MULTIDISCIPLINARY CHARACTERISATION AND MODELLING OF A SMALL UPLAND CATCHMENT IN SCOTLAND

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ABSTRACT

A combination of conventional surveying and non-invasive techniques have been applied to characterising the geomorphology, soils and shallow substrates of a typical small catchment in the Southern Uplands in Scotland, in three dimensions. Integration of geospatial, geophysical and geotechnical data, in the resulting digital 3D model, enable the nature and extent of individual components of the landscape to be measured and their relationships at

depth to interpreted and visualised. This type of baseline data is fundamental to understanding past, and monitoring and measuring the impacts of future environmental changes in environmentally sensitive areas.

Keywords: Quaternary landscape evolution, 3D modelling, non-invasive investigation techniques, shallow geophysics, geomorphology

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INTRODUCTION

This study reports on an integrated survey used to investigate the geomorphology, soils and substrates of part of a typical small mountainous catchment within Upper Tweeddale in the Southern Uplands of Scotland. The principle aims of the investigation were to (i) develop a combination of techniques for mapping the landscape in three dimensions and (ii) to establish a baseline from which the paleoenvironmental evolution of the area could be assessed and against which monitoring of impacts of future environmental changes could be undertaken. This required a multidisciplinary approach, where conventional surveying methods (mapping, augering, drilling and pitting) were combined with more advanced techniques (terrestrial LiDAR scanning, Electrical Resistivity Tomography [ERT], Ground Probing Radar [GPR] and Panda penetrometer traverses) to characterise the landscape and its components. The data from this integrated field methodology was combined within 3D modelling software, enabling holistic representation of Quaternary landforms and sediments from a remote upland area for which little previous data existed.

The site, now established by the British Geological Survey (BGS) as the Talla Earth Observatory, is on open grazing land in the Tweedsmiur Hills, 1km SE of Talla Linnfoots Farm [^{3}315 ^{6}204], 35 km south of Edinburgh (Figure 1). It forms part (3.2 km^2) of the catchment of the Talla Water, a small headwater tributary of the River Tweed, which drains north eastwards a distance of 660m from the NE margin of the site to feed into the Talla Reservoir, hence the site’s environmental sensitivity. The area is characterised by rugged topography (Figure 2) and dominated by the effects of erosion and deposition by glaciers that disappeared in the last 10 000 to 13,000 years. The mountain tops rise to elevations of 700 to 800 m above sea level and the study site lies largely within a pass at 400 to 450m elevation, between the Tweed Valley and Moffat Dale.

Although a varied assemblage of relict glacial, periglacial and post glacial deposits and landform overlies the bedrock in the region (Table 1) there are few modern published descriptions of their nature and distribution. Two recent studies from the surrounding area (Chiverrell, Harvey, Foster, 2007; Foster, Chiverrell, Harvey, Dearing, Dunsford, 2008) have focused on dating Holocene alluvial fan sequences and their use as proxies for palaeoenvironmental change over the last few thousand years. The proxy climate and vegetation record of the Talla area itself, for the last 5,500 years, was described by Chambers, Barber, Maddy, Brew (1997) from monolith samples of peat from the NE portion of the Earth Observatory area (Figure 1). They recognised that the site has been subjected to a markedly oscillatory climate during the late Holocene, with several specific episodes of exceptional wetness having occurred during the last 3.5ka.

<Figure 1 and 2>

<Table 1>

GEOLOGICAL SETTING

The bedrock of the site comprises highly resistant, weakly metamorphosed greywacke sandstones of the Gala Group (Upper Ordovician – Silurian) of the Southern Uplands of Scotland (Floyd, 2001). The glacial sediments and weathered bedrock both form bouldery and cobbly substrates that are difficult to penetrate by traditional percussive drilling methods, while steep slopes and unstable ground conditions make trial pitting difficult. Where the glacial debris has been reworked by frost action, or by rivers and streams the periglacial and post glacial sediments formed tend to be largely composed of cobbles and boulders and their genesis is often only clearly evident from their geomorphological expression and position within the landscape (Figure 3).

The Observatory site contains many, but not all of the features and sediments typical of an upland valley in southern Scotland (Table 1). It shows evidence of Weichselian and probable Younger Dryas glaciation with deposition of till and moraines on lower valley slopes and para or postglacial mass movements leading to the accumulation of tallus and solifluction lobes locally. Basin peat has formed in the valley bottom and hill peat flanks the mountain tops; organic and bouldery soils are developed on all but the steepest slopes.

<Figure 3>

TECHNIQUES USED TO CHARACTERISE THE TALLA EARTH OBSERVATORY SITE

Field investigations at the site took place in three main phases (Table 2). These were followed by the construction of a 3D model of the study area. The initial phase of field work established the geology and overall morphology of the site. The second phase produced data on the nature of the shallow subsurface to c. 1 m depth and more rigorous acquisition of digital elevation and ground morphology data. This enabled the targeting of the more complex areas with non-invasive ground investigation techniques in the third phase of the work.

<Table 2>

First phase surveys

The Quaternary sediments and features within the Talla Earth Observatory site were recognised using geological and geomophological mapping techniques. This involved interpretation of Digital Elevation Models (DEM) and hill shaded Digital Terrain Models (DTM) derived from NEXTMap British Elevation data (©Intermap Technologies) at 1 m vertical and 5 m horizontal resolution, as well as mapping from stereoscopic aerial photography. This provided baseline data that was incorporated into a walkover geological/geomorphological survey of the Observatory site and surrounding area, which is the basis for the Quaternary map shown in Figure 4.

Summary of the geomorphological features and deposits of the Talla site

Glacial features: The mountain sides have been oversteepened by glaciation, largely during the Weichselian, giving the valleys a typical 'u-shaped' cross section. It is possible that some further erosion of the slopes occurred during the Younger Dryas.

The lower valley slopes are mantled to an elevation of c. 550 m by a variable thickness of glacial till. It is of uniform clayey-gravel composition, and dominated by clasts of locally-sourced greywacke with some rare further-travelled coarser sandstones and lavas. The matrix of the deposit is highly consolidated and its morphology suggests subglacial deposition.

The upper reaches of the valley of the Talla Water, and its junction with the east-west pass between the Talla and Megget reservoirs, are dominated by accumulations of morainic debris (Figure 4). The forms of the moraines indicate that they were deposited by a small glacier that retreated toward the headwater area of the Talla Water. The moraines within the upper Talla Water (Figure 5) are 'classical' Scottish hummocky moraine comparable to those described by Benn (1992), they form a continuous spread of 'up-valley' arcuate ridges, 5-8 m in height. Natural exposures in the deposits are poor but they are composed of similar material to the till but with a slightly sandier matrix.

A small flat-topped spread of glaciofluvial outwash sand and gravel occurs on the northern bank of the Talla Water close to the centre of the site (Figure 4); more extensive spreads and larger outwash fans are associated with the course of the Megget Water NE of the Observatory area.

Periglacial features: Large areas of inactive bouldery and cobbly solifluction deposits are present on the upper slopes and on the hill summits. Low relief ridges and solifluction lobes are present on the southern slope of Fans Law (Figure 4). The solifluction deposits are composed primarily of frost shattered material, and appear to be derived from remobilisation of till.

Some small areas of inactive talus occur below bedrock exposures. The relict deposit is composed of angular clasts of greywacke up to 10cm in diameter.

Holocene Features: Small amounts of talus are actively accumulating beneath the steepest bedrock exposures and as cones at the mouths bedrock gullies. Relict alluvial fans are present at the mouths of gullies on northern valley sides above the Talla Water (Figure 6). Features associated with more recent fluvial activity reflect the small size of the Talla Water burn, with relatively narrow terraces, composed of cobbles and pebbles; the modern floodplain is similarly floored with coarse material. The burn flows directly on bedrock in the uppermost and lowermost reaches (Figure 4).

The northern slope of Calavin Hill and parts of the summit of Fans Law are mantled with thin relatively unhumified hill peat (Figure 4). The centre of the site (Figure 6) is covered by a waterlogged mire, composed of well humified peat, that extends over >30 hectares and blankets the underlying moundy topography.

<Figure 4 and 5>

Second phase surveys

Auger surveys

Auger surveys were conducted across the Talla site, supplemented by observations from the sparse natural exposures and in places augmented by shallow pits dug with a spade. These provided detailed data on the nature of the shallow subsurface at 191 data points, to depths that locally exceeded 1 m. The results were used to refine the resolution of the Quaternary map (Figure 4), to identify areas of thin Quaternary cover on bedrock and identify 13 Soil Series and 4 composite soil units, which form the basis of the 11 soil types shown on the soil map of the site (Figure 7).

Soils: The surveys showed that thick, commonly waterlogged, fibrous and humified organic soils are developed on the peat mires in centre of the site (Figure 7). Bouldery sandy clay loams, are locally developed on the mountain top solifluction deposits, on till and bedrock within the tributary valleys, and on the moraines flanking the upper reaches of the Talla Water. Bleached stony sandy loams with ferruginous pans, blanket moraines lower in the valley. Thin clay loams cap bedrock crags while thicker clay soils are also developed on till locally. Thin waterlogged gravel soils dominate on the floodplain of the Talla Water.

<Figures 6 and 7>

Terrestrial LiDAR survey and dGPS

A high resolution topographic survey of the Talla catchment was undertaken using terrestrial LiDAR (Light Distance And Ranging), commonly referred to as laser scanning. The aim of the LiDAR survey was the creation of a detailed surface DTM to aid geological and geophysical data interpretation.

The terrestrial laser scanner deployed was a Riegl LPM-i800HA (inset, Figure 8), with an effective range up to 800 m at an accuracy of ±25 mm. The scanner measures and records relative distance, and vertical and horizontal angle between the instrument and the target surface for each point, with a typical measurement rate of 1000 pts/sec. This scanner also incorporates a high-resolution digital camera, enabling true-colour information for surface point data, or calibrated digital photo images to be captured. The laser scan technique relies on the fact that the laser beam reflects from target surfaces. The intensity (strength) of the returned laser beam is recorded, which varies according to the reflectivity of the surface material being measured. The method is not effective where the subject is moving (e.g. water), not visible or where the laser beam is reflected by heavy rain or fog. The principal advantage of the LiDAR surveying technique is the speed, resolution and accuracy of data acquisition (Buckley, Howell, Enge, Kurz, 2008). It also enables data capture in terrain that is difficult to access (e.g. steep valley sides). For the Talla survey, multiple scans were taken from different aspects of the site in order to ensure almost complete terrain coverage, creating a higher resolution and more complete DTM for the site in less time than it would be possible by traditional surveying.

Key to the success of laser scanning is the accurate horizontal and vertical positioning of the instrument and other reference points. This is achieved with a dual frequency GPS, which enabled accurate orientation of the data to British National Grid coordinates. The altitude and location of the scan and reference point positions were measured using a Leica SR530 differential Global Positioning System (dGPS) corrected to Ordnance Survey National Grid and Ordnance Datum (OD) (Newlyn). The dGPS was deployed in Real Time Kinematic mode, allowing positional corrections to be received in real-time via radio link from a reference receiver. Using this system, altitude data was produced that is accurate to within 0.03 m, and 0.02 m in plan (The Survey Association, 2008). The terrestrial LiDAR data consists of ‘point-clouds’ comprising x, y, z point coordinates and intensity values. The raw point cloud data were input into surface modelling software to produce a solid high-resolution 3D terrain model of the Observatory site.

<Figure 8>

Figure 8 shows a 3D multiple-scan point-cloud image, shaded by intensity which enhances the recognition and interpretation of specific features. The image was taken from the southern side of the catchment, adjacent to Molls Cleuch Burn, looking north. The Burn can be seen in the left foreground, as a low intensity (black) feature where the laser signal was not returned due to running water. Another, low intensity area can be seen in the Talla Moss blanket peat area in the centre right of the figure, also associated with surface water. The medium intensity (dark grey) area in the centre images the alluvium adjacent to the main channel of Talla Water. In contrast, lower intensity (light grey) areas on the distant slopes depict the position of solifluction lobes on the southern flank of Fans Law.

Holes in the data for the LiDAR solid surface model occurred at localities where data were not captured due to the presence of surface water. In order to create an accurate and complete DTM, the LiDAR DTM was patched with data from the lower-resolution NEXTMap Digital Surface Model. It was not possible to simply splice the NEXTMap data into the LiDAR dataset, as it created too many data artefacts, resulting in a noticeably stepped terrain model. However, individually warped patches of the NEXTMap model were patched onto the LiDAR data, by creating a correction algorithm that compared elevations between the models at the margins of the holes in the LiDAR dataset. Applying the correction to the NEXTMap data created a best-fit join between the models at the margins of the data holes, with the effect of the warping decreasing towards their centres. This blended the NEXTMap patches into the LiDAR DTM effectively, to produce a ‘smooth’ terrain model. This DTM forms the surface topography of the 3D model of the Talla Earth Observatory and is also the basis of the DEM of the Talla Linnfoots area (Figure 2).

Third phase surveys

Invasive and non-invasive ground investigation techniques were used to investigate and characterise the shallow subsurface in detail. The invasive methods employed (trial pitting, shallow percussive drilling and light-weight cone penetration testing) were integrated with the results from shallow geophysical surveys. Synthesis of the results allowed visualisation and quantitative analysis of the physical properties of subsurface materials, while cross-calibration between different types of dataset increased confidence in the final geological interpretation and modelling of the subsurface conditions at the site.

Near-surface geophysical surveys

Geophysical techniques were used to elucidate the form and distribution of the shallow subsurface deposits in 3D, to identify locations for more detailed invasive investigations, and to obtain volumetric information about the nature of strata beyond depths that could be investigated by pitting and drilling.

Electrical Resistivity Tomography (ERT): As the vertical resolution of ARP techniques are limited, 2D ERT was employed to provide detailed geophysical cross-sections at key locations across the Observatory site. 2D ERT is capable of producing tomographic images of the spatial distribution of bulk subsurface resistivity (as opposed to apparent resistivity) along linear survey profiles (e.g., Dahlin, 2001). Modern data processing and inverse modelling algorithms allow for the integration of steep topography and complex geomorphology typically encountered on upland sites such as at Talla. ERT surveys were carried out on five major profiles (TAL-A, B, D, F and G) located across the valley at different elevations in the catchment (Figure 7). Specifically designed multi-channel measurement sequences based on the Wenner-Schlumberger array geometry were used for data acquisition (Chambers, Kuras, Meldrum, Ogilvy, Hollands, 2006), resulting in robust datasets with excellent lateral and vertical resolution, showing resistivity variations across nearly four orders of magnitude.

Figure 10a shows the resulting 2D resistivity model of Profile TAL-D as an example. The profile crosses peat deposits in the centre of Observatory site. The electrical signature of the waterlogged peat is a conductive layer (shown in blue) with resistivities of below 500 Ωm. The interpreted form of the base of the morainic deposits, seen between profile distances 170 m and 550 m coincides with resistivities above c 5000 Ωm.

Automated resistivity Profiling (ARP): Due to its sensitivity to water content and variations in lithology, electrical resistivity was seen as a key geophysical parameter to differentiate between various types of Quaternary deposits. To provide baseline resistivity across a large part of the Observatory site, an ARP survey was undertaken (Besson, Cousin, Dabas, Biozard, Richard, 2005). A towed survey system capable of making measurements of the apparent soil resistivity across three different depths of investigation was deployed. An ARP survey involves towing a mobile electrical sensor array across the site using an all-terrain vehicle (Figure 9). Dynamic positioning was achieved via integrated RTK-GPS and measurements were processed on board, with the operator guided by a real-time GIS system. The methodology allowed the production of preliminary digital maps of apparent resistivity (geo-referenced bitmaps) for approximately 13 hectares within a few hours, at a lateral resolution of approximately 15 m for the final maps (Figure 10b).

The maps show resistivity distributions at 0 - 0.5 m, 0 - 1.0 m and 0 - 1.7 m depths, that reflect the mapped geology, in particular the extent of the peat moss (shown by low resistivity values in blue) and the location of river terrace gravels (high resistivity values in red) at several locations immediately adjacent to the northern bank of the Talla Water (Figure 10b). However, much additional detail was obtained that reflects the nature of subsurface features, notably the form and extent of moraines concealed beneath the peat. They are picked out by high resistivity values that begin to be apparent in 0 - 0.5 m dataset, but are better defined in the deeper datasets, which show that the peat basin is bisected by a buried N-S trending morainic ridge.

<Figure 9 and Figure 10>

Ground Penetrating Radar (GPR): GPR is used to investigate the subsurface by penetration and reflection of high-frequency electromagnetic waves in the ground (Davis and Annan, 1989). In near-surface investigations GPR can provide a high degree of vertical and horizontal resolution, ideally complementing the ERT technique (Slater and Reeve, 2002), as they are each controlled by contrasts in different electrical parameters (resistivity and permittivity, respectively).

The suitability of GPR surveying in peatlands was initially reported Theimer, Nobes, Warner, (1994). Their study found that the principal peatland interfaces detected were the near-surface aerobic to anaerobic transition within the peat and the peat to mineral basement contact. More recently, Comas, Slater, Reeve (2004, 2005) have used GPR to determine peat basin morphology and the stratigraphic controls on pool formation in a domed bog, whilst Sauer and Felix-Henningsen (2004) used it to measure the thickness of Pleistocene periglacial slope deposits. At the Talla site, GPR has been used in conjunction with the ARP and ERT techniques, mentioned above, to characterise the vertical and lateral extent of peat and the underlying glacial sediments.

A Pulse Ekko IV system (Sensors and Software Ltd) with 100 MHz antennae was used to map the base of peat over traverses TAL-A and TAL-D. It accurately delineated peat thickness variations and added near-surface detail enhancing interpretation of 2D ERT sections. The GPR traverses were later calibrated by Panda penetrometer profiles (see below).

Trial pitting and drilling

Eleven trial pits were excavated using a tracked, low ground-pressure excavator, capable of traversing both steeply inclined ground and areas of unstable water-saturated peat. Pit sites (Figure 7) were concentrated at the ends of 3 of the 5 ERT traverses, as well as on the valley sides and the margins of the blanket mire (where the geological and geophysical surveys indicated that the surface peat was generally < 0.5 m thick). In all instances the pits enabled a direct evaluation of the nature of Quaternary sequence to 2-3 m depth. Bouldery or gravelly glacial and periglacial deposits were encountered in 10 of the pits, gravelly relict alluvial fan deposits, with buried peat lenses containing wood fragments, were encountered in the other; all provided samples that enabled calibration of the geophysical signatures of the deposits by their geotechnical and sedimentary characteristics.

A shallow cored borehole was sunk on the floodplain of the Talla Water and 4 others were drilled within the areas of thickest peat interpreted from the ARP and ERT data. Drilling was undertaken, using a light weight Dando Terrier drilling rig. The drilling equipment was unable to reach rockhead, but the boreholes provided data on the nature and thickness of the postglacial sediments where pitting was impossible. The boreholes are now instrumented to provide real-time measurements of shallow groundwater level fluctuations within the lower portions of the Talla site.

Light-weight penetrometer

Geotechnical techniques are well known for enhancing characterisation of glacial sequences (Gerrard, 1981) and understanding the formation of peat bogs (Moore and Bellamy, 1974; Hobbs, 1986). Characterisation of peat types and peat stratification is aided by using properties, such as undrained shear strength values, as a proxy for amount of compaction and consistency of the sediments. Although it does not provide measurements of undrained shear strength, the Panda ® Dynamic Cone Penetrometer is a tool commonly used for compaction control testing and for investigating natural soils in geotechnical site investigations (Langton, 1999). It provides vertical profiles of cone resistance, which relate to the variations in strength and density of superficial materials.

The penetrometer apparatus weighs around 20 kg and can be operated by one person making it a useful rapid, low-cost probing of soils on sites where terrain is restrictive. The apparatus measures the frictional resistance of a soil, measured in ‘qd’ (1qd = 1MPa). It works by driving a 2 cm diameter cone into the ground to depths of up to 6m. Penetrometer measurements have been previously used to characterise cohesive glacial till deposits (Gunn, Pearson, Chambers, Nelder, Lee, Beamish, Busby, Tinsley R., Tinsley W., 2006) but, at the Talla site, they were used to characterise the stratigraphy of the peat deposits, alluvium and glacial deposits across the low lying portions of the area. The technique is restricted to ‘very soft to very-stiff’ fine grained soils (as defined by British Standard 5930:1999) and it was physically unable to penetrate very densely packed sand and gravels or competent cobbles.

At Talla penetrometer profiles were taken at 20 m intervals along the geophysical lines and also at borehole locations. The profiles all intercept a highly resistive boundary between 0.2 and 2.5 m characterised by a sudden increase in the cone resistance. Comparison with the borehole logs indicates this response is commonly due to a change in resistance at the base of the topsoil. Similar minor variations in the cone resistance at greater depths equate with lithological changes with in the peat and alluvium as illustrated in Figure 11c, d and e. The interpolation of peaks above 1MPa, indicating materials with the engineering strength of rock, provides a continuous cross section of the base of peat deposits.

Comparison of Panda, GPR and ERT data: The GPR results (Figure 11a and b) were validated by comparison with Panda penetrometer profiles and borehole descriptions (Figure

11c and e). The strength profiles and borehole logs were overlaid onto the geophysical pseudo-sections to provide a validation check for the estimated velocity parameters used in the geophysical inversion. The peaks in the penetrometer data correspond well to reflectors in the GPR image indicating that the GPR can be used to map the base of the peat in detail across the section. The resulting geological sequence (Figure 11d) shows lateral and vertical variability of these deposits.

<Figure 11>

Calibrated radargram (Figure 11a) also proved the existence of three distinct peat-filled palaeochannels (c. 50 m wide and 2-3.5 m deep), cut into the underlying moraine ridge (labelled as major peat accumulations). The most northerly palaeochannel (Figure 10b) shows a 2 m thick upper reflective layer related to fibrous peat overlying a basal, more amorphous layer (Figure 11c). This suggests two peat layers of different water content, which is due to the variation in the density and its degree of humification (Leopold and Volkel, 2003). The aerobic to anaerobic contact between growing sphagnum moss and underlying peat, appears to be marked by the large amplitude reflector at a depth of 0.6m (between 490 to 520 m) caused by the peat's high level of water saturation. A comparable strong reflection, caused by a decrease in water content indicates the contact of the peat with the underlying unsaturated morainic deposits.

3D MODELLING AND VISUALISATION

Methodology

The modelling package used in this study is Geological Surveying and Investigation in 3D (GSI3D) software, which has been co-developed by BGS and INSIGHT GmbH since 2001. The GSI3D methodology is easy to use, simple and intuitive and its success is based on the fact that it utilises exactly the same data and methods, albeit in digital forms, that geologists have traditionally used to make geological maps and cross-sections (Kessler and Mathers, 2004).

Basic data formats used in GSI3D are geo-registered raster images such as topographic base maps and air photos, DTM loaded as standard ASCII grid file, digital borehole data, geological map data loaded as ESRI shape files and geo-registered planar vertical sections and horizontal slices. The backbone of the software is the GVS text file, which contains all geological units in their correct and unique stratigraphical order, which defines the “stack” that is calculated to make the 3D geological model. A more detailed description of the software methodology is given in Kessler, Mathers, Sobisch (2008). In short, the software normally combines a DTM, geological surface linework and downhole (borehole, trial pit, auger hole) geological data to enable construction of regularly spaced intersecting cross sections, by correlating boreholes and the outcrops-subcrops of units, to produce geological fence diagrams. The Talla study combines the results of a suite of geophysical and geotechnical surveys to produce additional interpreted cross-sections to constrain the model beyond the depth reached by the more usual methods of ground investigation. Mathematically interpolating between nodes along the geological, geophysical and geotechnical cross-sections, together with the mapped surface extent of the units, produces a 3D model. This is built from a series of stacked Triangulated Irregular Networks (TINs), corresponding to the top and basal surface of each geological unit.

Talla 3D Model

Constructing the model initially involved collating the main geological, geophysical and geotechnical datasets described above, and ensuring all of the data were in a compatible geo-referenced digital format for import into the GSI3D software. This was a relatively simple task for many of the data sets collected during the first and second phases of the study. Most of the geological log data (from auger holes, trial pits and boreholes) were recorded digitally in the field on tablet pc’s with integral GPS positioning systems. The data was loaded into BGS customised Microsoft Access 2003 geodatabases and linked to location and cartographic data generated in a customised ArcMap 9.1 © ESRI based GIS. The methodology is described in more detail in Jordan, Bee, Smith, Lawley, Ford, Howard, Laxton (2005). During survey of the third phase, all of the geophysical field data and most of the geotechnical were recorded digitally. Accurate locations, which were required for the import of these traverses and data points into GSI3D, were provided by dGPS.

The GSI3D model of Talla incorporated: a merged high-resolution Lidar/NextMap DTM, black and white aerial photography, British Ordnance Survey 1: 10 000 scale topographic data, 1:10,000 scale geological mapping of bedrock and superficial deposits, logs of auger holes, boreholes and trial pits, geophysical profiles and maps, and Panda penetrometer profiles. Screen shot in Figure 12 shows the model construction in GSI3D with its three interactive map and section windows in which the user draws the intersecting cross-sections and envelope units. By combing the information from the cross-sections and the envelopes, the software calculates the volumes of each geological unit and stacks them in the correct stratigraphical order. The methodology on incorporating geophysical data in GSI3D is described in more detail in Williams and Scheib (2009).

<Figure 12>

Results

The geological units modelled include (in stratigraphical order) alluvium, peat, talus, head, alluvial terraces, alluvial fans, glacio-fluvial deposits, moraine and glacial till. The model is particularly successful for characterising and visualising the extent and thickness of these near surface deposits. The best results were obtained when the data from geological, geophysical and geotechnical transects were combined to provide the interpretation along given sections (such as TAL-D, Figure 10a). Figure 12b shows geophysical sections along with correlated geological sections in a 3D fence diagram. They were also used in the section window (Figure 12c), where the modeller used the resistivity profile as guidance to correlate a more accurate and refined extent of peats (low resistivity) and gravelly morainic deposits (high resistivity). This integrated approach produced the highest degree of confidence in the modelled accuracy of the depth and extent of the Quaternary successions and enabled better interpretation of the hidden geology.

The GSI3D package also produced realistic areal extents and calculated volumes for several of the shallow deposits. For example, the areal extent of peat within the model area is 406,000 m^2, the calculated volume is 569,444 m^3, giving the deposit an average thickness of 1.4 m; comparable figures for the morainic deposits were 1,088,000 m^2, 6,770,776 m^3 and 6.2 m. These appear to be geologically realistic values, based on empirical observations of the features and deposits in the field.

The modelling was less successful constraining rockhead at depth. It was limited by a lack of direct geological evidence (from drilling and pitting) in the central parts of the observatory site, to calibrate geophysical interpretation of rockhead beneath the thickest parts of the Quaternary sequence. This is a consequence of a combination of factors, particularly the ground conditions (thick waterlogged blanket mire), which precluded the use of heavy weight drilling equipment and limited mechanical excavations to the flanks of the mire. Nevertheless, the geophysical results (particularly from the ERT and GPR surveys) combined with inferences of bedrock morphology at depth, from evidence at the more peripheral localities, provide a much improved estimation of rockhead across the site area than is possible from ‘traditional’ walkover surveys alone.

DISCUSSION AND OUTLOOK

The Talla Observatory is remote and environmentally sensitive, with limited access possible for heavy equipment. It is however typical of many upland catchment sites in northern Britain, in both the diversity of landforms and sediments that it contains. Consequently, to characterise the area so that its environmental baselines could be established, an innovative combination of conventional geological, geomorphological, mapping and invasive point-measurement techniques, were employed, in conjunction with shallow geophysical methods. Invasive techniques, such as drilling and pitting, had to be used sparingly, as both are destructive and the ground conditions meant that they provide an incomplete characterisation of the subsurface (Lapen, Moorman, Price, 1996). The integration of these 'traditional' methods with shallow geophysical techniques (GPR, ARP, ERT) and geotechnical measurements enabled a more complete evaluation of the extent and thickness of the deposits than would otherwise be possible. The use of terrestrial LiDAR scanning with remotely sensed NEXTMap data also provide a high accuracy DTM that enabled detailed and accurate modelling of the site as a whole as well as characterisation of individual landform elements.

When the survey data were combined in a 3D geological modelling and visualisation package, a unique picture emerged of the relationship between the landscape and the glacial and postglacial sediments at the Talla Observatory site. This provides a rigorous framework for recording its past environmental evolution and monitoring its future environmental changes.

Some of this work has already begun. ^{14}C dating of plant macro fossils from peat cores taken from the deepest parts of Talla Moss has already been undertaken and an extensive programme of analyses pollen and insect fossil assemblages are underway. Cosmogenic ^{10}Be dating of erratic boulders from the moraines being used to establish the date of the last glaciation of the site and monitoring of shallow groundwater levels linked to precipitation records has commenced. Further investigations of the permeability of the glacial sediments by means of Guelph permeameter measurements are planned, with the eventual aim of constructing a quantified model of the shallow groundwater component of baseflow to the hydrology of the Talla Water Burn.

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