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FULL TITLE:

APPLICATION OF GROUND PENETRATING RADAR TO THE IDENTIFICATION OF SUBSURFACE PIPING IN BLANKET PEAT

SHORT TITLE:

GPR AND WETLAND PIPING

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Abstract

Natural soil pipes are common and significant in upland blanket peat catchments yet there are major problems in finding and defining the subsurface pipe networks. This is particularly important because pipeflow can contribute a large proportion of runoff to the river systems in these upland environments and may significantly influence catchment sediment and solute yields. Traditional methods such as digging soil pits are destructive and time-consuming (particularly in deep peat) and only provide single point sources of information. This paper presents results from an experiment to assess the use of Ground Penetrating Radar (GPR) to remotely sense pipes in blanket peat. The technique is shown to be successful in identifying most of the pipes tested in the pilot catchment. Comparison of data on pipes identified by the GPR and verified by manual measurement suggest that pipes can be located in the soil profile with a depth accuracy of 20 to 30 cm. GPR identified pipes were found throughout the soil profile except that those within 10 – 20 cm of the surface could not be identified using the 100 or 200 MHz antennae due to multiple surface reflections. Generally pipes smaller than 10 cm in diameter could not be identified using the technique although modifications are suggested that will allow enhanced resolution. Future work would benefit from the development of dual frequency antennae that will allow the combination of high-resolution data with the depth of penetration required in a wetland environment. The GPR experiment shows that pipe network densities were much greater than could be detected from surface observation alone. Thus, GPR provides a non-destructive, fast technique which can produce continuous profiles of peat depth and indicate pipe locations across survey transects.

Keywords : Ground penetrating radar, soil pipes, peat, uplands, runoff.

Introduction

Jones (1981) and Anderson and Burt (1982) noted the need for increased investigation into natural soil piping. Since then a limited amount of research has been persued yielding enhanced information on the role of piping in hillslope drainage, flood generation and channel development. Soil pipes have been found in many areas of the world. Laboratory work (e.g. Sidle *et al*., 1995), modelling (e.g. Stocking, 1981; McCaig, 1983; Nieber and Warner, 1991) and field measurement (e.g. Roberge and Plamondon, 1987; Gutierrez *et al.,* 1997; Zhu, 1997; Carey and Woo, 2000) have shown that piping can be a very important hydrological phenomenon particularly in humid temperate regions (Jones, 1971; Cryer, 1979; Gilman and Newson, 1980; Jones, 1981; Anderson and Burt, 1982; Jones, 1990; Muscatt *et al.,* 1990; Jones 1994; Bryan and Jones, 1997; Jones *et al*., 1997; Uchida *et al*., 1999). Jones and Crane (1984) reported, for example, that 49 % of streamflow in the Maesnant catchment was generated through the pipe network. Soil pipes have also been considered as important in landform development (e.g. Jones, 1994). Piping is involved with channel extension through roof collapse often forming gullies (Higgins, 1990).

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 in the Maesnant catchment, mid-Wales. The soils studied were thin peaty-podzols (of the order of only 30-50 cm deep). Pipe locations were identified mainly by observation of collapse features, water jets emerging from pipes and the sound of flowing water (Jones, 1982). However, these techniques do not give a detailed or complete picture of the subsurface network and can result in underestimates of the pipe density. Often destructive techniques must be used to investigate the pipes (Jones, 1981) and there have been few other attempts to accurately locate and map subsurface piping. Little is known about the interlinkages of pipeflow with other flow processes, nor of the form and spatial density of many pipe networks. The majority of piped catchments surveyed in detail are confined to the shallow peaty podzols of mid-Wales, at least in terms of pipeflow and network identification. However, piping is widespread throughout the deep blanket peat of the UK uplands; Pearsall (1950) and Bower (1960) both observed deep-seated pipeflow. Anderson and Burt (1982) report pipe diameters up to 50 cm in Shiny Brook, South Pennines and the existence of deep and shallow pipes. Gunn (2000) showed that pipes on Cuilcagh Mountain, Ireland, range from a few centimetres in diameter to those that are large enough to crawl into. In peat catchments pipes have been found at the interface between the peat and the underlying mineral layer, solely within the peat itself usually where there is rapid change in peat properties such as bulk density (Gilman and Newson, 1980), or with outlets entirely within the substrate (Holden and Burt, in press). For shallow pipes, a change in surface vegetation may often indicate the presence of a pipe (Jones *et al.*, 1991). Jones (1997) and Bryan and Jones (1997) noted that a major problem bedevilling assessment of the role of piping is the difficulty of finding and defining the networks. Often pipes are defined by the nature of their observed outlets, frequently seen only at the streambank or on gully sides. They suggest that new techniques are urgently needed for surveying the pipe networks and their subsurface area.

Traditional point-measurement techniques, such as soil coring or pit excavation are destructive and provide an incomplete characterisation of the subsurface. Ground

Penetrating Radar (GPR), originally developed for military applications, provides an alternative. GPR has been used in fields as diverse as architecture, engineering, environmental management and mineral prospecting (Mellet, 1995; Reynolds, 1997). It has aided examination of internal glacial structures (e.g. Murray *et al*., 2000) and is frequently used to study contaminants in groundwater (Benson, 1995; Daniels *et al.*, 1995), the nature of subsurface faulting (Benson, 1995) and the location and size of plastic or metal pipes (e.g. Peters *et al*., 1994) and other objects, particularly in archaeology (Conyers and Goodman, 1997). GPR has been used successfully to map peat deposits (e.g. Warner *et al*., 1990; Hanninen, 1992; Theimer *et al.*, 1994; Lapen *et al*., 1996), soil and rock stratigraphy (e.g. Olson and Doolittle, 1985; Davis and Annan, 1989; Dominic *et al.*, 1995), bedrock topography (e.g. Olson and Doolittle, 1985) and the water table (e.g. Lapen *et al.*, 1996). The technique has been shown to produce better near-surface resolution in the upper few metres of soil and bedrock than seismic refraction (Olson and Doolittle, 1985).

GPR has been used to construct continuous bottom profiles through peatlands (Bjelm, 1980; Hanninen, 1992) and is capable of recording peat depth and differentiating internal irregularities due to peat composition, water content, and bulk density (Warner *et al*., 1990). Much of the work on peatlands utilising GPR technology has been performed by the Geological Survey of Finland which in 1983 noted the need to improve the rapidity and accuracy of field survey, then heavily dependent on traditional drilling methods (Hanninen, 1992). 2000 km of GPR measurements were carried out in 104 peatlands across Finland resulting in detailed datasets on peat thickness, stratigraphy and underlying topography. Hanninen (1992) notes that the depth data obtained from GPR in peatlands are markedly more detailed than those obtained by traditional means. Predictions of mineral basement depth have been reported to an accuracy of 10 cm, which is of comparable accuracy to coring (Theimer *et al.*, 1994). Warner *et al.* (1990) applied GPR to the mapping of peat stratigraphy and thickness in a large bog in south-western Ontario. Their survey was undertaken in conjunction with a conventional coring survey and measurement of peat physical properties. The results indicated that GPR responds to peat moisture content and bulk density, which vary with stratigraphic changes. In particular, the acrotelm-catotelm boundary (Ingram, 1983) and the basal clay were GPR reflectors.

With GPR, where there is a sharp variation in water content, there will be a strong reflection. Hence cavities and soil pipes may be detectable within the blanket peat. To the authors' knowledge, GPR has never been used before to identify soil piping in peat. Indeed, there are no detailed studies of pipe network morphology in deep blanket peat catchments (Holden and Burt, in press a). This paper will present results from an exploratory investigation performed to assess the application of GPR in identifying subsurface pipes within blanket peat catchments.

General principles

Short pulses of high frequency (10 -1000 MHz) electromagnetic energy are transmitted by the antennae through the ground surface and reflected from boundaries between layers or from internal irregularities which have differences in electrical properties. The reflection is detected on the surface, and the time between transmission and detection is proportional to depth. Moving the transmitter and receiver antennae across the test area builds up a complete cross section of the site. The depth of penetration depends on the ground conditions at each site. Increased depth can be obtained with lower frequency radio waves, but this reduces the resolution of the radar reflections. Therefore the frequency used is a compromise. To detect relatively small features such as soil pipes a sufficiently high frequency must be selected so that the radar wavelength is short, allowing detection and suitable resolution. The frequencies used in peatland GPR surveys have ranged from 50 MHz to 600 MHz, but surveys using frequencies above 300 MHz have been less successful. A 500 MHz antenna suited examination of structural layers in peat by the Geological Survey of Finland (Hanninen, 1992) particularly for the surface layer which could not be investigated successfully using frequencies below 300 MHz. However, the 500 MHz antenna had limited probing depth. Therefore for the present study, and due to limited time available to use the equipment, it was decided to compromise at frequencies of 100 and 200 MHz.

Although the length of time for the electromagnetic waves to reflect to the GPR receiver is proportional to depth, the velocity of the wave through the medium must be calculated in order to determine depth. The dielectric constant (γ_r) (otherwise known as the relative permittivity) is a direct measure of the water content in the soil and rock which is directly related to the velocity (V) of an electromagnetic wave through this material. This and electrical conductivity (EC) govern radar propagation velocities through a medium. When EC is small it can be ignored as γ_r overwhelmingly controls V. Many soils, because of their high EC, are essentially 'radar opaque'. The low EC of the soil pore water in peatlands results in non-dispersive signal propagation and allows velocity profiles of the organic and mineral soil to be estimated (Theimer *et al.*, 1994).

Thus although the high moisture content attenuates the signal the low EC means that eight to ten metre depths can be successfully investigated in peatlands (e.g. Chernetsov, *et al*., 1988, Theimer *et al.* 1994). However, care is needed: Warner *et al.* (1990) undertook a survey when the bog was frozen to allow ready access and a solid working surface for the portable GPR instruments, but unfortunately the frozen layer acted to overwhelm other received signals and attempts to remove these signals were difficult. Hanninen (1992) noted similar problems with winter peatland measurements in Finland.

Study site

The study area is the Moor House National Nature Reserve (NNR), in the northern Pennine Hills, UK (54^{o} 41'N, 2^{o} 23'W). The reserve is one of the largest areas of blanket bog in Great Britain and is now a World Biosphere Reserve; the site is therefore recognised for its worldwide importance. Lower Carboniferous sequences of interbedded limestone, sandstone and shale provide a base for a glacial till (Johnson and Dunham, 1963). The glacial clay is often around 30 cm deep, although it can contain coarse clasts resulting in a clayey diamict. The overlying clay has resulted in poor drainage which has led to the development of blanket bog around two to three metres deep. Peat formation began in the late Boreal as bog communities began to replace a birch forest, macro-remains of which are commonly found at the base of the peat (Johnson and Dunham, 1963). The vegetation is dominated by *Eriophorum* sp. (cotton grass), *Calluna vulgaris* (heather) and *Sphagnum* sp. (moss). Further information on the site is given in Johnson and Dunham (1963), Heal and Perkins (1978), and Evans *et al*. (1999).

Runoff in these upland peat catchments is flashy, with high peak flows and limited baseflow (Evans *et al*., 1999). Lag times are short and runoff production is dominated by saturation-excess overland flow (Holden and Burt, 2000; Holden *et al.* 2001, Holden and Burt, in press b). Macropores have been shown to be important runoff generating pathways within the upper layers of blanket peat (Holden *et al.,* 2001) and pipes have been found throughout the Moor House reserve. Holden and Burt (in press a) have monitored pipeflow in the 0.44 km^2 Little Dodgen Pot Sike (LDPS) catchment (54^o 41'N, 2^o 21'W), a tributary of the Tees on the NNR. On average 10 % of streamflow is generated through the pipe network, although occasionally this can be as high as 30 %. The longest flowing pipes appear to extend over 150 m across the 1-3^o terrace slopes and have mean outlet diameters ranging from 3 cm to 70 cm. Half of the pipe outlets are greater than 1 m deep; hence the pipe networks upslope of outlets are very difficult to detect from surface observation alone.

Field equipment and methodology

The GPR used was a Ramac™ from Mala Geoscience; Figure 1 is a schematic diagram of the system when connected. In its simplest form the system consists of a computer, control unit, transmitter and receiver. The control unit was connected to the transmitter and receiver with optical fibres and to the computer with a communications cable. The control unit organises procedures and controls the transmitter and receiver. It also keeps track of current position and time. Each component in the system was powered individually by an external battery pack. These packs give up to eight hours field usage before recharging is necessary. Given the poor life of many internal laptop battery cells (often less than one hour), it is usual to have an external long-life battery source for the laptop computer too. This can be strapped around the user's shoulder in the field. The contact points on the system, particularly to battery packs, are likely to fail during even the lightest rain such that it was found necessary to cover the contact points with a small amount of plastic sheeting to keep the sensitive areas dry. The system is fairly lightweight (up to 9 kg) and portable, with the control unit carried on the fieldworker's back, the laptop computer being a standard item and the GPR antennae easily taken to the next sample point along a survey transect.

In order to test the ability of GPR to detect soil pipes, the equipment was traversed across 30 known pipe locations. If the pipe was detectable, the GPR was then used in transects upslope of the original site to assess how far the pipes extended within the peat mass. GPR-detected pipes were then tested where possible by digging trenches to determine if the 'apparent' pipe on the radargram was in fact a real feature within the peat profile. In total, 4 km of peat was covered by GPR survey on the Moor House NNR. Since the focus of the present study is soil piping, only a small part of the data generated will be presented here.

A 50 m tape was placed taut across the surface of the study transects and used as a guide to the nearest two centimetres as to where to place the antennae (which were spaced at a 0.5 m interval using a wooden brace). Radar signals ("traces") were transmitted and received every 10 cm along shorter transects and every 50 cm or 1 m on longer transects (over 50 m). The scan was conducted so that traces were collected equidistantly as this simplifies location of subsurface objects. Ground-surface truthing was performed using a Leica WILD TC1010 Electronic Distance Meter (EDM) for short transects or a differential Global Positioning System (GPS) for longer transects (Higgitt and Warburton, 1999). Although not very accurate for altitudinal measurements (+/- 20 m) the Magellan GPS was found to provide fairly accurate relative height data during one continuous session (+/- 5 cm) when compared to EDM surveys of the same transect. However, terrain surfaces are notoriously uneven in peat. The quality of the GPS return signal will therefore depend on the nature of the contact with the peat surface under foot and the nature of the movement of the individual holding the mobile GPS.

Ramac^{TM} software was used on the laptop computer for data collection and field display of results from the operating transect. Post-processing was done using the GRADIX software from INTERPEX Incorporated which filters the data to allow particular features to be identified more easily. Frequent measurements of peat depth done by reference coring allowed checking of depth conversions.

Results and Discussion

The basal reflector

A good example of the ability of the GPR to quickly and easily generate digital elevation data on peat depth comes from a survey of a 100 m x 100 m plot on the Moor House NNR. The plot is the UK Environmental Change Network (ECN) target site where long-term terrestrial monitoring work is being carried out (Sykes and Lane, 1996). Here five transects were taken running north-south spaced at 25 m intervals with five transects running east-west. GPR traces were collected at 50 cm intervals. A north-south profile is shown in Figure 2. Here an area of deeper peat can be identified around 60 – 90 m along the profile. Distinct reflections can also be identified from certain peat layers. More stratigraphic reflections are seen in the deeper section of the peat. This suggests that peat growth may have started in the hollow before spreading over the rest of the hillslope, the wetter location allowing peat to build up locally in advance of more widespread peat formation. Whilst not the focus of the present paper, careful coring has allowed correlation of radargram reflectors with specific peat layers such as those which are *Sphagnum*-rich or rich in woody material. This will allow the development of improved models of blanket peat development. Multiple reflections (or echoes) within the peat profile may lead to misinterpretation; most of the radar energy that is returned by a reflector (e.g substrate interface) is transmitted directly back to the surface and recorded at the receiving antenna. Some of the reflected energy is, however, reflected back into the subsurface at the ground-air interface, and then reflected back again to the surface from the same subsurface interface. Thus, secondary 'apparent' layers appear at approximately twice the depth of the real layer. The secondary reflection is usually much lower in amplitude due to geometric spreading during its travel, energy attenuation, and additional reflection from numerous other interfaces along its path. The software used for data analysis can display the relative amplitudes of reflections so that these secondary reflections can be removed from the analysis.

Surface peat topography generally slopes in the direction of the substrate topography on the ECN target site. However, the surface topography is usually much gentler in slope than that of the substrate, the subsurface topography having been smoothed by the greater build up of blanket peat in the hollows with their faster peat accumulation rates. A contour plot of surface slope and peat depth across the 100 m x 100 m plot is shown in Figure 3. This demonstrates the ease with which peatland surface and subsurface terrain can be mapped using GPR. Depth probing using a soil auger or rod would have been very time- consuming across this site requiring 2000 separate measurements to achieve the same spatial density of measurements as the GPR; the GPR readings were taken in approximately one hour.

<u>Pipe identification, depth, size and interpretation of radargrams</u>

The ability of the GPR to detect soil piping in blanket peat can be seen in Figure 4. A short transect was traversed across a known pipe location in the LDPS catchment. The pipe was clearly detected using the 200 MHz antenna and is identifiable in the radargram (Figure 4a). The pipe can be seen to be at the interface between the peat and the substrate; this was verified by field observation. Upslope of this transect it was unclear where the pipe was located below the surface or how far upslope the pipe extended. Therefore several more short transects were traversed across the peat uplsope of the first transect. Two of the radargrams are shown in Figures 4b and c as examples. In each the pipe was located at the interface. It became evident that this pipe ran approximately 20 m further upslope than original field mapping had suggested although its origin was not located. Thus, the possible contributing area to the pipe was much greater than previously envisaged.

Accurate measurement of the dimensions of pipes using the GPR technique is difficult. This is because of multiple reflections from the pipe roof, floor and sides and also because the cross-sectional area of a pipe displayed by the GPR will depend upon what angle the profile cuts across the pipe. A perfectly cylindrical pipe cut across at right angles should produce a circular pipe form on a profile. However, if the profile cuts through the pipe at any other angle, the result will be an ellipse. Theoretically, if the GPR transect followed the lateral direction of the pipe perfectly then a pipe of infinite width would be displayed. Furthermore, images seen in radargrams are not like images from x-rays in medical technology. Reflection profiles printed in two dimensions can look significantly different from the buried structures being searched for. The GPR antennae transmit energy through the ground in a wide beam; the antenna is therefore not only looking straight down but also to the front, back and to the sides. For example, when the antenna is in front of a soil pipe the travel time for a wave to leave the antenna is longer than when the antenna is directly over the pipe. Thus, the net effect is a hyperbolic-type reflection (Conyers and Goodman, 1997) of the pipe as the GPR moves over it, with the apex of the hyperbola denoting the top of the pipe. This hyperbolic reflection can be seen in Figures 4 a-c. Clearly, interpretation of the radargrams is subjective, but with a little experience and some corroborative field evidence it is possible to confidently identify subsurface features from the plots.

In order to test the ability of GPR to detect the depth of soil pipes, profiles were taken across several known pipes in the LDPS catchment. The depths of the pipe roofs were determined by excavation or by direct measurement where outlets were visible on streambanks or gully sides. Figure 5 plots the relationship between actual pipe depth and GPR detected pipe depth. There is a close correspondence between the two measurements. Thus, although no pipes were observed at depths greater than 2 m (owing to obvious difficulties in digging trenches) it was decided to accept the GPR detection of pipe depths below 2 m as correct with an accuracy of +/- 30 cm. Pipes smaller than around 10 cm in diameter could not be identified on radargrams and four known pipes at shallow depths (5-20 cm) could not be detected. The mean diameter of manually measured pipes in the study catchment is 19 cm (standard deviation = 16 cm), with a median of 16 cm. Thus application of the GPR may be of limited use hydrologically as many of the pipes are below 10 cm in diameter. However, 70 % of the pipes measured manually were larger than 10 cm in diameter (Holden and Burt, in press a) and were successfully detected. Simple changes to the technique would allow pipe cavities below 10 cm in diameter to be identified. This would be more time-consuming and involve taking radar traces every 5 cm or less along a transect. The fact that GPR has been demonstrated to have the ability to detect pipe cavities is the most important finding; the resolution of the return signals will depend on the sampling resolution. In the Maesnant, mid-Wales, pipe diameters ranged from 9-30 cm and were between 15-80 cm deep (Jones and Crane, 1984) suggesting that most pipes in the catchment would be detectable by taking GPR readings every 10 cm along a transect. Most pipes in the Cerrig yr Wyn catchment would not have been detectable using the technique as they are below 10 cm in diameter (Morgan, 1977). However, since the pipes in these Plynlimon catchments are much shallower they would be easier to map from surface observation. It is for uncharted deep-seated piping that the real benefits of quickly moving GPR across peat terrain are to be found. It was found that the GPR could be used to pick out cavities within the peat, whether they were air-filled or water-filled. Thus, it did not matter whether GPR measurements were made when the water table was high or low.

Comparison of antenna frequency

The GPR profiles shown in Figures 2 and 4 indicate that use of the 200 MHz antenna produces multiple reflections from the peat surface. The thick shading on the figures within the top 30 cm are merely multiple reflections, or echoes, of the peat surface. These are difficult to remove from the radargram because the reflections are strong; the surface being located close to the antennae. Thus, use of the 200 MHz antenna means that objects (including pipes) within the upper 30 cm of the peat would be difficult to identify; neither the water table nor the acrotelm/catotelm boundary can be observed.

Data produced using the 200 MHz antenna compared with those from the 100 MHz antenna are shown in Figure 6 for a transect in the LDPS catchment. Clearly the resolution is poorer using 100 MHz although it does seem to pick up extra information on layering within the peat, whilst not picking out the substrate as clearly. A greater depth of the upper layer of peat is covered by surface echoes when using the 100 MHz antenna, although at the same time more information appears to be provided on laminations within the upper 60 - 70 cm of the peat. However, it is clear that, in line with the findings of Hanninen (1992), higher frequencies are required to allow more detailed analysis of the near-surface layers. With higher frequencies, the depth of probing will decrease. Given the nature of soil pipes at Moor House which are often found two to three metres deep, it was decided to use the 200 MHz antenna as this gave better resolution for identification of pipes and was found to give penetration depths up to 5 m. Furthermore, it allows more near-surface pipes to be identified than when using the 100 MHz antenna whilst allowing the full depth of peat to be examined. Ideally, it would have been best if the 200 MHz antenna was used in conjunction with an antenna of much higher frequency (e.g. 500 MHz) but with present technology this would have meant repeating every survey transect.

Spatial distribution of pipes

By moving the GPR across peat hillslopes along regularly positioned transects, pipe locations can be mapped. This was done at several locations in the LDPS catchment providing quick and remote information on the spatial nature of pipe network morphology. One example is given by a valley-bottom survey performed using the radar. The pipe system was located on a valley bottom flanked on either side by blanket peat hillslopes of 3-5^{o} slope. The GPR transects were confined to the valley bottom as it was thought the pipe drainage was likely to be restricted to this zone. The GPR was taken across 19 transects spaced at 10 m intervals downslope of a known pipe origin. The origin of the pipe was at the mouth of a gully within the LDPS catchment; water running over the floor of the gully fell into an opening in the peat and moved downslope through the pipe (flow into the pipe often exceeded seven litres per second). It was impossible to map the route of the pipe downslope of the gully without severely disturbing the peat substrate except at three locations where the pipe roof had collapsed allowing the pipe to be seen from the surface.

Figure 7 plots transect locations and the spatial distribution of GPR-identified piping downslope of the gully. The pipe system does not consist of a simple single thread channel; more than one pipe can be identified along some transects. On other transects no pipe could be identified and thus the pipe system cannot be confirmed as continuous. Examination of slope data suggest that areas with the greatest number of pipes (perhaps where the pipe system anastomoses most) tend to be on the gentlest slopes. This was found to be the case in other areas of the LDPS catchment. The pipe network appears to be branching with subsurface convergence and divergence of pipes. Measurements of discharge at LDPS indicate that pipeflow can decrease and increase along the course of a pipe, because other pipes drain the main pipe upstream and also feed back into the pipe downstream. The pipe systems are therefore more complex in form than surface observations might suggest. Gilman and Newson (1980) described a shallow anastomosing pipe network in the Welsh uplands but this has never before been observed in deep blanket peat; the depth of piping makes these morphologies difficult to detect.

Twelve of the eighteen pipes identified on the GPR radargrams along the valley bottom were within the peat layer whereas the other six were at the interface between the peat and underlying substrate. Figure 8 gives examples of transects where pipes were found at different depths in the profile. With the peat almost three metres deep in places and the pipes frequently located near the base of the peat, the benefits of being able to identify pipes using this remote sensing technique are clear. Figure 8 shows that the pipes along the valley bottom were not always at the same depth within the peat profile. Three pipes were identified beneath transect 10; these were all located close together but at different depths within the peat mass. It is difficult to say how these three pipe sections might be linked (if at all). In blanket peat, the GPR work, coupled with field observation, shows that the pipes undulate throughout their profile, varying from being at the surface to having contact with the substrate. Given that around 10 % of streamflow in the LDPS catchment is generated through the pipe network, this is therefore an important component of mire hydrology that is often ignored. Traditionally, wetland modelling utilises a bi-component model of the acrotelm and catotelm with mean hydraulic conductivities of each layer used as important model values. Indeed although surface flow dominates the hydrological response of blanket peat catchments, groundwater flow models have frequently been applied (e.g. Ingram, 1982; McDonald and Harbaugh, 1988; Armstrong, 1995). These suffer from under-representation of the surface flow component. MacAlister and Parkin (1999) suggest development of models that sufficiently incorporate the dominance of surface flow in peatlands but again these do not represent the important linkages between the acrotelm and catotelm that pipeflow provides. Mapping pipes in deep blanket peat catchments using GPR suggests that pipes branch out, undulate, and that braided networks can develop. Often pipes connect to the surface. Occasionally they are found entirely within the underlying substrate; evidence for this comes from the fact that pipes with an outlet wholly within the peat mass can produce sediment which is minerogenic in nature (Holden and Burt, in press a). Thus, the feeding pipe network upslope must make contact with the substrate at some point. Hence characterising a soil pipe by its outlet characteristics (e.g. depth, shape, size, location in the soil profile) may be meaningless because the pipes can be very different in form and profile location just a few metres upslope. Terajima *et al*. (2000) found through use of a fibrescope that pipe morphologies can change rapidly over very short distances. We therefore have much to learn about subsurface geomorphology in upland catchments. GPR is one tool that can aid our understanding of these pipe morphologies.

It is clear that to accurately map the deep LDPS pipe network a very high density of transects would be required. Nevertheless this preliminary experimental work with the

GPR gives some indication of the complex nature of deep-seated piping in blanket peat. The subsurface drainage density of pipes at Moor House seems much greater than can be mapped on the basis of surface observation alone and GPR can be used to give an indication of the pipe densities within blanket peat catchments. This helps explain why the pipes in LDPS contribute 10 % of streamflow and occasionally as much as 30 % whilst apparent piping density mapped from surface observation is only 4 km km^{-2} (Holden and Burt, in press a). Further work utilising GPR technology is required to produce a more accurate estimate.

Conclusions

Summary

GPR has been used for the first time, to the authors' knowledge, to remotely sense soil pipes in blanket peat. The pilot study at Moor House has shown that the application of GPR to subsurface pipe detection is successful within these upland catchments. The following findings were made regarding use of GPR in peatlands to remotely sense soil pipes:

1) GPR can identify pipes in blanket peat catchments.
2) Comparison of pipes identified by GPR and by manual measurement suggest that pipe depth can be located in the soil profile with an accuracy of 20 to 30 cm.
3) In agreement with ground survey, soil pipes were identified throughout the soil profile (except near the surface)
4) Pipes very close to the surface of the peat could not be identified using the 100 or 200 MHz antennae due to multiple surface reflections.

5) The smallest verified pipe identified by the GPR was 9 cm in diameter.
6) The GPR work did strongly suggest that pipe densities were much greater than could be recognised from the surface.
7) It was not possible to confirm the connectivity of pipe networks between transects.
8) Substrate topography and peat stratigraphy appear to be easily identifiable on radargrams. In this way deeper peat-filled hollows have been identified within small hillslope plots at Moor House.

Suggestions for improvements to the technique and further applications

The suggestion of a more anastomosing pipe system on flatter areas of peat is reminiscent of Bower's (1960) Type I and Type II gully erosion systems in blanket peat. Bower (1960) argued that gullies are more branched on flatter slopes, feeding into straighter, unbranching gullies on steeper slopes. Further work is required to test the possibility that gentler peat slopes contain more anastomosing pipe networks and to test linkages between piping, hummock-pool terrain and gully erosion, and those between gully erosion and substrate topography.

Higher frequency antennae or a greater density of survey points (ie at a smaller distance apart than the diameter of the pipe) are required to increase resolution in order to identify pipes smaller than c. 10 cm in diameter (as long as the reduced probing depth of the higher frequencies still provides adequate coverage). In order to map the full range of pipes in deep peat from the substrate to the surface it may be necessary to develop multiple frequency antennae, the results from which could be digitally combined to produce full-depth profiles. For blanket peats around 3 m deep a 200 MHz antenna should be combined with that of a much higher frequency (500+ MHz). This would allow both deep and shallow piping to be identified at the same time and to examine whether deep pipes are frequently connected to the near-surface to be fed by the shallow runoff that dominates blanket peat catchments. The GPR technique should also be applied to other soil types to test its merit in examining soil pipe network morphology in a range of environments.

Further improvements in using the GPR for soil pipe work would come from applying recently developed GPR techniques in archaeology. In archaeology synthetic computer GPR profiling and computer-generated three-dimensional maps have been developed which allow the subsurface features to be visually plotted and viewed from all angles on-screen (Conyers and Goodman, 1997). A comparable approach would aid our understanding of pipe form, connectivity and sources. Whilst quicker than traditional means, the speed and density of GPR surveying needs to be increased. Currently mesh transects with 0.1 m step in two directions (parallel and perpendicular to the slope), which would provide improved density of coverage, would be too time-consuming to perform over large areas. A radar system with an array of portable transmitters and receivers that can be placed across the hillslope may prove too expensive to develop but with modifications and appropriate software it should be possible to rapidly construct three-dimensional models of the soil profile. With this information hillslope hydrologists will make significant gains in understanding an important component of subsurface catchment runoff and GPR will prove a useful tool for understanding long-term landform development in upland areas.

As it stands GPR, with the appropriate antennae, can remotely detect the location of soil pipes in blanket peat catchments if they occur below the areas along which the equipment is taken. Given the difficulty in detecting pipes from surface observations this is an important geomorphological and hydrological tool. The application is limited, however, in that GPR demonstrates the presence of pipes but does not establish their hydrological importance or connectivity.

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Figure captions

Figure 1. Schematic diagram of the GPR equipment

Figure 2. Radargram across a transect on the ECN target site. Traces were taken every 50 cm. The subsurface topography is a clear reflector. There are many other thin stratigraphic layers that are acting as reflectors within the peat mass itself.

Figure 3. Contour plots of a) surface topography (altitude, metres) and b) peat depth (metres) across the 100 m x 100 m ECN target site.

Figure 4. Example radargrams with natural soil pipes as reflectors

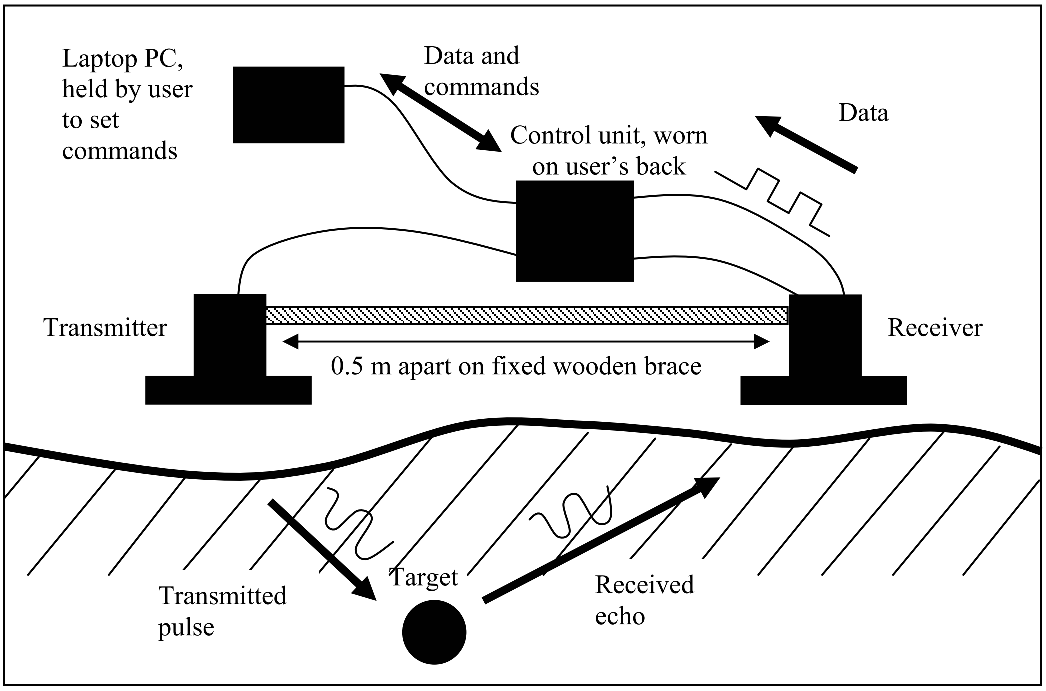
Figure 5. Pipe roof depth against GPR measured pipe roof depth as determined by the depth of the apex of each pipe on the radargrams.

Figure 6. Comparison of two radargrams on the same transect. a) using 200 MHz, b) using 100 MHz antennae

Figure 7. Spatial distribution of pipes along a valley floor as determined by GPR survey across 19 transects in the Little Dodgen Pot Sike catchment.

Figure 8. Location of pipes in the soil profile of four valley floor transects in the Little Dodgen Pot Sike catchment. (Transect locations are given in Figure 7). Peat surface and substrate interface depth is given in each case, shaded area indicates pipe location.

Figure 1.



Laptop PC, held by user to set commands
Data and commands
Data
Control unit, worn on user's back
Transmitter
Receiver
0.5 m apart on fixed wooden brace
Target
Transmitted pulse
Received echo

Figure 2

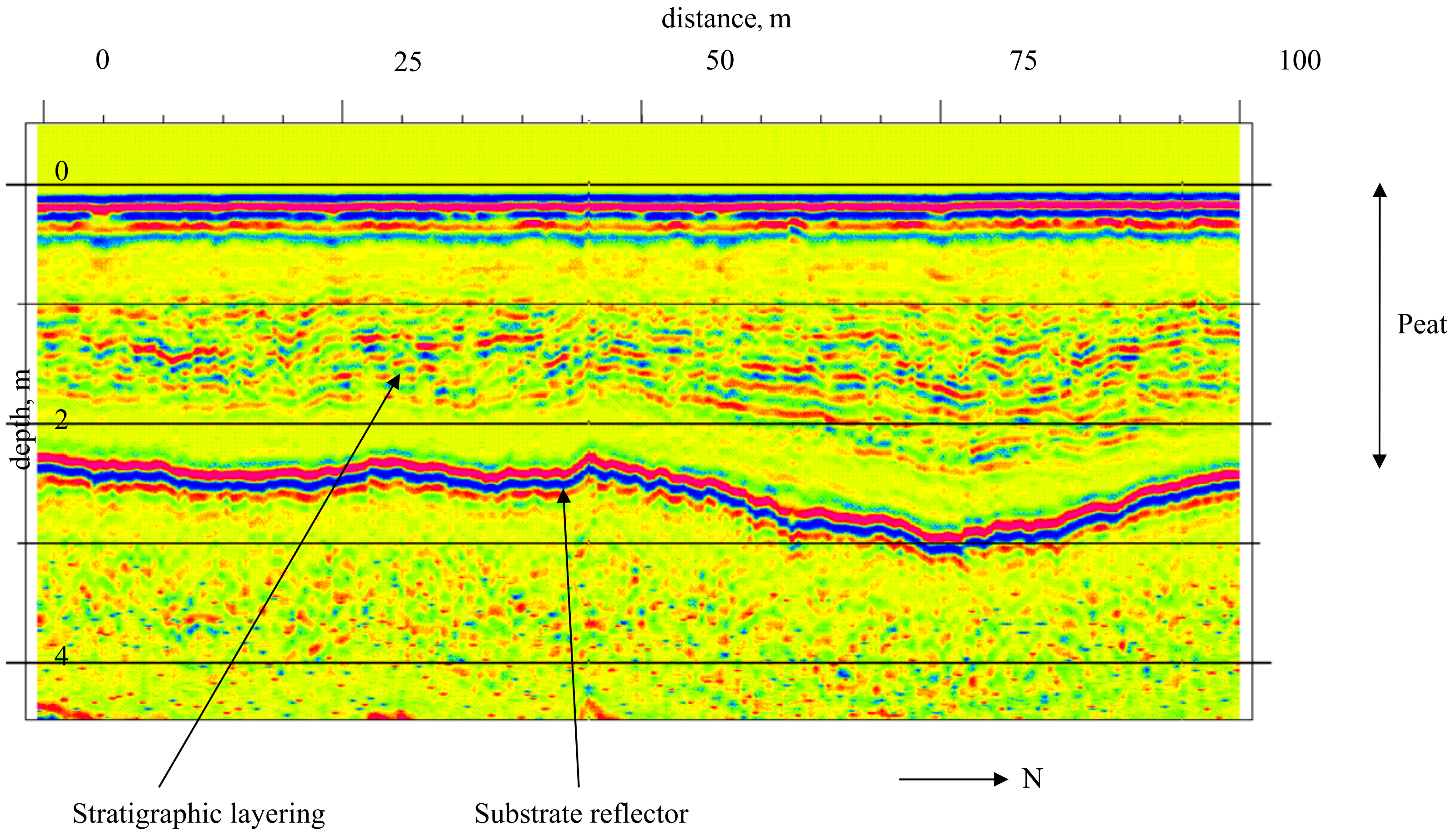

distance, m
0
25
50
75
100
0
2
4
depth, m
Peat
Stratigraphic layering
Substrate reflector
N

Figure 3.

a) topography

b) peat depth

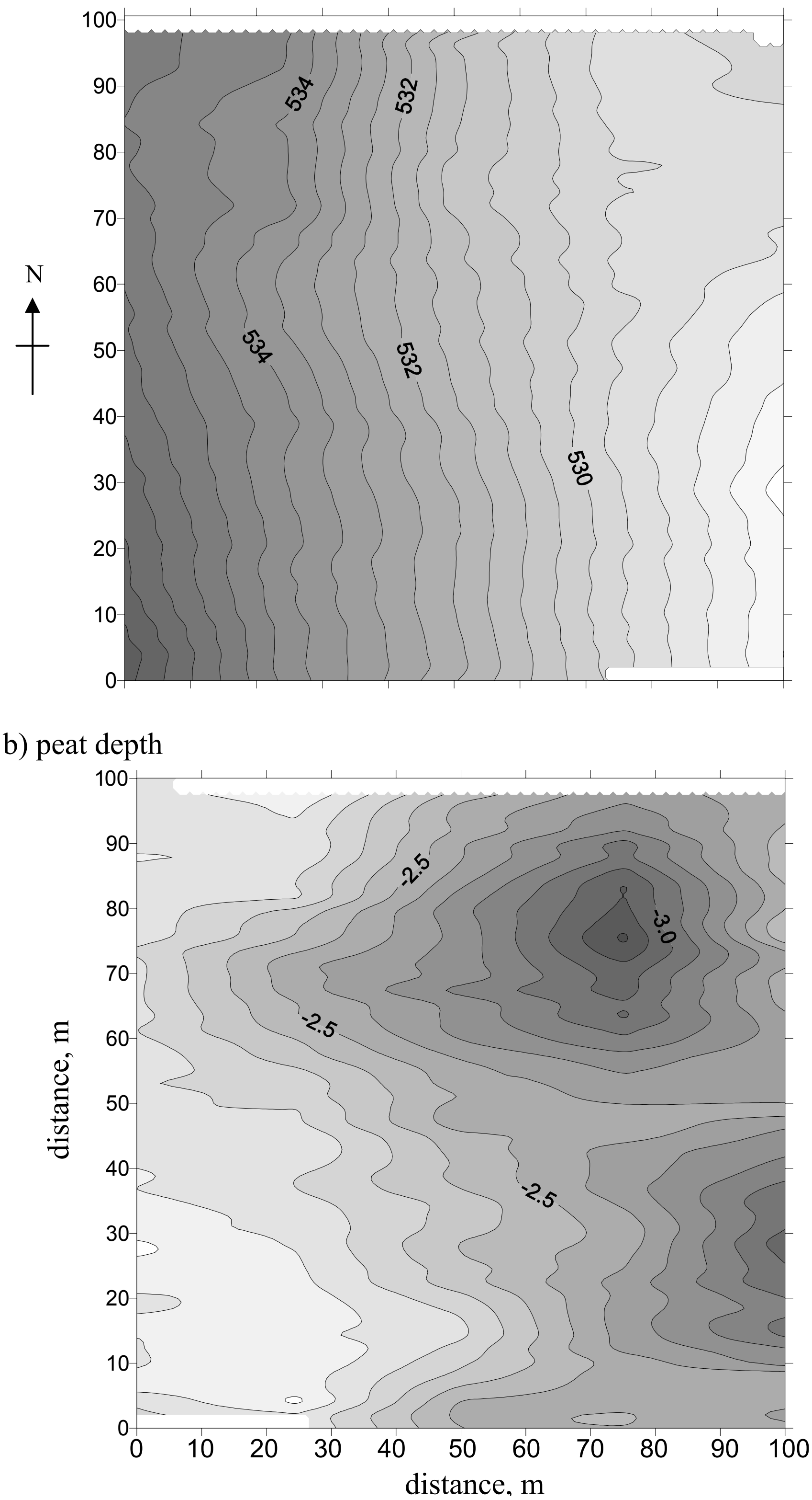
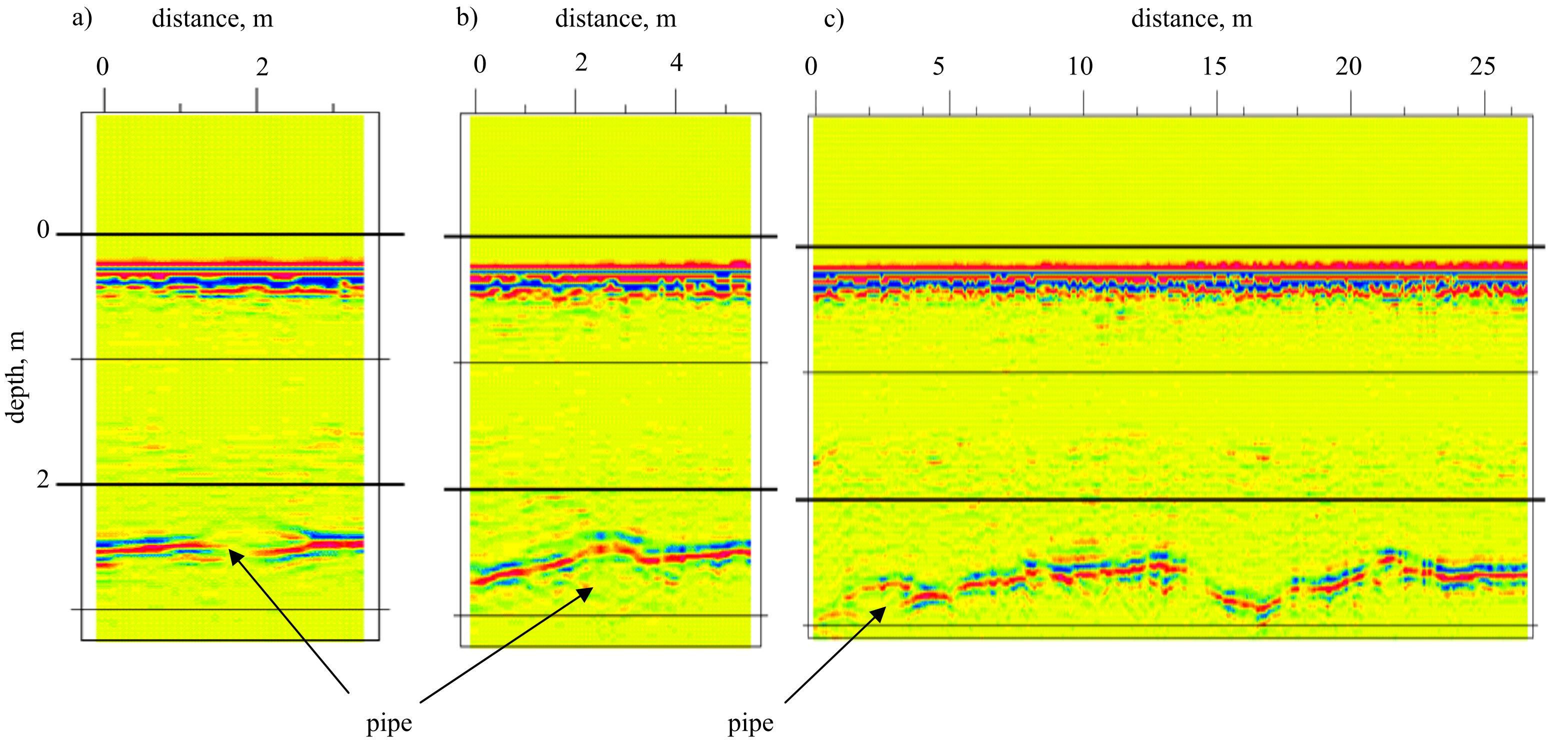
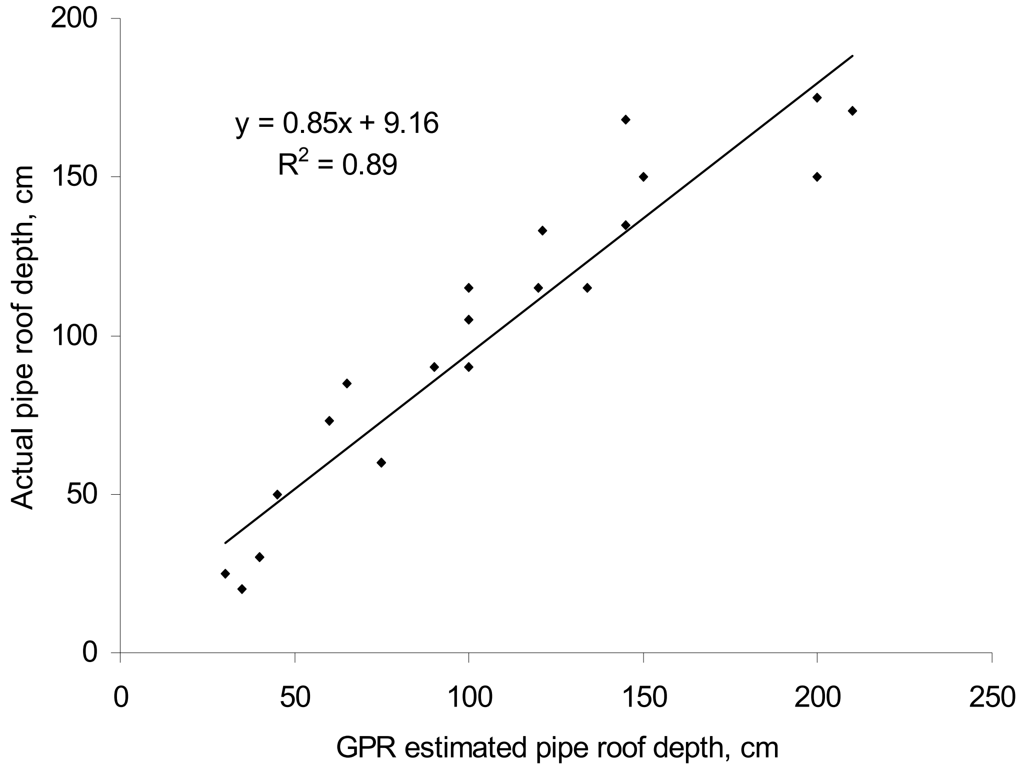


Figure 4.



a)
distance, m
0
2
b)
distance, m
0
2
4
c)
distance, m
0
5
10
15
20
25
0
2
depth, m
pipe
pipe

Figure 5



200
150
100
50
0
0
50
100
150
200
250
y = 0.85x + 9.16
R2 = 0.89
Actual pipe roof depth, cm
GPR estimated pipe roof depth, cm

Figure 6.

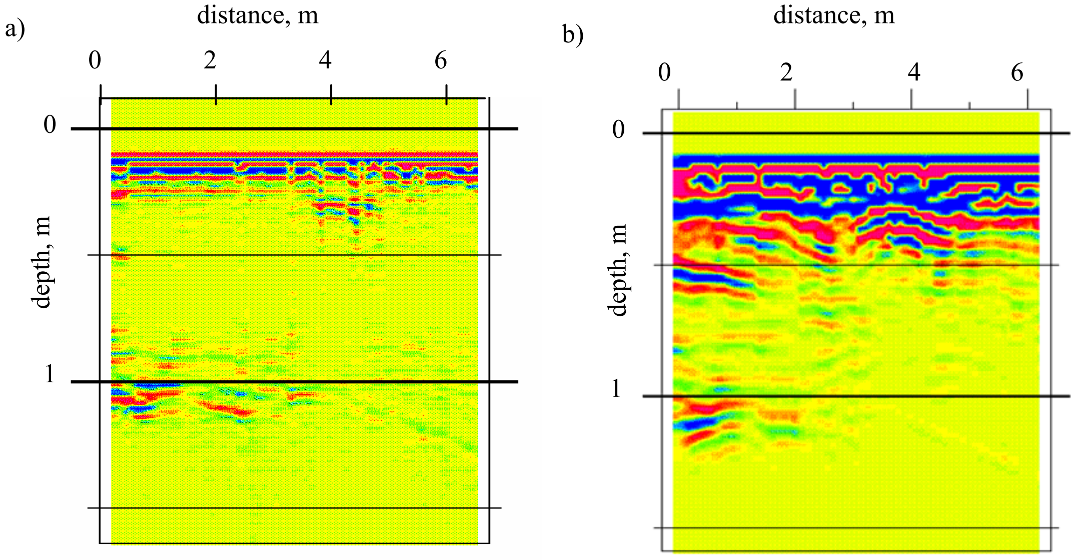
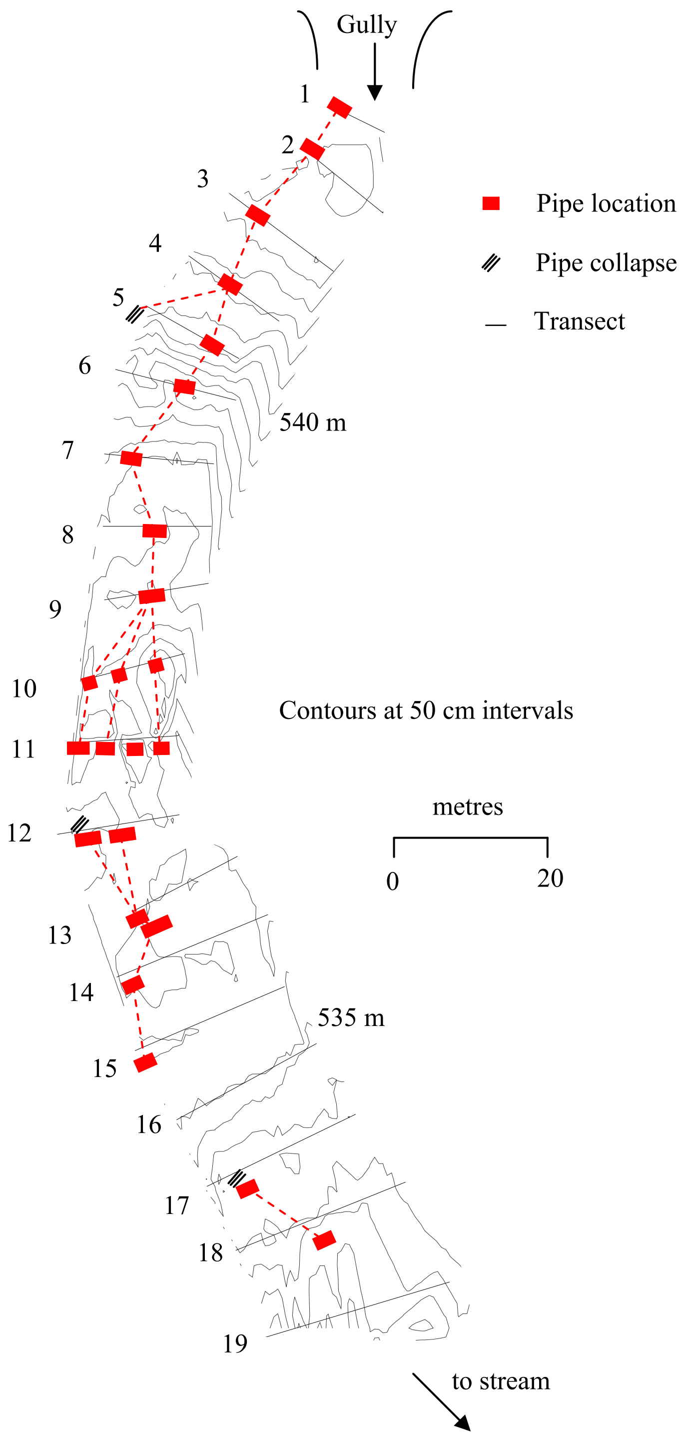


Figure 7.



Gully
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
540 m
535 m
Pipe location
Pipe collapse
Transect
Contours at 50 cm intervals
metres
0
20
to stream