observations around other isolated trees at the site in order to determine if a general pattern of permeability around the trees can be detected.

## FIELD SITE

Field measurements were undertaken in an area of parkland (National Grid Ref: SD 485 577) on the campus of Lancaster University, which is located approximately three and a half miles south of the City of Lancaster in the north west of England (figure 1). The parkland was established in the early 1900s and became part of the new Lancaster University campus site when it was purchased in 1963 (Lancaster University, 2002). The site slopes gently to the west and is used for light recreation. A number of isolated trees grow in this area, including the mature oaks that are the focus of this study. These trees can be seen clearly marked on the Ordnance Survey map of the 1930s, so it may be confirmed that they are more than 70 years old and it is likely that they have been growing here for more than a century. The grass at the site is mown regularly with a heavy mower. This may result in some compaction of the soil; however the grass is generally cut to within a metre of the trunks of the trees, so this is unlikely to affect comparisons between soil permeability measurements at the site. Mean annual rainfall (1974 – 2005) recorded at the nearby Hazelrigg weather station is 1096 mm (Lancaster University Met. Observer, pers. comm.).

The soils at the site belong to the Brickfield series, forming part of the Charnock association (Hall and Follard, 1970). They were formed on glacial till, underlain by Millstone Grit, and contain variable amounts of sandstone and shale fragments (Hall and Follard, 1970). Under the classification for soils in England and Wales (Avery, 1990) they are classed as a cambic stagnogley soil, or under the FAO classification (FAO-UNESCO, 1990) as a dystric gleysol. These soils tend to be seasonally waterlogged as a result of poor natural drainage, owing to a slowly permeable subsurface horizon. This is fairly typical for the county, sixty percent of which is covered by surface water gley soils.

## METHODS

A total of six isolated English oaks at the experimental site were found to be suitable for study. The mean diameter at breast height (dbh) of these trees was 0.92 m (standard deviation = 0.23 m). A study of the influence of these trees on soil permeability was made within the A horizon of the soil profile (plate 1) by measuring saturated hydraulic conductivity at a depth of approximately 0.1 to 0.2 m. For most trees the majority of the fine roots grow in the upper 0.2 m of soil (Pritchett and Fisher, 1987). The A horizon has a sandy loam texture and

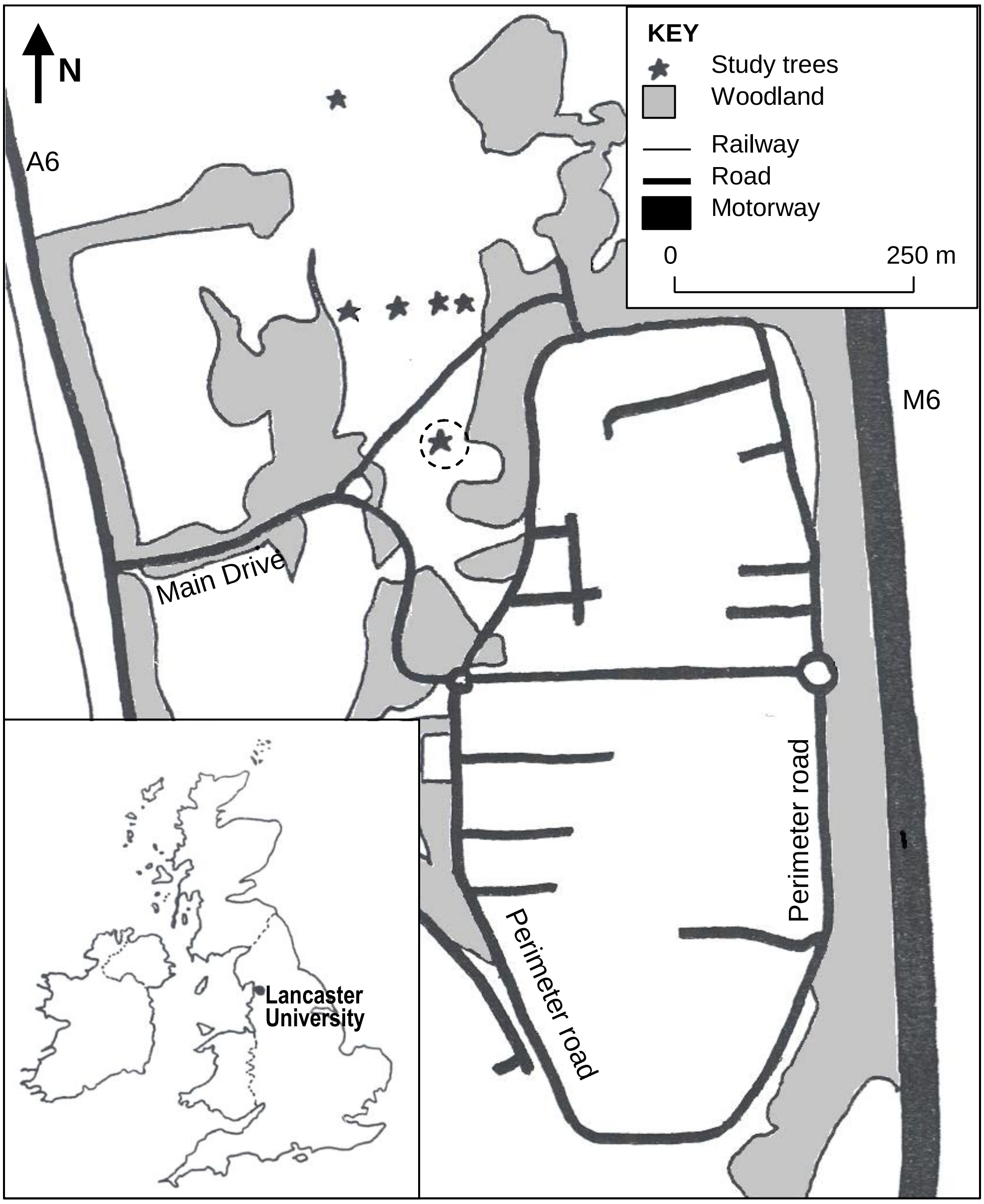

**Figure 1.** Map of the Lancaster University campus showing the location of the isolated oak trees studied indicated by a star. Detailed measurements were undertaken around the encircled tree. The location of Lancaster University is shown on the inset map.

intermittent waterlogging is indicated by a rusty coloured mottling, which occurs when iron is reduced, mobilised, concentrated and reoxidised (Singer and Munn, 2002).

Detailed measurements of saturated hydraulic conductivity were first undertaken around a single tree in order to determine if a circle of influence could be detected. The tree chosen for study (see figure 1) had a dbh = 0.99 m and a crown projection of between 7 and 10 m from the trunk. Measurements were recorded along eight transects extending radially outward from the tree along the eight points of the compass. These measurements were taken at 2 m intervals along each transect, from 1 to 13 m from the tree. The maximum distance was chosen to extend beyond the greatest projection of the crown, the minimum distance was chosen as the closest practical distance to the tree at which measurements could be taken. Each distance was measured from the straight part of the trunk at breast height to ensure consistency along each transect, since root buttresses created an irregular base to the tree. Saturated hydraulic conductivity measurements were also taken at eight random points under the area of grassland surrounding the tree for comparison. These measurements were recorded at distances of greater than 20 m from either this or any other tree in order to avoid the possible influence of tree roots. This distance was determined on the basis of a study by Lucot and Bruckart (1992), which found that the rooting systems of the 150-year old oaks that they studied spread up to 20 m from the tree and that it represented twice the distance of the crown projection.

Soil samples were taken from under the single tree in order to investigate soil properties that may have been altered by the tree and therefore affected the soil permeability. Samples were taken at the same depth at which the hydraulic conductivity measurements had been recorded. Sampling was carried out along the south transect at distances of 1, 5, 9 and 13 m from the tree and an additional sample was taken from the grassland. Tests were conducted to determine the organic matter content and pH and a particle size analysis was carried out.

Further saturated hydraulic conductivity measurements were then taken from around other isolated trees at the site to enable investigation for a general pattern of influence around them. Measurements were taken along two transects from each of four more trees and one transect under a fifth. Additional measurements were also made for the grassland soil to encompass the area in which the five trees are located.

### *Hydraulic conductivity measurement*

*In situ* measurement of soil saturated hydraulic conductivity ($K_s$) was performed using the constant head well permeameter method (Reynolds *et al.*, 1985). A Dutch auger was used to drill holes to a depth of 0.2 m into which a borehole permeameter was inserted and a constant head of 0.1 m maintained. The borehole permeameter used (plate 2) follows the design of Talsma and Hallam (1980), however it was constructed with smaller dimensions, therefore requiring less water to operate (200 cm$^3$) and making it more portable. This method was chosen because the narrow diameter of the well makes it easier to obtain measurements close to the tree and between the roots in comparison with alternative *in situ* techniques. It has been shown that underestimation of $K_s$ may result from the use of this method as the well walls can become smeared with clay during augering, blocking structural pores. This is a particular problem in gleyed soils, such as those at the study site (Chappell and Lancaster, 2006); however, since all tests were conducted on the same soil type and should therefore be subject to similar error, this should not prevent comparison between them.

$K_s$ is calculated from a steady-state flow rate from the permeameter. Plotting permeameter discharge against time, a steady-state flow rate was determined from the gradient of the linear portion of the graph. It should be noted though that, although steady-state flow is considered to indicate a state of saturation around the well, Reynolds *et al.* (1983) argue that air entrapment during the infiltration process means that complete saturation can never be fully achieved with this technique and it is, in fact, a 'field-saturated' hydraulic conductivity ($K_{fs}$) that is being measured. For the purposes of this paper, however, the measured hydraulic conductivity will continue to be referred to as the saturated hydraulic conductivity ($K_s$).

Various analytical solutions have been developed to estimate $K_s$ from a borehole permeameter discharge (Cassiani, 1998). The problem was initially solved by Glover in Zangar (1953 cited in Cassiani, 1998). However, Glover's solution has been shown to overestimate $K_s$ because it does not account for gravity flow out of the well and makes the assumption that the soil is saturated throughout (Elrick and Reynolds, 1992). Since measurement is carried out above the water table, this assumption is invalid. Instead, when steady-state flow is reached, a saturated bulb exists adjacent to the well, surrounded by a larger wetted, but unsaturated, volume (Philip, 1985) and steady-state flow is influenced by the capillary properties of this unsaturated region (Reynolds *et al.*, 1985). Solutions that account for both the saturated and unsaturated components of flow were subsequently developed independently by Reynolds *et al.* (1985) and Philip (1985) and these solutions have been shown to give comparable results (Elrick *et al.*, 1989). Other approaches have been proposed by subsequent authors, essentially attempting to solve the same problem (Cassiani, 1998). However, since each is based on slightly different assumptions, estimation of $K_s$ will be dependent on the solution chosen and the solutions themselves can be a source of systematic error (Chappell *et al.*, 1996).

The solution chosen for use in this study was developed by Elrick *et al.* (1989) and is based on the Reynolds *et al.* (1985) solution. Since the Reynolds *et al.* (1985) solution involves two unknown values, discharge for two tests maintaining different constant head values must be obtained and the resulting equations solved simultaneously. In order to overcome this problem Elrick *et al.* (1989) adapted this solution to allow a single-height analysis to be carried out. The resulting equation can be written as

$$K_s = CQ/(2\pi H^2 + \pi r^2 C + 2\pi H/\alpha^*) \qquad (1)$$

where $K_s$ ($L\ T^{-1}$) is the saturated hydraulic conductivity, H (L) is the constant head of water in the well, r (L) is the radius of the well, Q ($L^3\ T^{-1}$) is the steady-state discharge from the permeameter, C a dimensionless shape factor dependent on the geometry of the well, $\alpha^*$ ($L^{-1}$) is the ratio of $K_s/\varphi_m$ and $\varphi_m$ is the matric flux potential. The three terms in the denominator of equation (1) represent, respectively, the approximate contributions of hydrostatic pressure, gravity and capillarity to the total flow from the well (Elrick and Reynolds, 1992).

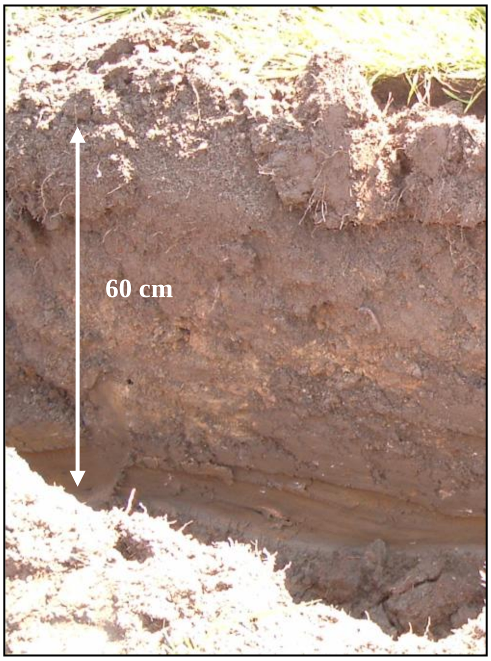

**Plate 1.** The upper part of the soil profile at the study site.

**Plate 2.** The borehole permeameter. Measurements were taken along transects extending radially from the tree.

**Plate 3.** Air dried soil samples taken (from left to right) 1, 5, 9 and 13 m from the first tree studied together with the grassland sample (right).

The shape coefficient, C, depends primarily on the H/r ratio (Bagarello and Giordano, 1999). Although Glover's solution includes an equation for C, this does not satisfy the boundary condition of constant hydraulic head along the wetted surface of the well (Elrick and Reynolds, 1992). Improved approximations were published by Reynolds *et al.* (1983) and Philip (1985). The Reynolds *et al.* (1985) 'half-source' solution has been developed for ratios of H/r between 5 and 10. Since the H/r ratio in this study is less than 5, Philip's (1985) solution, which allows for a greater range of values, was chosen to solve for C. This formula takes the form

$$C = 0.56 + 0.35H^{-1} \quad (2)$$

Although the matric flux potential, $\varphi_m$ is unknown, the ratio $K_s/\varphi_m = \alpha^*$ may be estimated from soil structural/textural considerations (Elrick *et al.*, 1989). Estimated values are summarized by Elrick and Reynolds (1992). $\alpha^*$ was chosen as 12 $m^{-1}$, representing most structural soils. Elrick and Reynolds (1992) suggest that, in most instances, site evaluation of $\alpha^*$ will be in error by no more than one category, leading to an error in $K_s$ by a factor of 2 or 3 at the most. They consider this to be an acceptable level of error given that soil $K_s$ can range from $10^{-9}$ to $10^{-4}$ m $s^{-1}$. For a single soil type comparison between measurements will not be affected by incorrect choice of $\alpha^*$ since the value will remain constant between them.

Since $K_s$ is dependent, not only on the properties of the soil, but also on the viscosity of the fluid flowing through it, the values of $K_s$ calculated by these equations are representative of the water temperature at the time each test was carried out (Chappell and Ternan, 1997). A correction factor was applied in order to standardise the values for a water temperature of 20°C.

All of the above calculations were performed by a Matlab program written for this purpose (see Appendix).

### *Soil sampling and analysis*

Soil samples were collected from a depth of 0.1 to 0.2 m in the soil profile to coincide with the depth at which hydraulic conductivity was measured. The organic matter content of the soil was determined from loss on ignition (Rowell, 1994). Particle size analyses were carried out to determine the sand, silt and clay fractions of the soil using the hydrometer method (Gee and Bauder, 1986). Soil pH was determined from a 0.4 g $cm^{-3}$ soil-water suspension using a glass electrode pH meter (Radojevic and Bashkin, 1999).

### *Data analysis*

Statistical analysis of the hydraulic conductivity data was undertaken in order to determine if differences in soil permeability were detectable around individual trees compared with adjacent grassland.

Results from around a single tree were initially investigated. Data collected from transects around this tree were grouped according to distance from the tree and a further data set was compiled from the measurements taken under the surrounding grassland. The distribution of these datasets was investigated and confirmed using the Kolmogorov-Smirnov test. A comparison was made for each dataset representing a distance from the tree with the grassland dataset using the unpaired Student t-test. Comparisons were also made between each of these data sets and the significance levels used as a basis to determine the distances at which hydraulic conductivity measurements were to be taken from around other isolated trees at the site. Since measurements were taken along radial transects the data was paired, therefore a paired Student t-test was used.

Measurements taken from around the other five trees in the study were all grouped, also according to the distance from the tree at which they were measured, and a further grassland dataset compiled. After checking the data for the same distribution as around the single tree, each dataset was compared with the corresponding one from the single tree analysis using the unpaired Student t-test. Following confirmation that no statistically significant difference existed between each of them, the data was grouped into larger sets representing data for all six trees studied. Comparison was then made between each of the datasets representing distances from the trees with that representing the grassland hydraulic conductivity in order to determine if the influence of the single tree was representative of a general pattern for oak trees at the site.

Finally, a possible relationship between the soil permeability and the distance from the tree was investigated by plotting mean $K_s$ against distance from the tree for both the single tree and all six trees.

## RESULTS AND DISCUSSION

The influence of individual trees on soil permeability was initially tested for a single isolated tree at the study site. Additional data were then collected for five other isolated trees at the site and the data grouped in order to determine if a general pattern of permeability around these trees could be detected.

### *Statistical distribution of soil permeability*

Datasets compiled to represent distances from the single tree each comprised eight $K_s$ values, with the exception of the 1 m dataset, which had one less owing to the fact that a large shallow root prevented measurement at this distance along the northwest transect. The dataset representing grassland soil in the area surrounding the tree also consisted of eight values. Additional datasets representing permeabilities around the other five trees each included nine $K_s$ values and for comparison a set of eleven values was compiled from further grassland measurements. A Kolmogorov-Smirnov (K-S) test applied to each set of data indicated that the values are normally distributed, where a significance value greater than 0.05 indicates that there is no evidence against the hypothesis that the distribution is normal (Kinnear and Gray, 2000). A summary of the calculated statistics is given in table 1.

After confirming that all the datasets had the same distribution, unpaired t-tests were undertaken to compare the means of datasets representing distances from the five additional trees with the corresponding datasets for the first tree. No statistical difference was indicated, so the data from the first tree were added to that from the additional trees, to generate new datasets representing values for all six trees. The grassland datasets were also combined. Sample size has an important bearing on the level of error in any statistical analysis. By grouping data for all six trees, sample size for the analysis of a general pattern around isolated trees at the site was approximately doubled. The distributions of these larger datasets were also analysed with a Kolmogorov-Smirnov test and found to be normal (table 1).

**Table 1.** Results of the Kolmogorov-Smirnov tests, showing the K-S test statistic and significance.

| | **Single tree** | | **Other trees** | | **All trees** | |
|---|---|---|---|---|---|---|
| **Dataset** | **Z** | ***p*** | **Z** | ***p*** | **Z** | ***p*** |
| 1 m | 0.367 | 0.999 | | | | |
| 3 m | 0.809 | 0.530 | 1.002 | 0.267 | 1.221 | 0.101 |
| 5 m | 0.539 | 0.934 | | | | |
| 7 m | 0.906 | 0.834 | 0.871 | 0.434 | 1.224 | 0.090 |
| 9 m | 0.825 | 0.504 | 0.324 | 1.000 | 0.542 | 0.931 |
| 11 m | 0.461 | 0.983 | 0.421 | 0.994 | 0.395 | 0.998 |
| 13 m | 0.795 | 0.552 | 0.601 | 0.864 | 0.569 | 0.902 |
| grass | 0.698 | 0.714 | 0.448 | 0.988 | 0.688 | 0.731 |

The normal distribution of saturated hydraulic conductivity at this site contrasts that of many other permeability studies, which typically show a logarithmic distribution (*e.g.* Talsma and Hallam, 1980; Bonell *et al.*, 1983; Chappell and Franks, 1996; Chappell *et al.*, 1998). However, other distributions with a much lower degree of skew have been reported (*e.g.* Elsenbeer *et al.*, 1992; Chappell *et al.*, 1996).

### *Soil permeability around isolated trees*

The results of t-tests comparing the mean values of $K_s$ around the single tree and in the surrounding grassland area are summarised in table 2. A significant difference ($p < 0.05$) from the mean permeability of the grassland soil was found at 1, 3, 5 and 7 m from the trunk of the tree. This coincides approximately with the crown of the tree, which extends 7 to 10 m from the trunk. No significant difference was evident at either 9 or 13 m from the tree, however the t-test did indicate a significant difference at 11 m.

$K_s$ values recorded around the single tree are shown in figure 2a. From this it may be seen that the data recorded closest to the tree, at 1 and 3 m, exhibit a greater range than at greater distances. Since the data are normally distributed they may be summarised by the arithmetic mean and these values, plotted against the distance from the tree, are shown in figure 2b. The underlying mean permeability recorded for the grassland soil surrounding the single tree is also indicated in this figure. The highest mean permeability, of $5.05 \times 10^{-6}$ m $s^{-1}$, is found 1 m from the tree and is a factor of 3.1 higher than that in the surrounding grassland. The decline in permeability with distance from the tree, seen in figure 2b, may be described by the linear relationship

$$\langle K_s \rangle = (4.9 - 0.3d) \times 10^{-6} \qquad (3)$$

where $\langle K_s \rangle$ is the arithmetic mean of the saturated hydraulic conductivity (m $s^{-1}$) and d is the distance from the tree (m). This relationship has a high coefficient of determination ($r^2$ = 0.83), however the significant difference between mean grassland permeability and the mean permeability at 11 m, but not at 9 m, could suggest that the actual relationship is non-linear.

To test for a general pattern of permeability around oak trees at this site the data from around all six trees was grouped. Any changes in the underlying permeability of the soil across the site could potentially obscure any patterns within it. T-test results had already shown that there was no significant difference between the mean permeability recorded in the area of grassland surrounding the single tree and the additional grassland measurements taken across the site. Coefficients of variation, of 52 and 56% respectively, indicate that there is also no significant increase in the variation of permeability when measurements are taken for the wider area.

Before grouping the data for all six trees, a comparison was made between the mean $K_s$ for each distance from the group of five additional trees and mean $K_s$ for distances from the first tree. These values were found to correspond well and are shown in figure 3a. Since approximately half of the total datasets for the grouping of all six trees comprise data collected around the first, an analysis of an overall pattern would obviously be weighted in favour of any pattern around that first tree. Since the plotted data indicates very little difference in the mean values at each distance this should not unduly bias the results.

**Table 2.** Summary of t-test results between datasets collected around the single tree.

| | Dataset | | | | | | |
|---|---|---|---|---|---|---|---|
| Dataset | 1 m | 3 m | 5 m | 7 m | 9 m | 11 m | 13 m |
| Grass | ** | * | ** | * | ns | * | ns |
| 1 m | | ns | ns | ns | * | ns | * |
| 3 m | | | ns | ns | * | ns | ns |
| 5 m | | | | ns | ns | ns | ns |
| 7 m | | | | | ns | ns | ns |
| 9 m | | | | | | ns | ns |
| 11 m | | | | | | | ns |
| 13 m | | | | | | | |

Level of significance: * $p < 0.05$; ** $p < 0.01$; ns = no significance

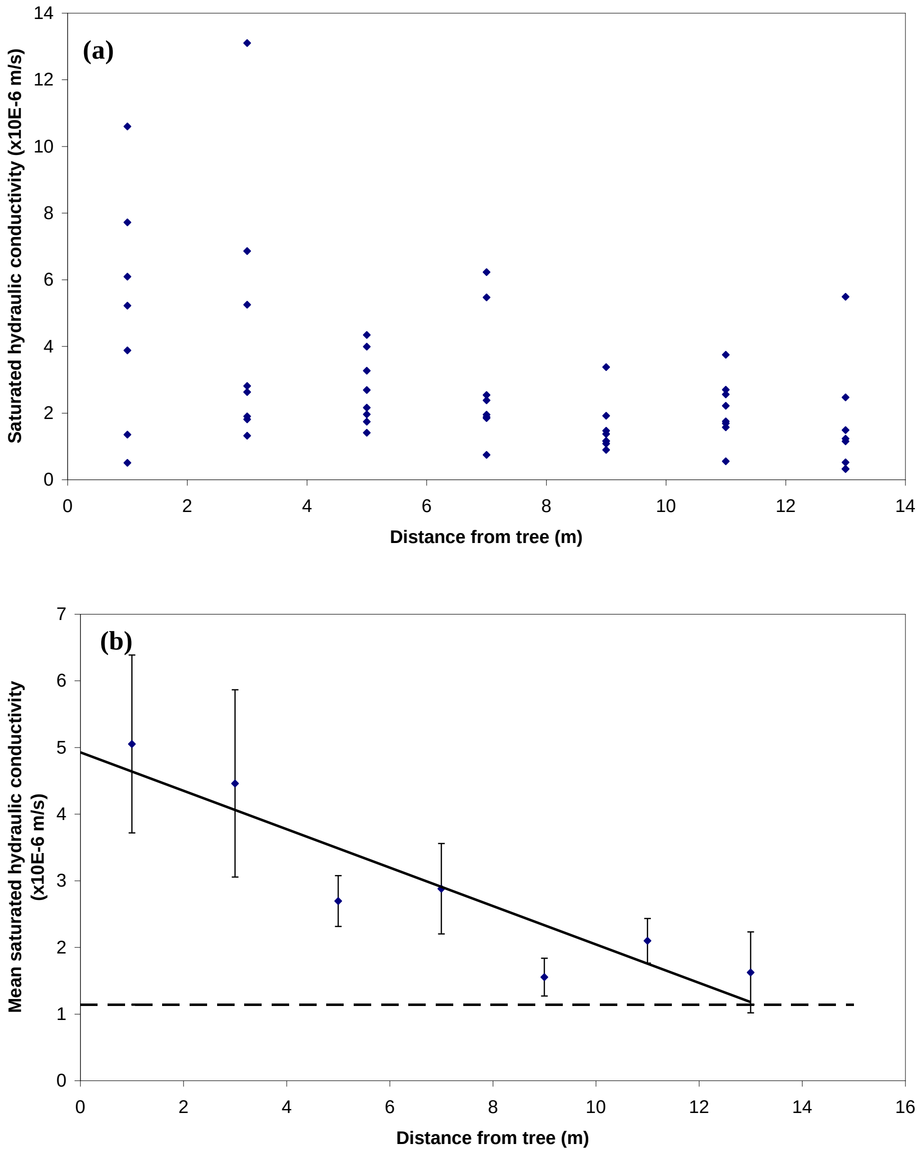

**Figure 2.** **(a)** A plot of the hydraulic conductivity values recorded around a single tree; **(b)** The relationship between mean hydraulic conductivity around the same tree and distance from it. Error bars show the standard error of the mean. The dashed line indicates the mean permeability of the soil in the area of grassland surrounding the tree.

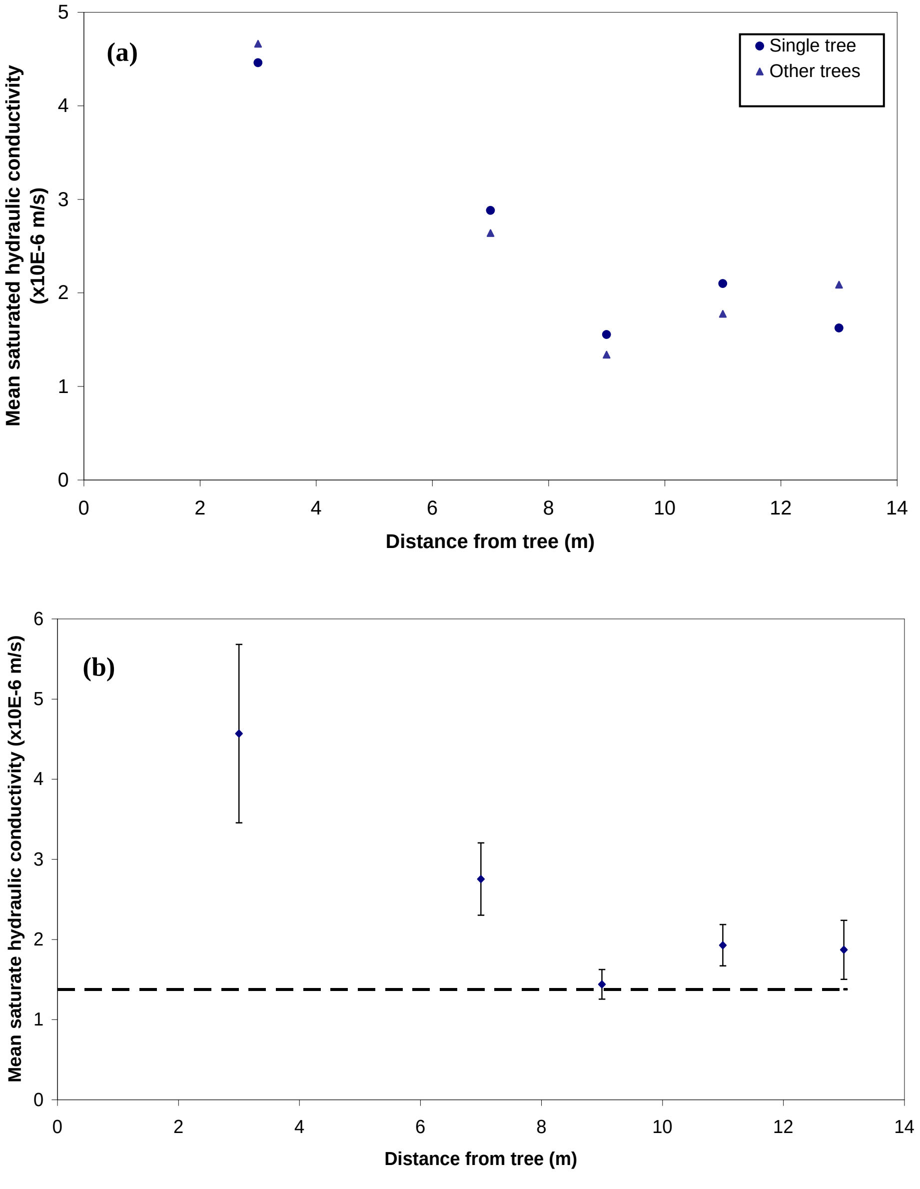

**Figure 3.** **(a)** Graph showing a comparison of the mean hydraulic conductivity recorded around the single tree and the other five trees studied. **(b)** The mean hydraulic conductivity determined around all six trees studied. Error bars show the standard error of the mean. The dashed line indicates the mean permeability of the soil in the area of grassland surrounding the tree.

The results of t-tests comparing the mean values of $K_s$ around the group of all six isolated trees with the mean $K_s$ of grassland soil indicate that permeability 3 and 7 m from these trees is significantly different ($p < 0.05$) from the grassland permeability. Mean permeability at greater distances is not significantly different from the grassland permeability at the 5% ($p < 0.05$) level of significance. However, for a 10% ($p < 0.1$) level of significance the permeability at 11 m is significantly different, although permeability at 9 and 13 m is not.

Mean $K_s$ values plotted against distance from the adjacent tree are shown in figure 3b. Permeability shows an initial decline up to and including 9 m from the tree, however the mean permeability then increases again beyond this distance.

Considering both the t-test results and plotted mean values of $K_s$ with distance from the tree around which the values were recorded, there is evidence to suggest that a circle of influence around the tree may be detected for mean soil permeability and that a general pattern exists for all isolated oaks at this site. This pattern shows a decline in mean permeability with distance from the tree up to 9 m from the trunk. A significant difference from grassland soil mean permeability is also evident up to 7 m from the tree. This pattern approximately coincides with the projection of the tree crown. There is also evidence to suggest that the tree exerts a significant influence on permeability just beyond the projection of the crown. It is hypothesised that the influence of the tree on permeability has both positive and negative components, with a net positive influence evident for the same radius as the crown of the tree. An increase in mean permeability beyond this point may then be explained if the extent of the influence of some negative component coincides with the crown projection, but a positive component extends beyond it.

### *Possible mechanisms to explain changes in soil permeability*

There are four mechanisms that may influence the permeability of the soil around a single tree. These are the presence of living and decayed tree roots, the weight of the tree, changes to soil chemistry and the addition of organic matter to the soil.

Both living and decayed roots can create large pores or channels in the soil called macropores (Beven and Germann, 1982). Flow through macropores can be up to several hundred times faster than flow through the soil matrix and large volumes of water may move through macropores without appreciably wetting the soil mass (Aubertin, 1971). Buttle and House (1997) demonstrated that the presence of macropores can mask the influence of soil physical properties on permeability and the presence of old root channels, in particular, has been found to be closely correlated with overall permeability (Aubertin, 1971). It is therefore probable that the higher permeability observed around isolated oak trees is mainly attributable to the presence of macropores associated with the tree's roots and that the decrease in permeability with distance from the tree corresponds to the reducing density of the root system. Since the roots of oak trees can extend well beyond the crown area (Hocker, 1979), root associated macropores could also account for the significant difference in permeability observed beyond the radius of the crown. However, the possible contribution of soil structural differences to the overall influence of the tree on soil permeability should not be discounted at this site. The overall contribution of tree roots to soil permeability has been shown to be influenced by soil texture. The A horizon of the soil at the site is a sandy loam and it has been shown (Aubertin, 1971) that, compared with finer textured soils, a greater proportion of the overall flow occurs through the soil matrix in a sandy loam soil. This may be explained by the relatively larger soil matrix pores created by the coarser texture and the fact that old root channels tend to be less well preserved (Aubertin, 1971).

Although roots have a mainly positive impact on soil permeability by creating macropores, there is evidence that root growth can reduce the permeability of the soil surrounding the root by increasing its density (Whalley *et al.*, 2004). Soil density may also be increased by the weight of the tree. Both these influences are likely to be greatest around structural roots and therefore also likely to be greatest nearest the base of the tree, where the structural roots are closest to each other. This may possibly explain the greater range in hydraulic conductivity measurements recorded 1 and 3 m from the tree, where it was more likely that the proximity of a structural root could have influenced some of these measurements compared with further away.

The influence of trees on soil chemistry could have a significant effect on soil permeability by influencing the presence and abundance of soil fauna. Boettcher and Kalisz (1991) showed that nutrient cycling characteristics of different tree species affected the abundance of earthworms in the soil. Earthworm activity can have a positive effect on soil permeability by creating very stable soil aggregates (Graham *et al*., 1995) and earthworm tunnels also form highly connected macropores (Beven and Germann, 1982).

Changes to soil chemistry can also affect soil permeability by affecting the structural stability of the soil. An increased rate of dissolution of soil minerals has been linked to increased soil acidity under tree stands (Augusto *et al.*, 2000) and soil structural stability has been shown to decrease under coniferous stands following chemical changes in the soil (Ranger and Nys, 1994). This reduced stability can lead to a reduction in porosity and therefore permeability as aggregates collapse (Baumgartl and Horn, 1991). Although acidification of the soil by oaks is generally considerably less than by coniferous trees, a reduction in pH has been reported under oak stands (*e.g.* Moffatt and Boswell, 1990). Conversely, aggregate stability has been shown to be enhanced by increased organic matter (Chaney and Swift, 1984), so the input of organic matter to the soil around the tree, from leaf and bark litter and decayed roots, can have a positive impact on permeability.

Soil sampling was carried out under the first tree studied in order to test the possibility that the tree may be influencing structural changes to the soil by changing the pH and organic matter content of the soil. This testing was by no means intended to provide a comprehensive answer but, since a radial symmetry in pH around single trees has already been demonstrated (Zinke, 1962), sampling along a single transect could provide a useful insight into a possible direction for further study. A further sample was taken from the grassland soil for comparison. Qualitative observations of the air dried samples (plate 3) revealed differences in colour and aggregate sizes between the samples. The 1 m sample was dark in colour and formed fine crumbs. The 5 and 9 m samples were a slightly orange colour and had a quite powdery texture. The 13 m and grassland samples were also very similar to each other. These samples were lighter in colour than the 1 m sample but did not have the orange colour of the 5 and 9 m samples. Much larger aggregates were also observed in these samples. These qualitative observations therefore imply that soil structure is influenced by the tree and this may affect soil permeability. Results of analyses of soil pH, organic matter content and particle size are given in table 3. The distribution of particle sizes was similar for samples at all distances from the tree and in the grassland sample, indicating that soil texture has not been affected by the tree. The pH of the grassland soil indicates that soil at the site is already in the range described as strongly acidic (Singer and Munns, 2002). There is no evidence that the tree influences soil pH 5, 9 and 13 m from the trunk, however the 0.6 unit reduction in pH 1m from the trunk of the tree compared with the grassland value could be significant. Moffat and Boswell (1990) report a 0.5 of a unit decrease in soil pH under oak stands in Yorkshire. The percentage of organic matter in the soil showed a small elevation 1 m from the tree compared with other distances, which would explain the darker colour and crumbly structure of this sample. Organic matter may therefore influence soil permeability under the tree, but only around the base of the trunk. Although the limited sampling around the tree means that these results are inconclusive, they do suggest possible influences by pH and organic matter 1 m from the tree trunk, which may be worth further study. However, since these influences oppose each other, they may well cancel each other out.

**Table 3.** The results of tests on soil samples taken from under the first tree studied.

| | | Particle size | | | |
|---|---|---|---|---|---|
| Sample | pH | Sand (%) | Silt (%) | Clay (%) | Organic Matter (%) |
| 1 m | 4.5 | 64 | 25 | 11 | 9 |
| 5 m | 5.0 | 62 | 27 | 11 | 6 |
| 9 m | 4.9 | 62 | 27 | 11 | 6 |
| 13 m | 5.0 | 62 | 25 | 13 | 6 |
| Grass | 5.1 | 61 | 28 | 11 | 7 |

### *Putting the findings into context*

This study has demonstrated that oak trees can increase the permeability of a dystric gleysol in relation to grass. The approximately three-fold increase in permeability 1 m from the tree in relation to the surrounding grassland soil also supports differences reported by other studies that make comparisons between different locations under forest and grass. For example, Burch *et al.* (1987) report differences that range from a factor of 1.5 to 3.7, while Lorimer and Douglas (1995) report a factor of 2.0 higher permeability under the forest cover.

Mean permeability 1 m from the trees studied is 4.57 x $10^{-6}$ m $s^{-1}$. Neirynk *et al.* (2000) report slightly higher values of 8.8 x $10^{-6}$ m $s^{-1}$ and 1.05 x $10^{-6}$ m $s^{-1}$ under oak stands in Belgium. Since permeability will be influenced by soil type as well as tree species, these findings seem comparable.

The positive influence of isolated trees on soil permeability will have little impact at the catchment or even the hillslope scale, except possibly in an urban setting, where enhanced infiltration around individual trees could speed the flow of runoff from surrounding impermeable surfaces into the soil below and therefore possibly reduce areas of localised flooding. These findings do support the use of small areas of trees as buffer zones to reduce runoff from adjacent, less permeable land. However, since different tree species and soil types will interact differently to affect permeability, the influence of different species-soil combinations is an important area for further study.

It was suggested by Zinke (1962) that, in a forest, soil properties within a unit area are determined by the summation of the influence patterns of individual trees. However, this assumption is unlikely to hold in the case of soil permeability, especially since the spatially heterogeneous nature of soil permeability means that the pattern found around isolated oaks is one of mean rather than actual permeability at any point. Where the influence of trees on soil permeability is principally caused by root associated macropores, it will be the connectivity of the pores that will determine the overall permeability of a unit area of forest soil. It might be reasonable to assume that the network of roots created by multiple trees would increase connectivity and therefore further enhance permeability; however it has been shown that rooting patterns are influenced by competition, both between and within species (Hertel and Leuschner, 2005). The effect of interactions between trees on the pattern of permeability around them would therefore be interesting to study.

Although this research has shown an increase in permeability around isolated oak trees in the A horizon of the soil, the overall infiltration capacity and the direction of flow is a function of the least permeable layer (Schwartzendruber, 1960). Further work is therefore necessary in order to determine the depth of the tree’s influence in addition to its lateral extent. The depth of the influence of the tree on soil permeability could have important implications for flow pathways. Where a soil horizon with low permeability is underlain by more permeable layers, an increase in the permeability of the least permeable layer could allow flow to penetrate through it and into the more permeable layers below. For a large number of trees this could have a significant impact on the hydrology of a catchment.

By examining permeability around isolated trees this study has found a pattern that suggests that the tree has both positive and negative components of influence on soil permeability. Consideration of the possible mechanisms for change to the underlying permeability of the soil show that multiple influences may act together to create the overall pattern of influence. Further study of the individual mechanisms and how they act at different distances from the tree could allow us to better predict the impact of a particular species on the permeability of a particular soil type.

## CONCLUSIONS

Investigation of soil permeability around isolated English oak trees growing in parkland has demonstrated a positive influence by the trees on the mean permeability of the dystric gleysol soil. A single-tree circle of influence increasing the mean permeability of the soil around the trees is evident and a generalised pattern for all isolated oaks studied at the site has been shown. A significant difference in mean permeability from the surrounding grassland soil is evident up to 7 m from the trunks of the trees, a pattern found to coincide with the projection of the tree crown. One metre from the tree there is an approximately three-fold increase in permeability in relation to the surrounding grassland soil. Permeability then decreases with distance from the tree up to 9 m from it, where a small increase is then evident.

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## APPENDIX

Matlab program to solve for hydraulic conductivity:

```
% PROGRAM: Ks_Solver
% AUTHOR:  Kathy Chandler
% DATE:    20-08-2006
%
% Program to convert permeameter discharge to a hydraulic conductivity
% value using the solution by Elrick et al. (1989).
% The solution for the C coefficient is from Philip (1985).
% Calculation is for a permeameter with dimensions:
% inner pipe (outer diameter) = 1.6 cm
% outer pipe (inner diameter) = 2.4 cm
%
% INITIAL SECTION
% ------------------------
 clear all;
 close all;
%
% Initialise constant values:
 reservoir_area = 0.000251328;
%
% Load file containing permeameter discharges:
% Column 1 - Measurement id
% Column 2 - Water temperature (degrees C)
% Column 3 - Radius of auger hole (m)
% Column 4 - Depth of auger hole (m)
% Column 5 - Depth of reservoir base below ground surface (m)
% Column 6 - Soil structural/textural parameter (1/m)
% Column 7 - Permeameter discharge (m/s)
 load discharge.txt
%
% Store data from file in variables:
% (this step not actually necessary, but makes prog. easier to read)
 temp = discharge(:,2);
 r = discharge(:,3);
 h1 = discharge(:,4);
 h2 = discharge(:,5);
 alpha_star = discharge(:,6);
 q = discharge(:,7);
%
% Open output file to store hydraulic conductivity:
 fid=fopen('ksat.txt','w');
```

```
%
% PROCESSING SECTION
% --------------------------------
% Calculate head values (m):
 H = h1 - h2;
%
% Calculate volumetric discharge values (m3/s):
 Q = reservoir_area * q;
%
% Calculate Ks (m/s), correcting for viscosity at 20 deg. C, and save to
% output file:
 for c = 1:length(temp)
  viscosity_correction_factor = 1/(10^(((1.37023*(temp(c)-20)) + (0.000836*((temp(c)-20)^2)))/(109+temp(c))));
  C = 0.56+(0.35*(H(c)^(-1)));
  Ks = (Q(c)*C)/((2*pi*(H(c)^2))+(pi*(r(c)^2)*C)+(2*pi*(H(c)/alpha_star(c))));
  Ks_corrected = Ks * viscosity_correction_factor;
  fprintf(fid,'%d %.3g \r',discharge(c,1),Ks_corrected);
 end;
%
% FINAL SECTION
% -----------------------
% Close output file:
 fclose(fid);
%
% END
```