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FULL TITLE:

HYDROLOGICAL CONNECTIVITY OF SOIL PIPES DETERMINED BY GROUND PENETRATING RADAR TRACER DETECTION

SHORT TITLE:

HYDROLOGICAL CONNECTIVITY OF SOIL PIPES

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Abstract

Soil pipes are common and important features of many catchments, particularly in semi-arid and humid areas, and can contribute a large proportion of runoff to river systems. They may also significantly influence catchment sediment and solute yield. However, there are often problems in finding and defining soil pipe networks which are located deep below the surface. Ground penetrating radar (GPR) has been used for non-destructive identification and mapping of soil pipes in blanket peat catchments. While GPR can identify subsurface cavities, it cannot alone determine hydrological connectivity between one cavity and another. This paper presents results from an experiment to test the ability of GPR to establish hydrological connectivity between pipes through use of a tracer solution. Sodium chloride was injected into pipe cavities previously detected by the radar. The GPR was placed downslope of the injection points and positioned on the ground directly above detected soil pipes. The resultant radargrams showed significant changes in reflectance from some cavities and no change from others. Pipe waters were sampled in order to check the radar results. Changes in electrical conductivity of the pipe water could be detected by the GPR, without data post-processing, when background levels were increased by greater than approximately twofold. It was thus possible to rapidly determine hydrological connectivity of soil pipes within dense pipe networks across hillslopes without ground disturbance. It was also possible to remotely measure travel times through pipe systems; the passing of the salt wave below the GPR produced an easily detectable signal on the radargram which required no post-processing. The technique should allow remote sensing of water sources and sinks for soil pipes below the surface. The improved understanding of flowpath connectivity will be important for understanding water delivery, solutional and particulate denudation, and hydrological and geomorphological model development.

Keywords : Ground penetrating radar, soil pipes, peat, uplands, runoff, tracers, subsurface hydrology, pipeflow

Introduction

Soil piping is common in semi-arid areas, where soil shrinkage and desiccation cracking are frequent occurrences (Bryan and Yair, 1982), and in highly organic soils in humid uplands (e.g. blanket peats; Bryan and Jones, 1997; Holden and Burt, 2002; Holden and Burt, 2003). However, soil pipes can be found in virtually all climates, in organic and mineral soils, and on disturbed and undisturbed land. Laboratory work (e.g. Sidle *et al*., 1995), modelling (e.g. Nieber and Warner, 1991) and field measurement (e.g. Zhu, 1997; Carey and Woo, 2000) have shown that piping can be a very important hydrological phenomenon particularly in humid temperate regions (e.g. Gilman and Newson, 1980; Jones, 1981; Jones *et al*., 1997; Uchida *et al*., 1999). Jones and Crane (1984) reported, for example, that 49 % of streamflow in the Maesnant catchment, mid-Wales, UK was generated through the pipe network. Holden and Burt (2002) found 10 % of discharge in peat catchments moved through the pipe network but at times (depending on antecedent conditions) this could be as high as 30 %.

Until recently it has been difficult to find and define soil pipe networks. This is because pipes are often only visible at stream banks or where the pipe roof has collapsed creating a surface opening or forming a gully. Therefore it is difficult to map soil pipe networks or to measure pipe diameters, depth and channel length below the surface. In some soils a change in surface vegetation may often indicate the presence of a pipe (Jones, *et al.,* 1991) but this is only where pipes are very shallow features. Jones and Crane (1984) extensively mapped 4.4 km of pipes in a drainage area of only 0.23 km^2 by dye tracing and ground survey. Pipe locations were identified mainly by observation of collapse features, of water jets emerging from pipes and the sound of flowing water (Jones, 1981). However, these techniques do not give a detailed or complete picture of the subsurface network and can result in underestimates of the pipe density. Where pipes are several metres below the surface they cannot be readily identified. Often destructive techniques (e.g. soil trenches) must be used to investigate the pipes (Jones, 1981) and there have been few other attempts to accurately locate and map subsurface piping.

Recently, however, Holden *et al*. (2002) demonstrated that ground penetrating radar (GPR) could be used to remotely sense soil pipes. GPR work has shown that pipe network densities are much greater than can be detected from surface observation alone. The radar transmits short pulses of high frequency (10-10000MHz) electromagnetic energy through the ground surface. This is reflected from boundaries between soil layers or from internal irregularities which have differences in electrical properties. Thus, soil pipe cavities can be identified by the radar when it crosses over them. However, the application of GPR by Holden *et al*. (2002) was limited in that GPR demonstrated the presence of pipes but could not establish their hydrological connectivity. This paper aims to tackle this problem by using GPR not only to detect soil pipes but to remotely sense their hydrological connectivity through detection of tracer solution injected into pipe systems.

Methods

A Sensors and Software pulseEKKO 100 GPR was used for the experiment. GPR antennae frequency is usually chosen dependent on the spatial resolution desired, clutter limitations (the amount of noise detected) and exploration depth. At the study sites 100 and 200 MHz antennae were found appropriate for detecting subsurface soil pipes. Standard separation distances (1 m and 0.5 m respectively) and sampling intervals (800 ps and 400 ps) were used. The 100 MHz antenna provided a greater depth of exploration and the 200 MHz antenna increased the resolution of the near-surface features. Holden *et al.* (2002) and Conyers and Goodman (1997) provide further detail on the general principles involved. A real time kinematic global positioning system (RTK GPS) attached to the GPR allowed rapid ground-truthing with centimetre precision in x, y and z coordinates.

Holden *et al*. (2002) used GPR to successfully map pipes in blanket peat on the Moor House National Nature Reserve (NNR), in the northern Pennine Hills, UK (54^o 41'N, 2^o 23'W). Therefore, because pipe maps at the site existed from the Holden *et al.* survey, the location was also chosen for the pipe connectivity experiment. Pipes were also tested in a sandy loam soil at Bramham, North Yorkshire, UK (53^o 51'N, 1^o 22'W). Pipes ranged in depth at both sites from within a few centimetres of the surface to 4 m; pipe depths could be identified on radargrams to +/- 30 cm (Holden *et al*., 2002). Full details of the field sites are provided in Holden *et al*. (2002); Holden and Howard (2003); Evans *et al*. (1999).

The GPR was placed centrally over known pipe locations (as detected from earlier GPR survey). Five litres of sodium chloride solution were gulp injected into open pipe cavities upslope of the test pipes over which the GPR had been placed. The injection points ranged from 5 m to120 m upslope from the detection point. The same injection point could be used several times while the GPR was moved from one cavity to the next downstream. Collapsed pipes can frequently be found in blanket peatlands and provide an important route for overland flow to enter the subsurface pipe network. Where there were no obvious open pipe roofs the tracer was injected into the pipe network by using an elongated syringe inserted into the pipe from the surface. This consisted of a hollow steel rod of 2 mm internal diameter (in order to minimise surface disturbance) attached to a one litre PVC flask with a rubber plunger. The plunger forced the saline solution through the steel rod into the pipe (and forced out any soil that may have entered the rod when it was inserted into the ground). The length of rod used could be varied depending on local pipe depths, although the maximum depth for which the syringe was used in this experiment was 1.8 m. To aid ease of use, for the 21 cases where the syringe was used, one litre of saline solution was added to the pipe concerned rather than the five litres that was added where open cavities were available.

Once the tracer had been injected the GPR was then switched on and triggered once per second. The resultant radargram was then observed. Usually radargrams are plots of the reflection signal (travel times to subsurface reflectors, often calibrated against depth) against distance across a hillslope transect. However, in this case the GPR was kept stationary and the radargram was a plot of signal travel times against time. Once a radargram had been produced it could be checked for changes in reflectance over time. If changes could be observed then this was assumed to be caused by changes in the subsurface electrical conductivity. This was most likely to be a result of the passing salt wave moving through the soil pipe. This is because there would be a contrast between the electrical conductivity of the natural pipe water and the electrical conductivity of the water laden with salt solution. Hence, because the velocity of an electromagnetic wave through a medium is directly controlled by the electrical conductivity of that medium the time taken for a signal to pass through and reflect back from a flowing soil pipe will depend on the electrical conductivity of that water. The GPR was then moved further downslope to other known pipe locations and the test repeated.

In order to test the sensitivity of the GPR to detect the sodium chloride solution a range of input solution concentrations were used. Samples of pipe waters were taken using a syringe as described above. The water samples were then analysed in the field for conductivity. Pipe waters at Bramham had a background conductivity ranging between 116 to 136 μS cm^{-1} with the range between 29 to 78 μS cm^{-1} at Moor House. Concentrations of injected solutions ranged from 10, 000 μS cm^{-1} to 500 μS cm^{-1} at both sites with 70 sensitivity samples tested at Moor House and 23 at Bramham.

Results

Figure 1 shows typical radargrams produced during the experiment for two different soil pipes. The GPR was stationary over both pipes yet the radargram shows a distinctive change in signal over the study period. Because the GPR is stationary each trace should indicate the same travel times to subsurface reflectors. Thus, a series of repeated signals, which appear as horizontal features on the radargram, are evident for the first 30 seconds for Figure 1a and the for first 20 seconds for Figure 1b. However, when the salt wave passes through the pipe below the GPR, the travel times are altered because the conductivity of the water changes. This appears as a sudden change in travel times to given subsurface reflectors indicated on the radargrams. Once the salt wave has passed, reflector travel times return to their original values (after 52 seconds for the test shown in Figure 1a and 37 seconds for Figure 1b). Thus it was possible to determine hydrological connectivity of pipes using GPR. It was also possible to remotely detect salt wave travel times through the soil pipe network since the tracer injection time and GPR survey time could be synchronised. Furthermore, since the GPR could be left stationary it was possible to leave it unattended for several hours while monitoring proceeded. This was especially useful in cases where the salt wave moved only very slowly or over long distances through the pipe network.

Figure 2 illustrates the connectivity of a pipe system at Moor House as determined by the GPR RTK GPS salt dilution tracing technique. The pipe network was originally mapped as part of the Holden *et al.* (2002) survey. Before the tracer survey it was not possible to determine how the individual pipes identified by the GPR were connected. However, after GPR detection of pipe tracers, two separate pipe networks could be identified on the test hillslope shown and it was possible to show how each of the pipes were connected to others. The two separate networks can even be shown to cross each other on the test hillslope without being hydrologically connected (Figure 2). The pipes were at different depths within the soil profile at the cross-over points (see Holden *et al*., 2002). Only one of the pipe cavities detected on the GPR survey shown in Figure 2 could not be hydrologically linked with any other pipe that was detected during the survey. It is possible that this cavity was not an active soil pipe or was a short and discontinuous pipe. Near the foot of the slope the pipe flows were detected leaving the confines of pipe conduits by the GPR as shallow diffuse throughflow (indicated by the arrows on Figure 2). Thirty mm diameter crest-stage tubes with holes drilled at sampling depths of 5 cm intervals allowed the soil water to be sampled where this appeared to be occurring. This confirmed that the diffuse saline flow was just below the peat surface within the upper 5 cm of peat.

A range of salt concentrations were tested to assess minimum changes that were detectable using the GPR. It was found that approximately doubling the electrical conductivity of the pipe water was sufficient to change the trace signal on the radargram so that the salt wave was observable in the field without post-processing. Figure 3 shows these results for Moor House and Bramham. For some pipes, different concentrations of solution were repeatedly used on the same pipe and two highlighted examples of these replicate tests are shown in Figure 3. Only very weak solutions of sodium chloride were necessary in blanket peats where the background conductivity of pipe water was typically 30-70 $\mu S\ cm^{-1}$. Where higher background conductivities were detected (~120 $\mu S\ cm^{-1}$) in the sandy loam at Bramham, doubling the conductivities was also found appropriate. Estimating the tracer concentration necessary to increase the pipe water conductivity twofold requires an estimation of pipe water volumes and background conductivity. However, a twofold increase of conductivity is the minimal detectable level needed *without post-processing* and in many environments it will be feasible to more than double the conductivity of the pipe waters by adding an appropriate tracer. The benefits of using sodium chloride as a tracer is that it is cheap and generally safe in most environments; it is regularly used in dilution gauging of rivers for example.

Conclusions

On its own GPR can only detect subsurface cavities but when used in conjunction with tracers (e.g. sodium chloride) it can help establish the hydrological connectivity of soil pipes. This is because if the electrical conductivity of the water in the soil pipe changes below the radar this change will be detected by alterations in the travel times for reflections of the electromagnetic signal produced by the GPR. Thus, it is possible to remotely determine how pipes are connected to the others within a complex subsurface drainage network. The technique should therefore help develop understanding of flowpath connectivity in hillslope hydrology. The improved understanding of flowpath connectivity will be important for understanding hillslope denudation and hydrological and geomorphological model development. The technique was shown to work in blanket peat with pipe water of low conductivity and in a sandy loam with higher conductivity water. The method could easily be extended to examine the hydrological connectivity of pipes in a wide range of environments but will require testing for a wider range of soil-water conditions. The technique could also be adapted for a range of other uses including mapping of englacial and subglacial water flow paths. The technique could also be taken further by using it to help determine sources and sinks for pipeflow in a wide range of environments.

The technique is limited in that it cannot determine the hydrological importance of soil pipes and requires the pipes to contain pipeflow for the test to work. Nevertheless, the technique is non-destructive, relatively rapid and provides new data on hillslope hydrological connectivity.

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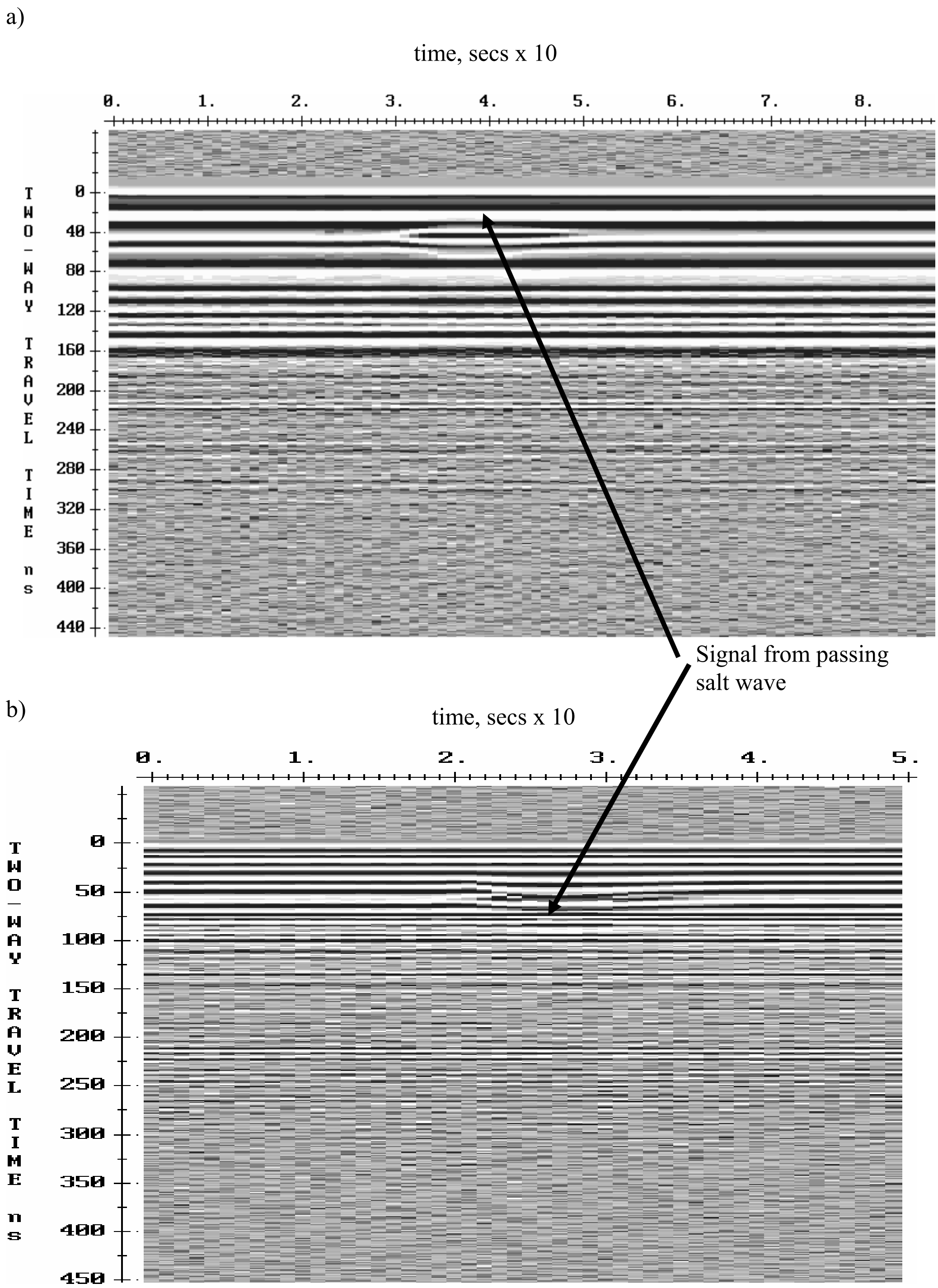
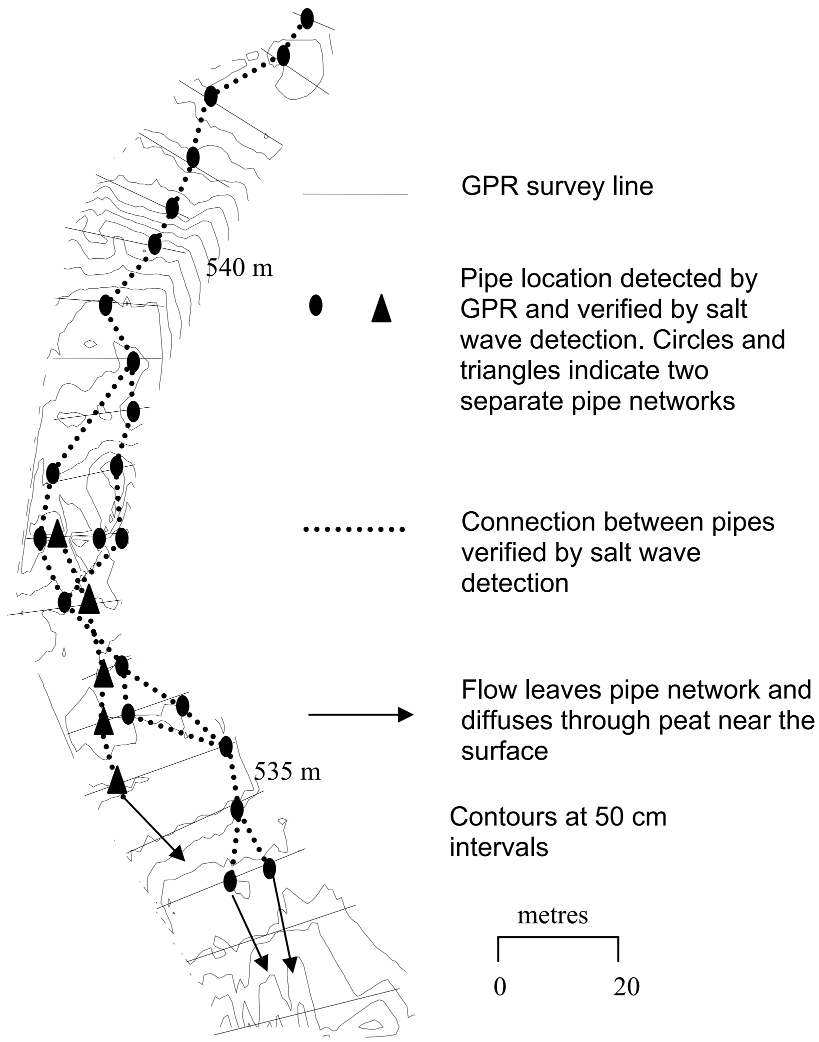
Figure captions

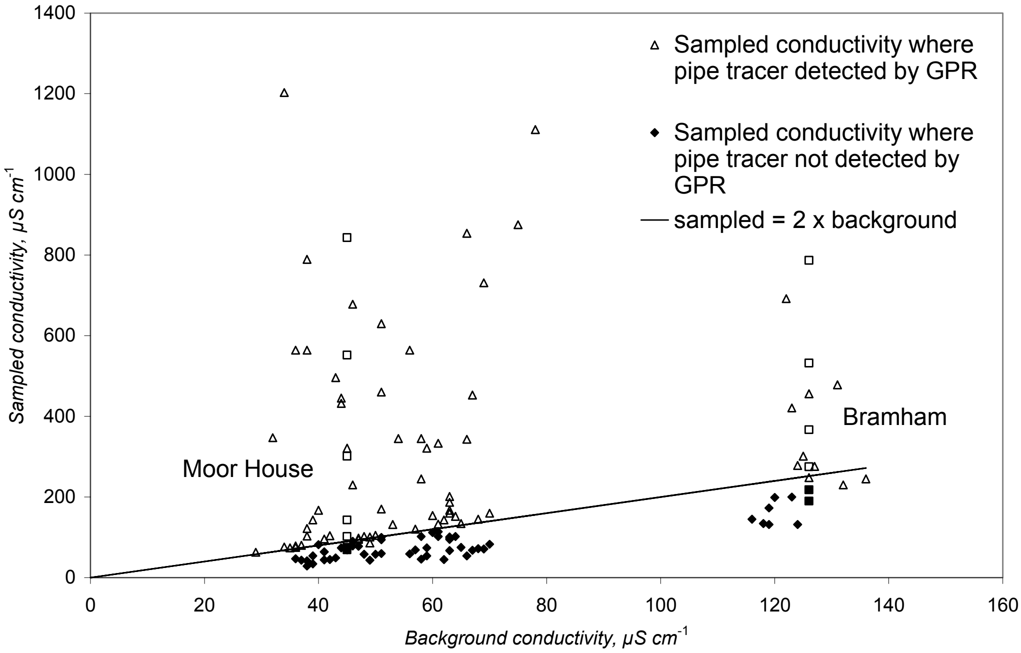
Figure 1. Radargrams produced above two soil pipes. When the salt wave passes below the GPR the trace signal alters; a) pipe at Moor House, 3.0 m depth, approximately 28 cm in diameter at sample point. b) pipe at Bramham, 1.8 m depth, approximately 15 cm in diameter at sample point.

Figure 2. An example of hillslope pipe connections as determined by GPR salt wave tracing.

Figure 3. Sampled pipe water conductivity against background conductivity for tracer tests. Samples were taken from pipes after tracer injection both where the GPR did and did not detect a salt wave moving below it. The line indicates where sampled conductivity is twice background level. Squares highlight examples of repeated tests on two individual pipes.


a)
time, secs x 10
0. 1. 2. 3. 4. 5. 6. 7. 8.
TWO-WAY TRAVEL TIME ns
0 40 80 120 160 200 240 280 320 360 400 440
Signal from passing salt wave
b)
time, secs x 10
0. 1. 2. 3. 4. 5.
TWO-WAY TRAVEL TIME ns
0 50 100 150 200 250 300 350 400 450


540 m
535 m
GPR survey line
Pipe location detected by GPR and verified by salt wave detection. Circles and triangles indicate two separate pipe networks
Connection between pipes verified by salt wave detection
Flow leaves pipe network and diffuses through peat near the surface
Contours at 50 cm intervals
metres
0
20


Sampled conductivity where pipe tracer detected by GPR
Sampled conductivity where pipe tracer not detected by GPR
sampled = 2 x background
Moor House
Bramham
Sampled conductivity, μS cm-1
Background conductivity, μS cm-1
0
200
400
600
800
1000
1200
1400
0
20
40
60
80
100
120
140
160