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The geomorphic impact of road construction: a case study of the A9 in Scotland

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The geomorphic impact of road construction: a case study of the A9 in Scotland

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Front cover

View north along the A9 in Strath Tay, to the east of Dunkeld (K Whitbread/BGS, NERC).

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Foreword

This report details the results of an assessment of the geomorphic impact of road construction along two sections of the A9 in Scotland; a southern area located approximately 10 km north of the city of Perth, and a northern area located approximately 10 km south of Inverness.

The study was developed to test methodologies for providing an independent estimate of ground surface change, erosion and deposition associated with road construction using borehole records held in the BGS archive and recently acquired digital elevation models.

The work was developed initially from mapping and modelling work undertaken in the Dunkeld area in 2013 under the Geology and landscape Scotland programme, with the analysis presented in this report conducted under the Urban Geoscience research programme.

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Summary

This study is a preliminary assessment of the geomorphic impacts of road construction based on two test areas located along the A9 in Scotland; a southern section 30 km in length just north of the city of Perth, and a northern section12.5 km in length just south of the city of Inverness.

Estimates of the depths of cuttings and embankments formed during road construction have been made through comparison of ground levels recorded in pre-construction borehole logs along the road route with digital elevation models representing the modern ground surface. This study trials two methods of assessing surface change and the volume of material excavated or deposited along the road route. Firstly a direct comparison of borehole ground levels with the modern ground surface is used. The second method involves reconstruction of the pre-road ground surface through re-interpolation of the digital elevation models which are then validated by comparison with the actual pre-road ground level recorded in the boreholes. Volumes of material excavated and deposited are then derived by comparison of the re-interpolated digital elevation model with original (the modern ground surface).

Both analysis methods indicate that there has been a net loss of material in the study areas, that equates to an average surface lowering along the road route of 2 to 2.5 m in the northern area, and 0.4 – 0.7 m in the southern area.

Comparison of average rates of ‘erosion’ resulting from road construction with natural river erosion rates indicates that erosion associated with road construction occurs at rates that are 2 – 3 orders of magnitude faster than even the most rapid erosion recorded in natural streams worldwide, and 3 – 4 orders of magnitude faster than previously measured river erosion rates in Scotland. Only rare catastrophic flood events are capable of excavating gorges at rates equivalent to the rate of cutting excavation during road construction.

The surface lowering and net material transfer associated with road construction is likely to strongly affect local geomorphic systems, with knock-on effects for hydrological and ecological systems in the vicinity of roads. As there are nearly 250 thousand miles of road within the UK, road construction is likely to have significant impacts on geomorphic and environmental systems at national scales.

1 Introduction

1.1 OVERVIEW

Natural geomorphic processes of sediment erosion, transport and deposition have received considerable research attention in recent decades because they are recognised as fundamental controls on landscape change. However, there has been relatively little attention paid to human-induced landscape change that results from excavation and deposition during infrastructure construction. By changing the form of the land surface, this anthropogenic landscape change may have considerable impacts on the operation of natural geomorphic systems with implications for associated hydrological systems and ecosystems. Quantifying the magnitude of landscape change associated with infrastructure construction is therefore important if we are to understand the potential impacts of future construction works on our environment, and to assess how our existing infrastructure affects how sediment is sourced and transported throughout our landscape.

During road construction large volumes of rock and sediment may be excavated or imported to modify the ground level, facilitating subsequent travel along the route. Although road routes may be selected to minimise the need for substantial import or export of material, most still require substantial ground modification during construction works. Man-made landforms including cuttings and embankments are therefore very common features along our road networks.

The magnitudes of ground surface change and the net transfer of material due to road construction are poorly characterised. Although construction companies commonly hold records on the volumes of material extracted or imported during their construction activities, these records are not readily accessible. Furthermore, records from different construction companies may be difficult to integrate to gain a wider understanding of the geomorphic impacts of road construction.

A spatially integrated understanding of ground surface change and net material transfer (erosion or deposition) due to road construction may be gained by comparison of historic ground levels recorded in borehole logs, in combination with digital elevation models of the modern ground surface derived from remotely sensed data.

1.2 RATIONAL

Site investigations, including borehole drilling and trial pit excavations, are generally conducted to aid the planning of road construction works. The ground surface level at the time of drilling is recorded as the 'start height' of the borehole or trial pit.

Modern ground levels are represented by digital elevation models (DEMs) which are derived using satellite or air-borne radar or photographic imagery. In the case of the UK, two types of DEM are available; digital surface models (DSMs), and their derivatives digital terrain models (DTMs) that have surface features such as trees and buildings removed. These models provide three dimensional representations of the terrain at resolutions of less than 1 m vertical accuracy and c. 5 m horizontal resolution (Table 1).

Ground surface change associated with road construction may be examined through comparison of the historic ground level recorded in the site investigation borehole records and DTMs captured after the road was built. Estimates of surface change and the volumes of material imported or removed may be made through either; a) a direct comparison of the borehole ground level and the DTM, or b) use of mathematical interpolation techniques to reconstruct an estimated pre-road DTM that can be validated using the site investigation borehole records and compared with the actual DTM. The deposition of sub-base, base and surface materials during road construction means that volumes of material excavated from cuttings will be minimum estimates.

1.3 A9 STUDY: TESTING METHODOLOGIES

A preliminary assessment of ground surface change associated with road construction was conducted for two test areas along the A9 in order to assess whether the ground levels of site investigation boreholes provide an accurate reflection of the pre-road ground surface, and to compare the different methodologies for quantifying surface change and the net volume of material 'deposited' or 'eroded' during construction.

The A9 is the longest trunk road in Scotland and the major transport route connecting the densely populated Central Belt (including the cities of Glasgow, Edinburgh, Stirling and Perth) with the Highlands and the city of Inverness (Figure 1). North of the city of Perth, the A9 crosses the rural, upland terrain of the Grampian Highlands. The southern test area comprises a 30 km section of the A9 around the town of Dunkeld, extending from Luncarty to Ballinluig. The northern test are covers a 12.5 km section of the road between Daviot and Moy (Figure 1).

The test areas were selected for their relatively high density of boreholes and in the case of the southern test area, because of the availability of recently derived mapping data on the distribution of made and worked ground along the A9 route (Whitbread and Finlayson, 2014).

	NextMap		PGA Height Data	
	DSM	DTM	DSM	DTM
Date raw data obtained	2002 - 2003		2005 - 2010	
Grid size	5 m	5 m	2 m	5 m
Horizontal accuracy	± 2.5 m 1 sigma (on slopes < 20°)	Not specified	Less than ± 40 cm RMSE	Not specified
Vertical accuracy	± 1 m	Not specified	± 50 cm RMSE	± 60 cm RMSE

Table 1 DTM and DSM dataset specifications[1]

1.4 REPORT STRUCTURE

The methods used in the analysis are outlined in section 2, followed in section 3 by a comparison of the different DTMs with respect to OS data to establish the most accurate DTM available for the study. The results of tests to assess whether borehole records are reliable indicators of the pre-road construction ground surface are presented in section 4. In section 5 ground surface change resulting from road construction is determined from borehole records and the DTM, and estimates of erosion and deposition are presented in section 6. A discussion of the results and their implications is presented in section 7.

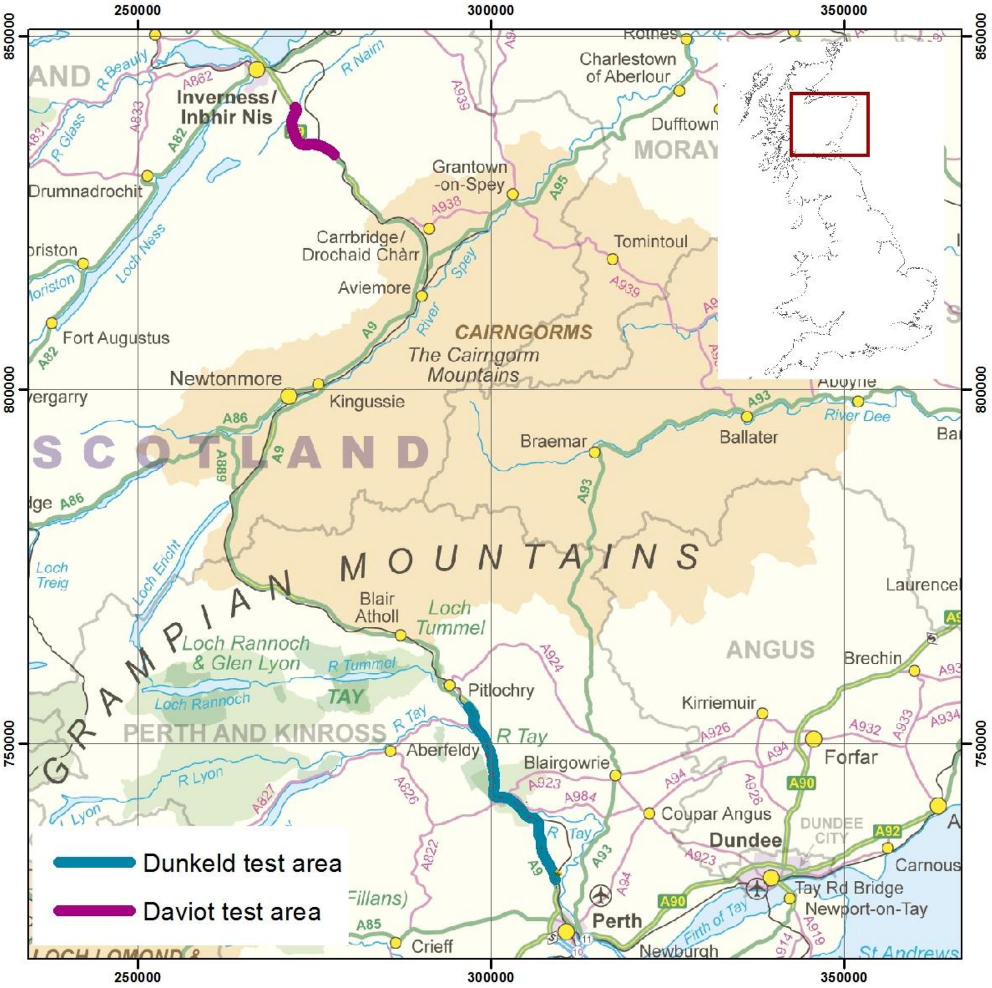

Figure 1 Location map of the two test areas along the A9. The location of the study area in the UK is shown in the inset map. Contains Ordnance Survey Data © Crown copyright and database rights 2014.

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[1] Given on http://www2.getmapping.com/

2 Methodology

2.1 DATA SETS

Site investigations were conducted prior to a major episode of construction forming the modern A9 route in the late 1970’s. Records of the boreholes and trial pits from these investigations are stored in the British Geological Survey (BGS) digital borehole database the Single Onshore Borehole Index (SOBI), and original paper logs are available as scanned images. These records include the borehole start height and drill date where originally recorded in the original borehole log. All borehole data along the A9 route in each of the test areas was extracted from SOBI. Topographic maps of varying detail and quality were provided in the original site investigation reports along with cross-sections along the road route. Digitisation of these records was beyond the scope of this study, but digitisation of maps and sections would to help constrain the pre-road ground surface in future studies.

Two high-resolution DEMs that represent the modern ground surface, the NEXTMap Britain dataset and the more recent ‘PGA’ dataset are available for whole the UK. The NEXTMap Britain dataset comprises surface elevation data derived from flown interferometric synthetic aperture radar (IfSAR) obtained between 2002 and 2003 (IntermapTechnologies, 2004). The PGA dataset was derived from analysis of stereo aerial photographs obtained between approximately 2005 and 2010[2]. Details of the resolution of the two datasets are given in Table 1. The relative accuracy of the two DTM datasets with respect to Ordnance Survey terrain data is assessed in section 3.

2.2 DATA PREPARATION

Borehole records containing information on the drill date, start height, and X and Y coordinates were extracted from SOBI for boreholes located within 50 m of the centre line of the A9 and plotted as point shapefiles in ARCGIS. Values of the surface elevation at the borehole point were extracted for each record from the DEMs using Spatial Analyst Tools.

The distribution of made ground (MGR) and worked ground (WGR) associated with cuttings and embankments, respectively, along the A9 route was mapped in ARC GIS using a combination of field surveying (in the southern test area only), Ordnance Survey (OS) 1:10 000 scale raster maps, OS VectorMap, aerial photographs, and Google Street View.

2.3 ATTRIBUTION OF BOREHOLE RECORDS

Ground surface levels for each borehole point were extracted from the DTM using ARC Spatial Analyst tools. The borehole records were also attributed according to whether they occur in areas mapped as made or worked ground by spatially joining the borehole and artificial ground Shapefiles. Analyses of the resulting data, including statistical tests, were conducted using Excel and Minitab.

2.4 DEM RE-INTERPOLATION

The PGA DTM for each site was converted to grid of points from which the points occurring in areas of made ground and worked ground were selectively removed by clipping to the artificial ground polygons. The clipped point clouds were then converted back to raster grids using different interpolation functions to estimate the pre-road ground surface in the areas of artificially modified ground. The interpolation functions used to derive the ‘pre-road’ DTM were Inverse Distance Weighting (IDW), spline and triangulation; details of the functions are given in appendix 2.

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[2] See http://www2.getmapping.com/Support/Aerial-Photography-Coverage for aerial photography coverage

Volumes of material input or removed along the road route were derived using the Cut-Fill function in ARC GIS Spatial Analyst tools. This function compares the ‘pre-road’ DTM the modern DTM, to identify regions of net gain or net loss and derive their volumes.

3 DEM assessment

Accurate reconstruction of ground surface change using a borehole – DEM comparison is dependent upon the accuracy of both the measured ground surface elevation recorded in the borehole log, and the DEM representation of the post-construction ground surface.

Neither the accuracy of the borehole ground surface levels (given in metres), nor the methods used to derive them are recorded in the logs of the boreholes utilised in this study. Consequently it is difficult to assess the accuracy of the recorded borehole surface levels. Indirect methods are used in sections 4 and 5 to assess the relative accuracy of the recorded borehole start heights.

The accuracy of the available DEMs was assessed for the southern test area through comparison with OS spot heights. Fifty nine OS spot heights were digitised in ARCGIS from 1:10 000 scale raster maps (last revised 2000) within a range of 500 m either side of the A9 corridor. The 1:10 000 scale raster maps have been superseded by OS VectorMap data products since March 2014, however comparison of the distributions of spot heights from OS VectorMap with the 1:10 000 scale raster maps demonstrated that significantly more spot height values were recorded in the vicinity of the A9 on the older dataset and therefore the 1:10 000 scale raster maps were used.

DEM elevations were extracted for each spot height from the NEXTMap 5 m resolution DTM, the PGA 2 m DSM (not corrected for trees/buildings), and the 5 m resolution PGA DTM. The specified vertical accuracy of these dataset is given in Table 1.

3.1 DEM VERSUS OS SPOT HEIGHTS

Comparison of the OS spot heights with the DEMs indicates that elevations derived from the PGA DTM (H_{PT}) show the closest correspondence with the OS spot height elevations (H_{OS}), i.e. the closest mean elevation and the lowest mean difference (Tables 2 and 3). A two sample t-test shows that there is no significant difference in the means of H_{PT} and H_{OS}, and a one sample t-test indicates that the mean of the difference between H_{OS} and H_{PT} is not significantly different from zero. These results indicate that there is good correspondence between the PGA DTM elevation and the actual ground surface level measured at the OS spot heights.

At the spot height locations, both the PGA DSM (H_{PS}) and the NEXTMap DTM (H_{NM}) yield mean elevations higher than the mean of H_{OS}, i.e. the models overestimate the real ground surface elevation.

	H_{OS} (OS Spot Height)	H_{PS} (PGA DSM)	H_{PT} (PGA DTM)	H_{NM} (NM DTM)
Mean	77.71	83.9	78.3	85.8
SE	2.57	2.8	2.57	2.96
St Dev	19.78	21.5	19.7	22.74
95 % CI	5.2	5.6	5.1	5.9
n	59	59	59	59

Table 2 Statistics for the OS spot heights and the extracted DEM surface elevation. (Calculated in Minitab)

	H_{OS} minus H_{PS}	H_{OS} minus H_{PT}	H_{OS} minus H_{NM}
Mean	-6.19	-0.32	-8.09
SE	1.02	0.27	0.88
St Dev	7.84	2.09	6.76
95 % CI	2.0	0.54	1.76
Variance	61.52	4.36	45.69
Skewness	-0.89	0.87	-0.54
Kurtosis	0.02	7.41	-0.80
n	59	59	59

Table 3 Statistics for the difference between OS spot heights and the DEM surface elevation. (Calculated in Minitab)

In the case of the NEXTMap DTM, H_{NM} is significantly higher than the mean H_{OS} ($p<0.05$) and the mean of the difference between H_{OS} and H_{NM} is different to zero ($p<0.001$). For the PGA DSM, the mean of H_{PS} is not significantly higher than the mean of H_{OS} ($p>0.05$), but the mean of the difference between H_{OS} and H_{PS} is significantly different to zero ($p<0.05$), indicating that the PGA DSM does generally over-estimate the surface elevation at the spot height locations.

3.2 DEM SELECTION

The overestimation of surface elevations by the PGA DSM is likely to be due to the effects of trees or buildings as many of the spot height locations are in forested or urbanised areas. The overestimation of the ground surface level by the NEXTMap DTM also suggests that the algorithms used to remove the trees and buildings from the model were not effective. By contrast the procedures used to remove surface features from the PGA DTM have yielded a terrain model that is consistent with the OS terrain data.

Within both of the test areas, the A9 route is flanked by extensive areas of woodland, and cuttings and embankments associated with the road construction are also generally forested. For this reason, the PGA DTM is used in the following analysis as it is found to be the most accurate ‘bald earth’ model in the site areas.

4 Borehole records of the ground surface

Before assessing ground surface change related to road construction using borehole records it must be established that the ground levels recorded in pre-construction borehole and trial pit logs provide reliable estimates of the actual ground surface. In lieu of information on the accuracy or precision of the methods used to derive the ground levels during the site investigations, tests were conducted for sample boreholes datasets for which no ground surface change is expected to assess potential differences between the recorded value and the DTM.

The first test, in the northern area, was conducted using a set of boreholes drilled in 1972 for a possible bridge crossing over the River Nairn, east of Daviot, which was not subsequently chosen for the road route (Figure 2).

A second test was conducted utilising boreholes drilled after the main road development at Ballinluig (in the south; Figure A1-2) and Moy (in the north; Figure A1-1) to examine how well their start heights corresponded to the DTM surface level.

The two test areas are located in rural upland settings with little urbanisation in the vicinity of the road and surface change due to non-road related construction or excavation activities is not likely to have resulted in measurable change over the period since the boreholes were drilled (up to approximately 40 years). Similarly, agricultural activity is limited and is unlikely to have been associated with ground surface change in the vicinity of the road since its construction. Natural processes of erosion and deposition may influence ground surface levels, particularly in the vicinity of rivers, or on unstable slopes prone to landslides. The A9 route within the test areas generally avoids river floodplain areas and inspection of aerial photographs and geological maps indicates that there are no significant recent or past landslips evident in the vicinity of the road.

4.1.1 The River Nairn test – boreholes drilled but no road constructed

Thirty boreholes were drilled in 1972 as part of a site investigation for an alternative location of the A9 viaduct over the River Nairn near Daviot. The boreholes lie approximately 1.2 km to the north-east of the site where the actual viaduct was constructed and lies 300 – 400 m east of the closest segment of the A9 (Figure 2).

The difference between the borehole start height (H_B) and the DEM surface level (H_{PT}) was investigated for 28 of the boreholes from this site investigation where the start height is known. The difference between the 1972 ground surface level and the c. 2010 surface level given by the PGA DTM was derived as

$$H_{diff} = H_{PT} - H_B \qquad \text{(Equation 1).}$$

The mean of H_{diff} for the 28 boreholes is -0.42 m (SE= 0.44, St dev = 2.3) and a 1 sample t-test indicates that it is not significantly different to zero ($p = 0.36$). This result demonstrates that the ground level as recorded in the boreholes drilled in 1972 corresponds well with the DEM ground surface level. This result suggests that that measurable surface change is likely to be minimal in areas away from the main road construction. Furthermore, by demonstrating that the ground levels recorded in the borehole logs from 1972 accurately reflect the modern ground surface, this test supports the inference that the recorded surface levels in pre-road boreholes reflect the real ground surface prior to road construction.

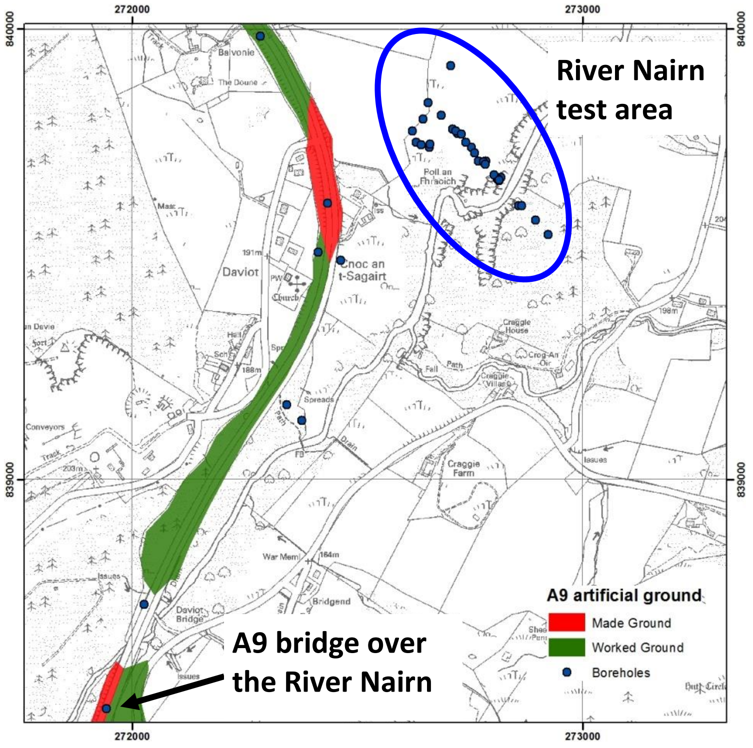


Figure 2 The Davoit area showing the location of boreholes along the main A9 route and in the area of the alternative crossing point of the River Nairn investigated to the east of the road. Contains Ordnance Survey Data © Crown copyright and database rights 2014.

4.1.2 Recent boreholes and ground surface change

Site investigations were conducted as part of road improvement works between 2005 and 2007 in the vicinity of Moy, in the northern test area, and Ballinluig in the southern test area (Figures A1-1 and A1-2). Analysis of H_{diff} values for 25 boreholes drilled between 2005 and 2007 in the Ballinluig area, yields a mean difference of 0.08 m (SE = 0.22, St Dev = 1.09) which is not significantly different from zero (p = 0.71). In the Moy area, 60 boreholes were drilled along the road route in 2005. Analysis of H_{diff} for all the Moy boreholes gives a mean of -0.01 m (SE = 0.13, St Dev = 1.00), which is also not significantly different from zero (p = 0.916).

These results indicate that the borehole ground surface levels are consistent with the PGA DTM representation of the ground surface (captured between 2005 and 2010), providing further support for the interpretation that ground levels in site investigation boreholes provide a reliable record of the ground surface prior to construction activities.

5 Quantifying ground surface change

It is hypothesised that ground surface change associated with road construction will be characterised by ground lowering in areas of excavation marked by cuttings (worked ground) and raising in areas of deposition marked by embankments (made ground). This translates to the prediction that values of H_{diff} calculated using only boreholes drilled in the 1970s (prior to road construction) will be negative in areas mapped as worked ground ($H_B > H_{PT}$), and positive in areas mapped as made ground ($H_B < H_{PT}$).

The distribution of worked ground (WGR) and made ground (MGR) in the test areas are shown in figures in Appendix 1. In the northern test area (Daviot – Moy) WGR covers approximately 47% of the road length and MGR covers approximately 36%. In the southern test area (Dunkeld) WGR covers 31 % and MGR 25% of the road length. Borehole records were attributed according to whether they occur in areas mapped as made ground or worked ground. Boreholes lying outside areas of made and worked ground were not attributed with an artificial ground type.

5.1 SURFACE ELEVATION CHANGE

Mean values of H_{diff} for the boreholes classified according to location in areas of mapped made or worked ground are shown for the different test areas in Table 4. For boreholes located in areas of made ground, the mean H_{diff} is significantly greater than zero for both test areas. The results indicate that where embankments have been constructed, the modern ground surface is on average 1.5 m higher than the pre-construction level in the Daviot area and 3.4 m higher in the Dunkeld area.

In areas of worked ground, the reverse is found; values of H_{diff} are significantly less than zero, and indicate that average reductions in the surface level in cuttings of 4.2 m and 4.7 m has occurred as a result of the road construction. H_{diff} values for each borehole relative to the extent of areas of made and worked ground along the road are shown for the northern test area in Figure 3 and the southern test area in Figure 4.

	Northern area (Daviot-Moy)			Southern area (Dunkeld)		
H_{diff}	**MGR**	**WGR^**	**Unknown**	**MGR**	**WGR**	**Unknown**
Mean	1.50	-4.29	-2.11	3.37	-4.22	-0.21
Std Dev	1.94	2.80	5.05	3.45	4.24	2.46
SE Mean	0.54	0.50	1.91	0.39	0.56	0.28
CI -	0.63	-5.30	-6.78	2.73	-5.15	-0.77
CI +	2.54	-3.28	2.56	4.01	-3.29	0.34
n	13	32	7	80	58	78
P for 1 sample t test*	0.006	<0.001	0.31	<0.001	<0.001	0.45

Table 4 Comparison of H_{diff} values for made and worked ground areas in the test sites.

^The values are for the sample with one outlier H_{diff} value of -19.29 removed (see Figure 3 for location of point). Inspection of this borehole and its surrounding location suggests the borehole start height recorded in the log may be wrong.

*For MGR and WGR one-tailed one sample t tests were used to assess whether the mean H_{diff} was greater than or less than zero respectively. For unclassified boreholes a two-tailed test for difference of the mean to zero was used.

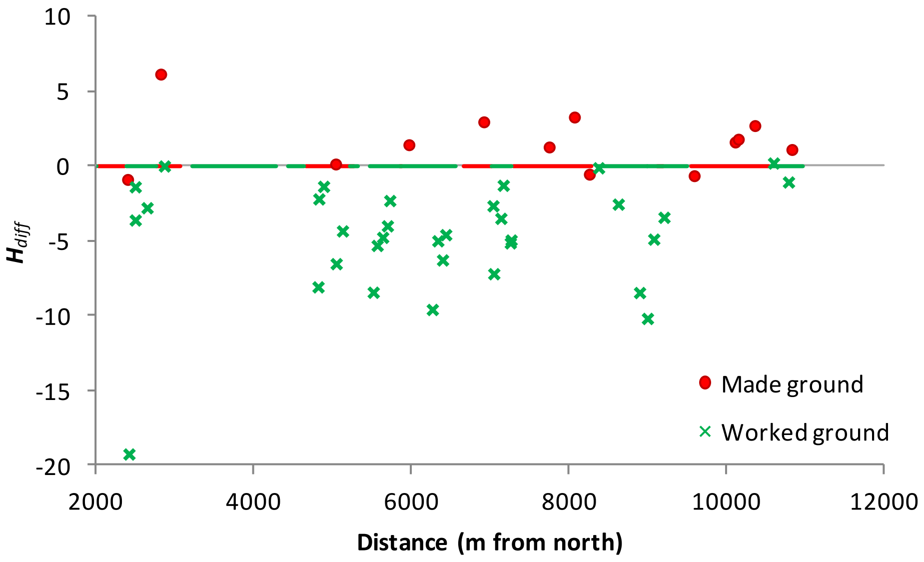


Figure 3 Plot of H_{diff} values for made and worked ground groups with distance along the A9 (measured from the northern edge of the test area) for the northern test area (Daviot-Moy). The distribution of made and worked ground along the section, taken at the centre of the road, is shown by the red and green lines at zero H_{diff}. (Note that most boreholes are not along the centre of the road and hence, in some cases, the borehole attribution does not appear to match the distribution of artificial ground.)

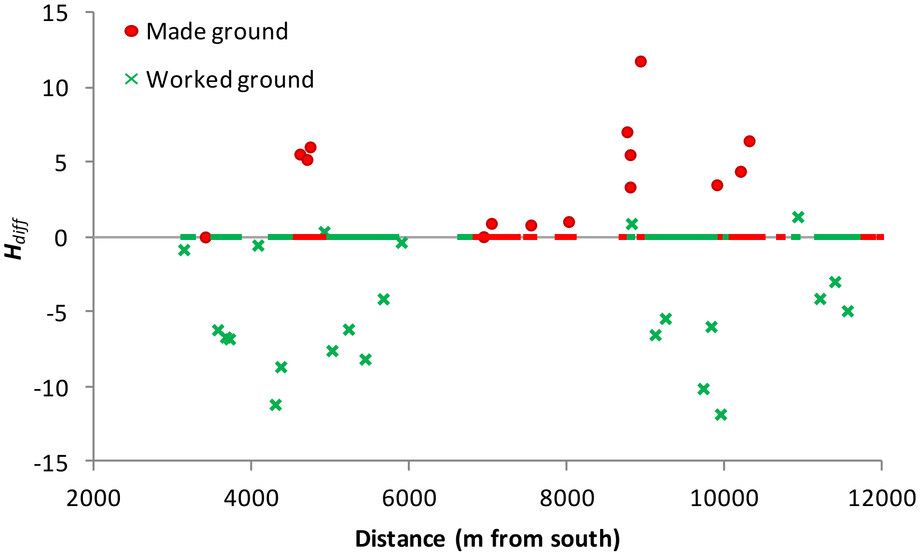


Figure 4 Plot of H_{diff} values for made and worked ground groups with distance along the A9 (measured from the southern edge of the test area) for the southern test area (Dunkeld). The distribution of made and worked ground along the section, taken at the centre of the road, is shown by the red and green lines at zero H_{diff}. (Note that most boreholes are not along the centre of the road and hence, in some cases, the borehole attribution does not appear to match the distribution of artificial ground.)

5.2 MGR IN BOREHOLE RECORDS

Based on the comparison of ground surface elevations, the surface change in areas of made ground is estimated to be an increase in elevation of 1.6 to 2.7 m. This estimate is compared with actual values of made ground thickness in boreholes drilled along the road route after initial road construction (after c. 1980). MGR thickness estimates are taken directly from the recorded logs and are therefore based on the driller’s interpretation. In some cases deposits not recorded as MGR were identified in logs, however, in most records it was not possible to verify the base of MGR from the descriptions given, hence the drillers interpretation was used.

The A9 route is largely through the rural upland landscape of the Grampian Highlands and pre-existing made ground is not considered likely to have been present along the route prior to road construction. This is confirmed by the borehole logs recorded in 1970 – 1977 site investigations; thin developments of made ground are only recorded in boreholes drilled where pre-existing railway lines, tracks or roads intersect the A9 route.

The thickness of MGR associated with the A9 road construction was estimated from boreholes drilled in 2005 in the Moy section of the northern test area. Pre-1980 boreholes in the same area have no made ground recorded, however all of the logs for boreholes and trial pits excavated in the vicinity of the road in 2005 record MGR deposits including Tarmac, concrete and sand and gravel fill.

Figure 5 shows a histogram of the thickness of MGR in 2005 Moy boreholes, indicating that there is a skewed distribution with most bores only proving MGR of less than 0.6 in thickness. By contrast the mean difference in surface elevation recorded for eleven 1970 boreholes that occur within the area covered by the 2005 site investigation is 1.19 m (SE = 0.43). The apparent thickness of MGR in the boreholes is considerably lower than the average thickness estimated from the change in ground level, only three of the 2005 boreholes record actual MGR thicknesses within this range

It should be noted that many of the borehole records contain the drillers interpretation only and boreholes and trial pits are located close but peripheral to the existing road, or in central reservation areas, where the full depth of made ground may not be encountered. It is also significant that in most of these boreholes a thin layer recorded as MGR is underlain by deposits of sand, gravel and cobbles which are recorded in several boreholes as containing fragments of concrete, timber and/or plastic but not classified as MGR (Figure 6). This layer of sand, gravel and cobbles, occurs consistently in boreholes along the road route, even in areas where geological maps indicated that the road is underlain by rock or glacial till (stiff to very stiff clay with gravel, cobbles and boulders), and it is thought likely to be a sub-base layer of fill (i.e. MGR). The sand, gravel and cobble layer ranges between 1 – 1.5 m in thickness, consistent with the estimated MGR thickness derived from the ground level change (1.19 ± 0.42).

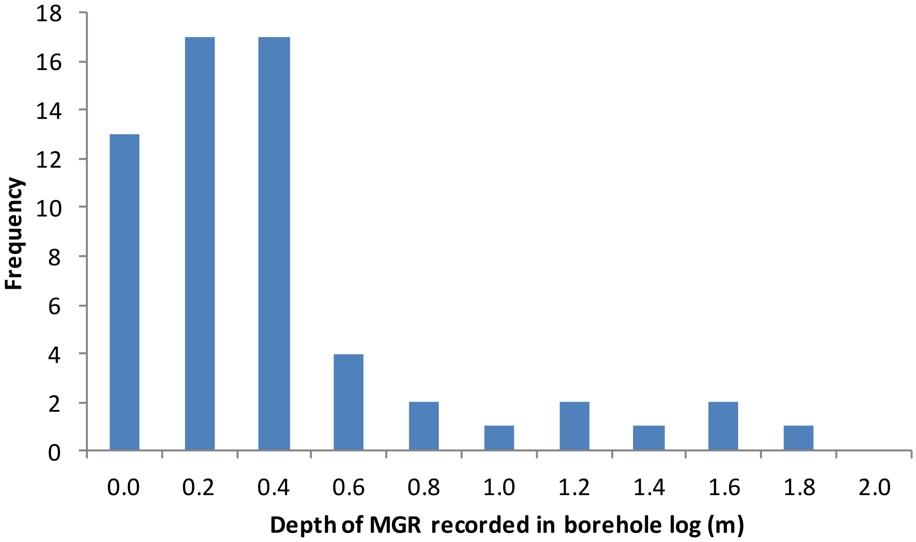
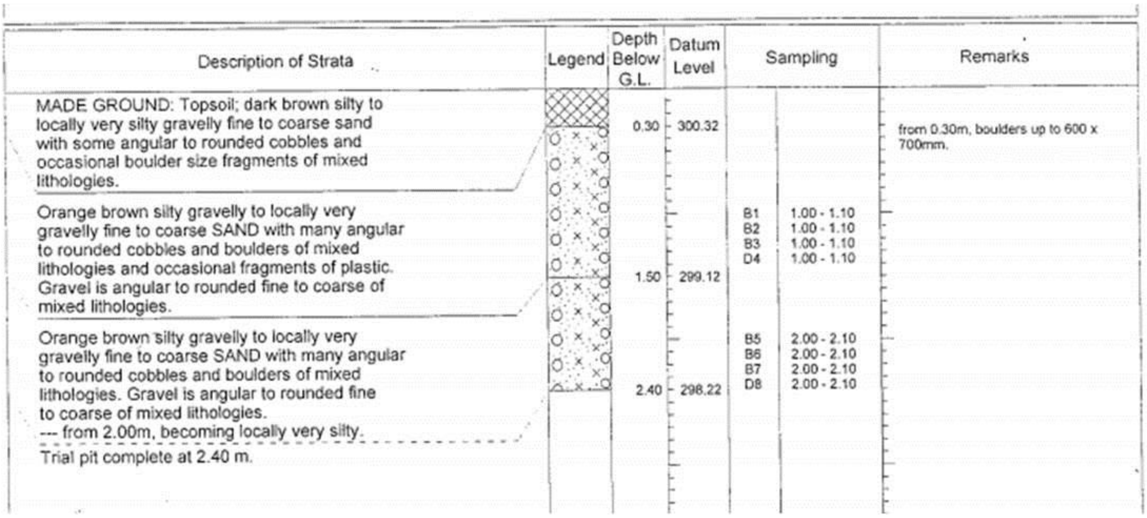


Figure 5 Histogram of depths of MGR recorded in boreholes in the Moy area drilled in 2005.



Description of Strata	Legend	Depth Below G.L.	Datum Level	Sampling		Remarks
MADE GROUND: Topsoil; dark brown silty to locally very silty gravelly fine to coarse sand with some angular to rounded cobbles and occasional boulder size fragments of mixed lithologies.		0.30	300.32			from 0.30m, boulders up to 600 x 700mm.
Orange brown silty gravelly to locally very gravelly fine to coarse SAND with many angular to rounded cobbles and boulders of mixed lithologies and occasional fragments of plastic. Gravel is angular to rounded fine to coarse of mixed lithologies.		1.50	299.12	B1 B2 B3 D4	1.00 - 1.10 1.00 - 1.10 1.00 - 1.10 1.00 - 1.10	
Orange brown silty gravelly to locally very gravelly fine to coarse SAND with many angular to rounded cobbles and boulders of mixed lithologies. Gravel is angular to rounded fine to coarse of mixed lithologies. --- from 2.00m, becoming locally very silty.		2.40	298.22	B5 B6 B7 D8	2.00 - 2.10 2.00 - 2.10 2.00 - 2.10 2.00 - 2.10	
Trial pit complete at 2.40 m.						

Figure 6 Log of trial pit for borehole record NH73SE39 showing 0.3 m of recorded MGR underlain by sand with gravel, cobbles and boulders containing fragments of plastic to a depth of 1.5 m below the surface.

6 Erosion and deposition due to road construction

Estimates of the net transfer of material resulting from road construction can be made using the mean surface change values derive by direct comparison of the borehole ground levels and the DTM described above. Alternatively mathematical algorithms can be used to reconstruct the pre-road ground surface from the DTM and volumes of material lost or gained can then be derived by comparison of the 'before' and 'after' DTMs. These two methods are compared in the following sections

6.1 METHOD 1: DIRECT BOREHOLE – DTM SURFACE ANALYSIS

Estimates of the volume of material excavated from cuttings and piled in embankments were calculated using the average depths of MGR and WGR from Table 4, combined with the mapped areas of each unit. A triangular cross-section was assumed for all the artificial ground areas.

The results demonstrate that there has been a net loss of material from along the road route in both the test areas. The net volume change in the southern area is two thirds that of the northern area despite the greater section length. This finding reflects a greater proportion of worked ground and a lower average thickness of made ground in the northern area.

Test area	Proportion of road length	Artificial Ground Type	Area (m^2)	A/Road Length (m^2/m)	Volume (m^3)	V/Road Length (m^3/m)	Net volume change (m)
North Daviot-Moy (12.5 km)	0.36	MGR	89715	8.3	134573	12.4	-604895
	0.47	WGR	172370	15.9	739468	75.4	
South Dunkeld (30 km)	0.25	MGR	239763	8.0	808001	27.0	-370585
	0.31	WGR	279286	9.3	1178586	39.4	

Table 5 Details of the surface area and volumes associated with areas or artificial ground along the A9. Volumes were derived for a triangular cross-section using the mean thickness of made and worked ground from Table 4.

6.2 METHOD 2: DTM RECONSTRUCTION

Reconstructed DTMs were derived for the test areas to model the ground surface prior to road construction. Areas of mapped artificial ground along the road route were removed from the DTM, and the remaining DTM was re-interpolated using three different methods for comparison: inverse distance weighting, regularised spline and triangulation (section 2.4). The inverse distance weighting interpolation was repeated using power factors of 1.5, 2 and 3, reflecting an increasing degree of influence given to points near to the cell.

6.2.1 Comparison of reconstructed DTMs with pre-road borehole ground levels

The surface elevation values in each of the reconstructed DTMs was compared with ground surface elevations from the pre-road (c.1970's) borehole records to assess how well they estimate the original ground surface level. The elevation differences between the borehole ground level and the reconstructed DTM were compared separately for areas of MGR and WGR.

For the northern area (Daviot-Moy), the IDW re-interpolation give the closest fit to the actual borehole ground levels, with the mean difference in elevation between the borehole start height and the re-interpolated DTM not significantly different from zero for either the MGR or WGR ($p>0.05$; Table 6). Both the spline and triangulation methods yield DTM elevations that are not significantly different from the borehole ground levels in areas of MGR, but are significantly different in areas of WGR; mean differences in WGR areas are 2.17 and 1.15 respectively, indicating that these DTMs tend to underestimate the actual ground level.

In the Southern test area (Dunkeld), all of the re-interpolation methods yield DTMs that are significantly different to the actual ground level. Mean differences between the borehole start height and the DTM are on average 1.31 – 1.86 m higher than the borehole ground level in areas of MGR, and 1.47 – 2.83 m below the borehole ground level in areas of WGR (Table 7). These offsets may arise if the delineation of areas of artificial ground does not quite cover the full extent of the embankment or cutting. Buffering the areas of made and worked ground prior to extracting them from the original DTM may help to minimise these differences in future.

Northern test area	IDW 1.5		IDW 2		IDW 3		Spline		Triangulation	
	MGR	WGR	MGR	WGR	MGR	WGR	MGR	WGR	MGR	WGR
Mean	0.28	1.13	0.27	1.13	0.24	1.13	-0.84	2.17	-0.69	1.15
Standard Error	0.59	0.72	0.59	0.72	0.59	0.72	0.55	0.41	0.34	0.33
Median	-0.08	2.31	-0.11	2.28	-0.16	2.22	-1.42	2.25	-0.62	1.01
Standard Deviation	2.03	4.09	2.04	4.08	2.04	4.07	1.90	2.35	1.18	1.87
Kurtosis	5.97	0.83	6.02	0.84	6.13	0.85	4.74	-0.57	0.71	0.69
Skewness	2.20	-0.99	2.21	-0.99	2.24	-0.98	1.98	0.11	-0.50	0.15
Max	6.0	7.8	6.0	7.8	6.0	7.8	4.3	6.6	1.2	5.3
Min	-1.6	-9.2	-1.6	-9.1	-1.7	-9.1	-2.5	-1.9	-3.2	-3.5
Count	12	32	12	32	12	32	12	32	12	32
2-tailed t-test P value	0.64	0.13	0.66	0.13	0.70	0.13	0.15	<0.01	0.07	<0.01

Table 6 Statistics for the difference between the pre-road borehole ground levels (boreholes dated 1970 – 1977) and the re-interpolated DTMs for the northern test area (Daviot – Moy). The different types of DTM interpolation are discussed in the text.

Southern test area	IDW 1.5		IDW 2		IDW 3		Spline		Triangulation	
	MGR	WGR	MGR	WGR	MGR	WGR	MGR	WGR	MGR	WGR
Mean	-1.31	1.47	-1.31	1.47	-1.33	1.46	-1.86	2.83	-1.48	1.91
Standard Error	0.26	0.54	0.26	0.54	0.26	0.54	0.29	0.49	0.23	0.39
Median	-0.69	0.99	-0.69	0.99	-0.74	0.98	-0.98	2.09	-1.00	1.12
Standard Deviation	2.65	4.21	2.65	4.21	2.66	4.21	2.92	3.79	2.94	3.06
Kurtosis	1.69	2.01	1.68	2.01	1.65	2.00	2.06	2.15	1.22	2.06
Skewness	-0.80	0.20	-0.80	0.20	-0.80	0.21	-0.95	1.10	-0.78	0.97
Max	5.5	13.4	5.5	13.5	5.5	13.5	5.3	16.8	3.9	12.5
Min	-10.7	-11.9	-10.7	-11.9	-10.7	-11.8	-13.4	-5.5	-10.6	-4.8
Count	105	60	105	60	105	60	105	60	105	60
2-tailed t-test P value	<0.01	0.01	<0.01	0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01

Table 7 Statistics for the difference between the pre-road borehole ground levels (boreholes dated 1970 – 1977) and the re-interpolated DTMs for the southern test area (Dunkeld).

In both test areas, the IDW approach gives the lowest mean difference, which appears to indicate that it more closely reflects the actual ground surface than the other re-interpolation methods. However, the IDW method also has higher standard deviations and a larger range in the data values, with differences between the actual and predicted ground levels of ± 8 – 9 m in the northern test area and ± 12 – 14 m in the southern area. By contrast, differences in actual and predicted ground levels for the spline interpolation are up to ± 7 m and ± 17 m in the north and south respectively and for the triangulation are ± 5 m in the north and up to ± 13 m in the south but with a lower range in values (Tables 6 and 7).

6.2.2 The volumes of cuttings and embankments

Volumes of MGR and WGR were derived for each test area by summing the volumes of cuttings and embankments as defined by the Cut-Fill tool in ARCGIS. This tool compares the pre-road construction ground surface (re-interpolated DTM) and the post-road construction surface (original DTM) to define regions of net gain or net loss of material. Values for the triangulation and IDW 2 DTMs only are shown; the IDW 1.5 and 3 interpolations are similar to the IDW 2 interpolation, and the spline interpolation results in the poorest correspondence with the pre-road borehole ground levels so the volumes derived are likely to be the least accurate (Tables 6 and 7).

The results are given in Table 8 and are compared with values derived from the average vertical ground level change estimated directly from comparison of the pre-road borehole records with the original DTM (Table 5).

In both test areas, the volume of WGR exceeds that of MGR indicating that there has been a net loss of material during road construction. This reflects the fact that areas of worked ground are more extensive than made ground in both areas, and that cuttings tend to be deeper than embankments (Table 5).

The re-interpolated DTMs tend to underestimate the depth of cuttings by 1 – 2 m and the heights of embankments by up to 1.5 m (Tables 6 and 7). Moreover, the underestimates for WGR are greater than those for MGR. This observation indicates that any future improvements in DTM re-interpolation methods for reconstructing the pre-road ground surface may result in even greater differences in the volumes of MGR and WGR

		Northern area (length 12.5 km)			**Southern area (length 30 km)**		
		MGR	WGR	**Total**	MGR	WGR	**Total**
Length and area	Prop. of road length	0.36	0.47		0.25	0.31	
	Area (m^2)	89715	172370	**315210**	239763	279286	**849049**
	Derivation method						
Volume (m^3)	Triangulation	215792	978805	**-763012**	852674	1309754	**-457080**
	IDW 2	346430	1118055	**-771625**	1178324	1762581	**-584257**
	Boreholes-DTM	134573	739468	**-604895**	808001	1178586	**-370585**
Average vertical ground surface change due to construction (m)	Triangulation	2.41	-5.68	**-2.4**	3.56	-4.69	**-0.5**
	IDW 2	3.86	-6.49	**-2.5**	4.91	-6.31	**-0.7**
	Boreholes-DTM	1.50	-4.29	**-2.2**	3.37	-4.22	**-0.4**
Erosion flux (m^3/m/yr)*	Triangulation			**-30.5**			**-7.6**
	IDW 2			**-30.9**			**-9.7**
	Boreholes-DTM			**-27.3**			**-6.2**

Table 8 Calculated volumes of MGR and WGR for the test areas derived from comparison of re-interpolated DTMs (IDW2 and triangulated DTMs only) with the original DTM and from direct assessment of the difference between the pre-road boreholes and the DTM (Boreholes-DTM). Note that the aggregate base and tarmac comprising the road surface constitutes MGR that will be present in areas of cuttings but is not accounted for in these figures. The volume of MGR along the road route is thus likely to be slightly greater than shown.

*assuming road construction took 2 years

The volumes of material estimated from direct comparison of the borehole ground levels with the DTM are lower than those derived using the re-interpolated DTMs (Table 8), and yield lower net differences. This may be because the direct method is based on the derivation of an average surface lowering value that depends on the number and distribution of borehole records available. It is possible that the average depth of cuttings and height of embankments is underestimated through this method, particularly in the northern area, due to the limited number of borehole records (Table 4) and lack of sampling in the deeper parts of many cuttings.

If the net loss of material from the road sections were distributed evenly along the road length, it would amount to surface lowering of 2 to 2.5 m in the northern area, and 0.4 – 0.7 m in the southern area. The higher value of vertical lowering in the northern area reflects extensive cuttings, and the relatively thin nature of the MGR along this road section.

7 Discussion

7.1 ROAD CONSTRUCTION AS A GEOMORPHIC PROCESS

Assuming that both sections of the road took approximately two years to construct, the average vertical lowering along the roads in the test areas is 1 – 1.25 m/yr in the northern test area, and 0.2 – 0.35 m/yr in the southern area (Table 7). Similarly, the net loss of material from each of the road sections equates to net erosion fluxes of approximately 32 and 6 m^3/m/yr for the northern and southern areas respectively. Localised erosion fluxes and vertical lowering rates during construction will have been substantially greater than these values in individual cutting areas.

In terms of the geomorphic impact of road construction, a comparison between road systems and rivers may be made, as both may be considered as linear systems associated with the erosion and deposition of rock and sediment. River erosion occurs along the lines of channel systems where the energy of the stream outweighs the sediment supplied to it. Excess stream power contributes to the erosion of sediments and rock along the line of the stream, with erosion rates related to the slope of the channel, discharge of the stream and the resistance of the underlying rock.

In a study of Scottish Highland streams in metamorphic rocks similar to those underlying the A9, Whitbread (2012) recorded river gorges up to 10 m deep that have been excavated by streams since deglaciation approximately 12 000 years ago. Although much of this erosion is likely to have occurred in the first few thousands of years after deglaciation, time-averaged erosion rates for the postglacial period were found to range between 0.0004 – 0.001 m/yr (0.35 – 1.3 m/kyr). At these average rates, it would take a Scottish stream 4200 – 12000 years to cut a gorge of equivalent depth to the average depth of a cutting (4.2 – 4.3 m).

If the formation of these river gorges is assumed to have occurred during an extremely rapid period of erosion occurring within 3 – 4 thousand years of deglaciation, the average rate of erosion for that period would be within the range 0.001 – 0.004 m/yr, and the time taken to erode a gorge of equivalent depth to an average cutting would be 1100 – 4300 years.

Maximum recorded rates of fluvial erosion worldwide occur in tectonically active high mountain terrains such as the Himalaya where average erosion rates of 0.002 – 0.012 m/yr have been recorded over timescales of 10^2 – 10^3 years (Burbank et al, 1996). In Taiwan, erosion rates of 0.002 – 0.006 m/yr have been recorded annually, with rates of up to 0.01 m/yr recorded in a single wet season (Hartshorn et al., 2002). In rivers fed directly by glaciers recorded erosion rates over periods of several years are up to 0.02 m/yr (Vivien, 1970). Even under these very high measured rates of erosion it would take rivers between 200 and 2000 years to excavate a cutting-equivalent gorge.

Only when the effects of cataclysmic floods are considered do erosion rates in streams become comparable with, or exceed the rate of erosion during road construction; Lamb and Fonstad (2010) describe a 7 m deep, 1.2 km long, canyon excavated into limestone and marl bedrock over a period of 3 days during a dam release. However, there are limited records of catastrophic erosion events, and there is no published information on potential maximum instantaneous erosion rates in resistant bedrock geologies such as those occurring in the Scottish Highlands.

In summary, road construction results in the formation of cuttings during a period of months to years which would take a river in comparable rocks several thousand years to form, even under conditions that are the most favourable for fluvial erosion (e.g. relatively soft rocks, high discharge and steep terrain). Worldwide, only rare cases of cataclysmic flooding due to lake or reservoir outbursts are likely to be capable of excavating gorges comparable to the A9 cuttings in timescales equivalent to or less than the time taken to construct the road.

7.2 IMPLICATIONS FOR MAPPING AND MODELLING ARTIFICAL GROUND

In this study, areas of MGR and WGR along the A9 were mapped independently of the borehole data. However, the findings indicate that the correspondence between mapped areas of MGR and WGR and positive and negative differences between the borehole start height and the DTM may be used to help determine the distribution and thickness of artificial ground in areas where borehole records pre-date road construction (i.e. no MGR is recorded in the borehole log).

The ground surface elevations of the pre-construction boreholes have been found to reflect the real ground surface level prior to road construction, and this should be accounted for when modelling artificial ground, superficial deposits and bedrock along road routes. In particular, boreholes drilled prior to developments should not be hung from the DTM during modelling.

8 Conclusions

This preliminary study of the geomorphic impact of road construction utilises site investigation records held in the BGS archive and recently acquired DTMs to provide an independent estimate of ground surface change and material transfer.

To assess the accuracy of the different methods used to quantify these geomorphic impacts, comparison of these results with import/export volumes recorded by the road construction contractors could be made if this data is available. In addition, further assessment of different interpolation methods, potentially using non-excavated areas to test how well interpolations reconstruct terrain along narrow route lines, would be useful to determine the optimal interpolation algorithms with which to reconstruct the pre-construction ground surface.

The analysis indicates that construction of the A9 in the two test areas has been associated with a net ‘erosion’ of rock along the road route that equates to an average ground surface lowering of between 0.5 and 2.5 m over the road lengths studied. Individual cuttings are on average over 4 m deep, but most are locally considerably deeper, whilst embankments are on average 1.5 – 3.4 m high and are less extensive than cuttings in the study areas. The depths and relative proportion of cuttings and embankments are likely to vary with the form of the landscape; the deeper and more extensive cuttings in the study areas likely reflect the test area locations in upland terrain.

Equivalent erosion rates calculated to compare road construction with natural fluvial erosion processes indicate that erosion associated with road construction occurs at rates that are 2 – 3 orders of magnitude faster than even the most rapid erosion in natural streams, and 3 – 4 orders of magnitude faster than previously measured erosion rates in Scottish streams.

Unlike rivers, road construction may be considered as a one-off erosion event relating to the initial period of road construction. However, in regard to the A9, a programme of works to widen and dual the road between Perth and Inverness is ongoing and several phases of upgrades have been recently completed or are currently in progress.[3] The ongoing development of new roads and widening of existing trunk roads means that ground surface change associated with road construction may not be limited to the initial construction phase.

Ground surface change associated with road construction typically results in excavation of cuttings into hillslopes and the construction of embankments where roads cross valleys or run along flood plain areas. The removal and transport of materials from road developments is an expensive component of construction. Quantification of the mass transfer of material and consideration of the role of topographic factors in determining net material fluxes during road construction may assist the development of planning and design strategies to minimise construction costs. Furthermore, an understanding of the surface change associated with road construction may be used to help mitigate the impacts on runoff and river flows (hydrology), and potentially geomorphic process systems (erosion and sediment transport).

This study focuses on a major trunk road in a rural, upland area. Comparison of the geomorphic impact of road construction in other types of terrain, including lowland areas and urban to semi-urban settings is needed to better understand the factors that control how much geomorphic work is done during road construction. For instance, the role of relief and terrain roughness in affecting the balance between excavation and embanking along road corridors, and the influence of road type (trunk road, local road) on the degree of ground surface change and net material transfer.

There are nearly 250 thousand miles of road within the UK, with 31 thousand miles of major road (motorway and ‘A’ roads).[4] Consideration of the impact of this road construction on our landscape is needed is if we are to understand the how, and by how much, human activity influences our geomorphic systems.

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[3] See http://www.transportscotland.gov.uk/a9dualling and a current news report http://www.bbc.co.uk/news/uk-scotland-tayside-central-29443417

[4] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/208692/road-lengths-in-great-britain-2012.pdf

Appendix 1 Maps of the distribution of made and worked ground

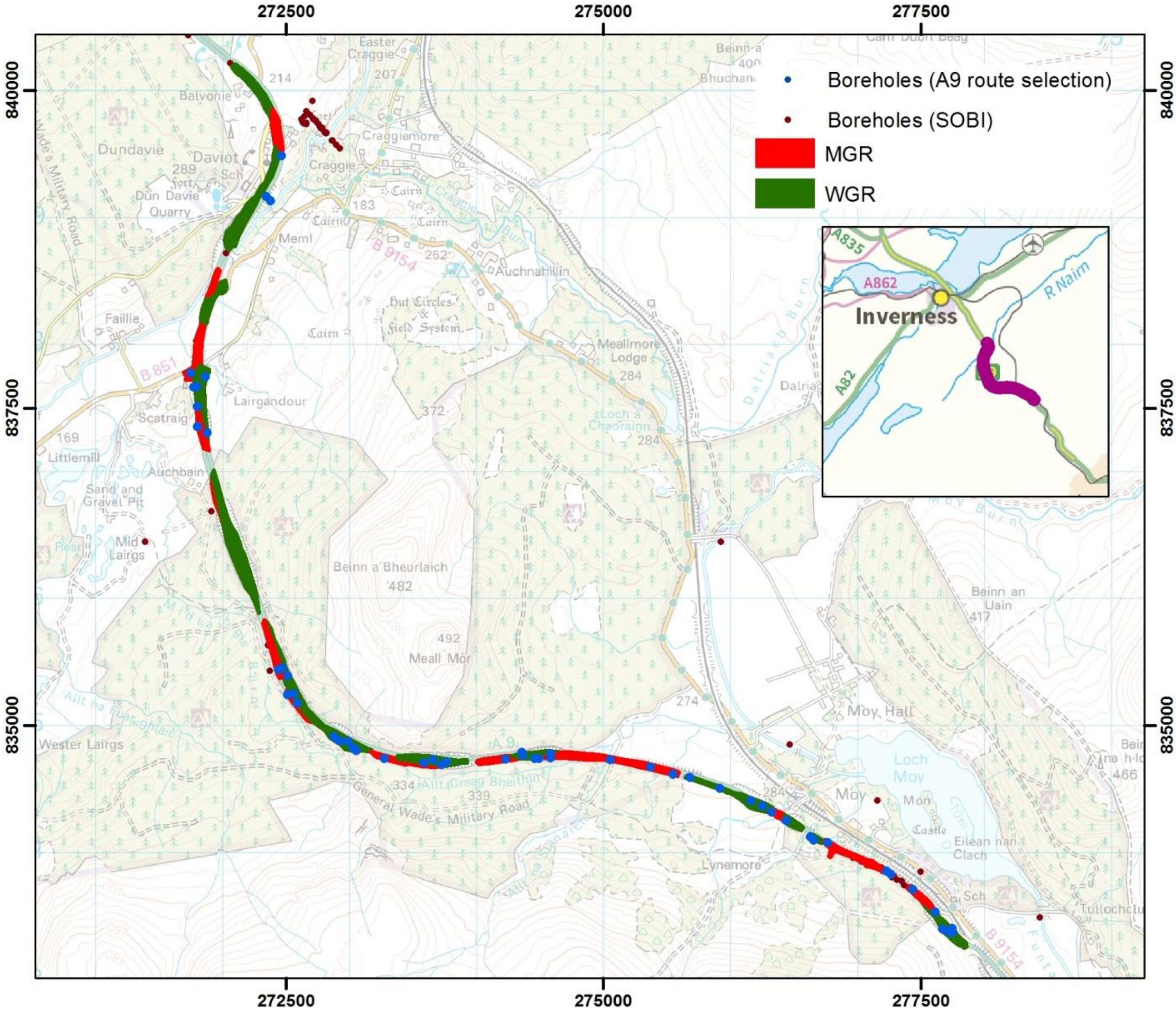

Figure A1-1 Map of the Northern area (Daviot) showing the distribution of made ground and worked ground. Location of the section is shown in the inset map. Contains Ordnance Survey Data © Crown copyright and database rights 2014.

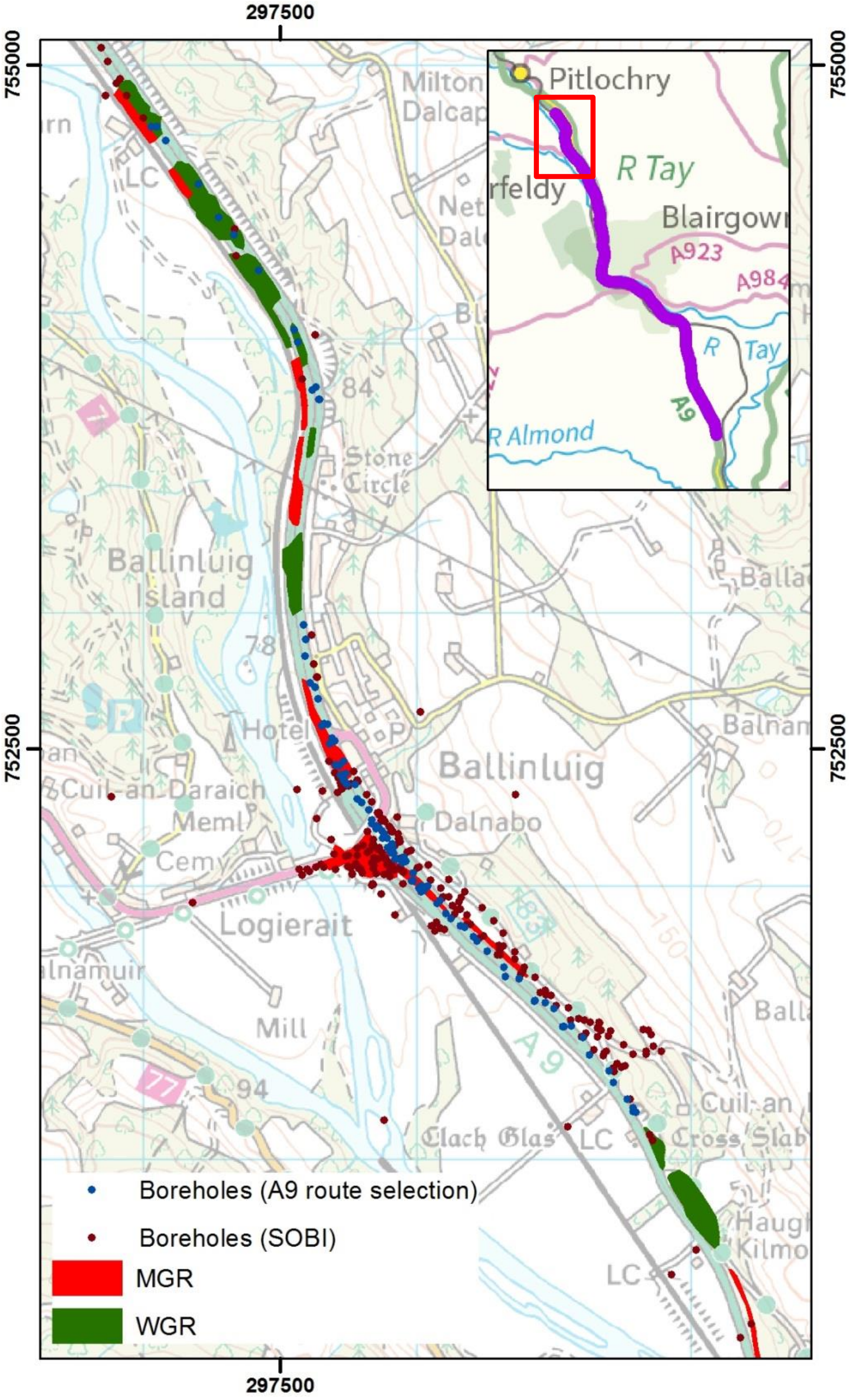

Figure A1-2 Map of the northern section of the Southern area (Dunkeld) showing the distribution of made ground and worked ground. The location of the main map is shown by the red box in the inset map. Contains Ordnance Survey Data © Crown copyright and database rights 2014.

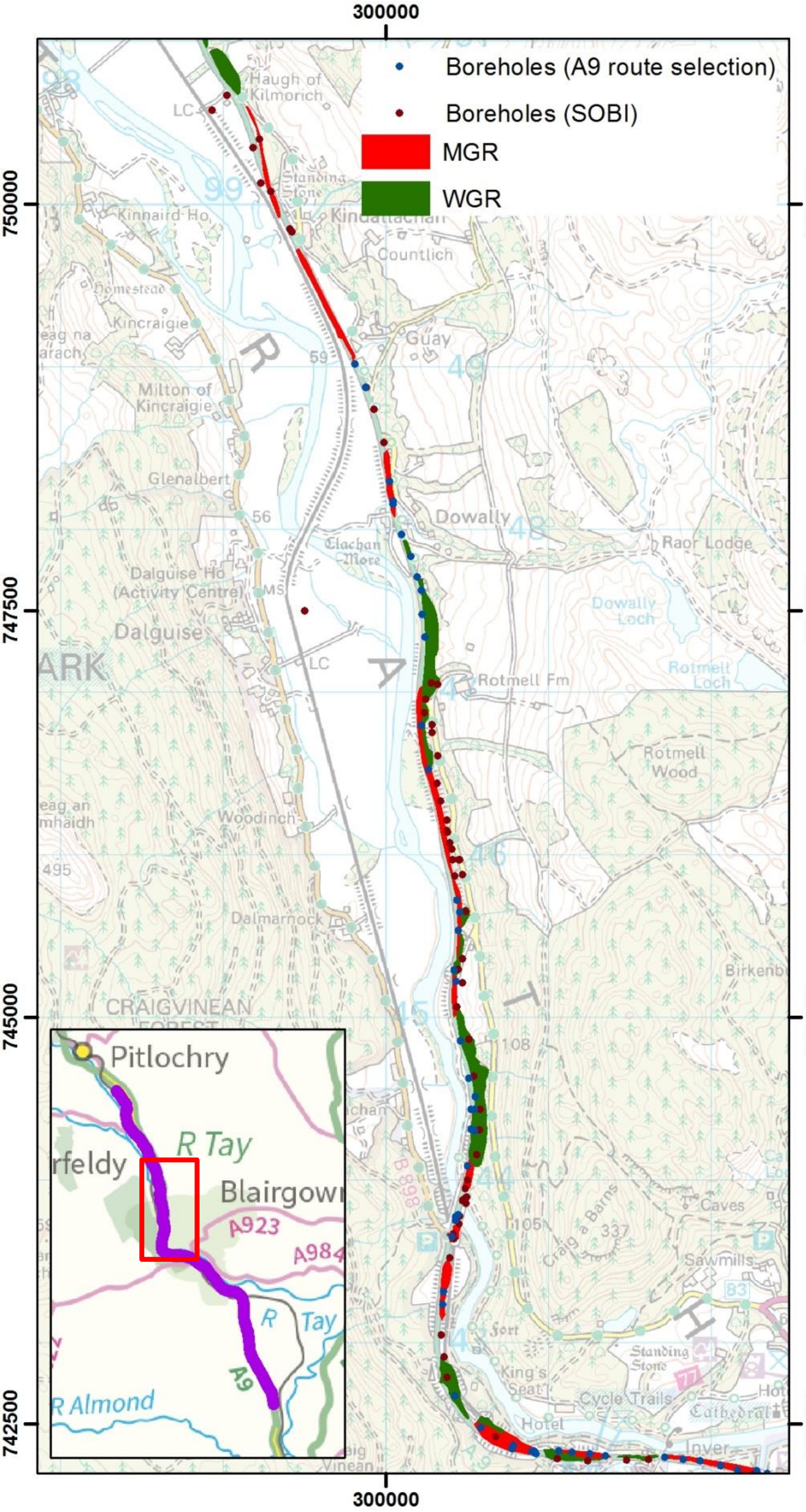

Figure A1-3 Map of the north-central section of the Southern area (Dunkeld) showing the distribution of made ground and worked ground. The location of the main map is shown by the red box in the inset map. Contains Ordnance Survey Data © Crown copyright and database rights 2014.

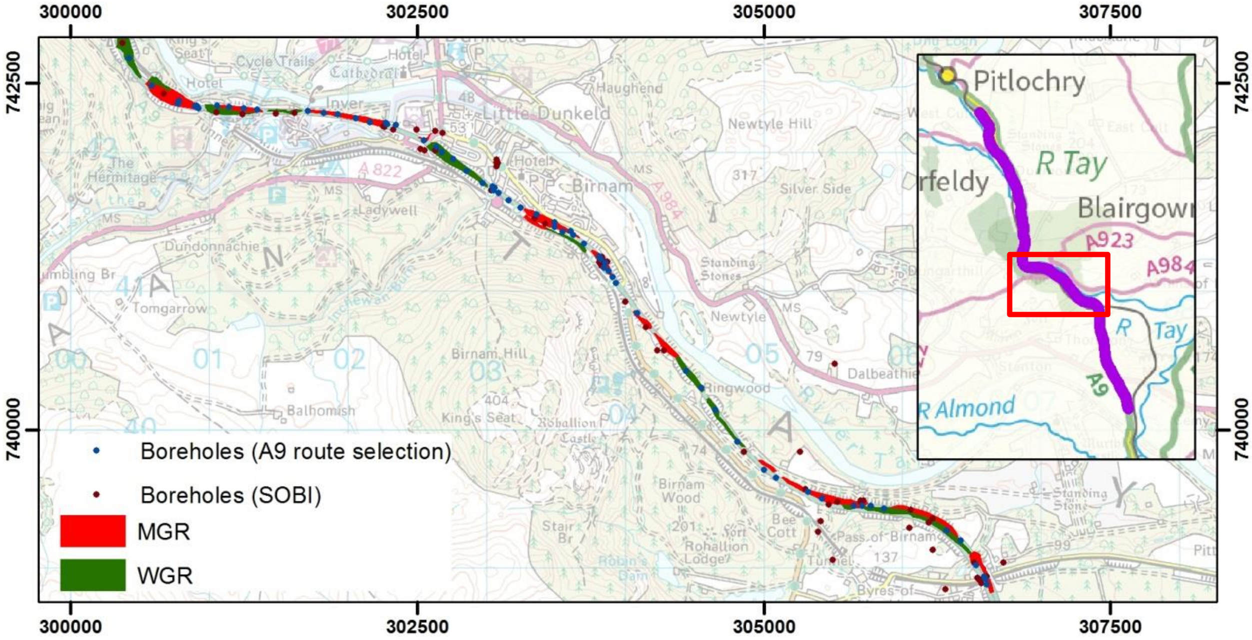

Figure A1-4 Map of the south-central section of the Southern area (Dunkeld) showing the distribution of made ground and worked ground. The location of the main map is shown by the red box in the inset map. Contains Ordnance Survey Data © Crown copyright and database rights 2014.

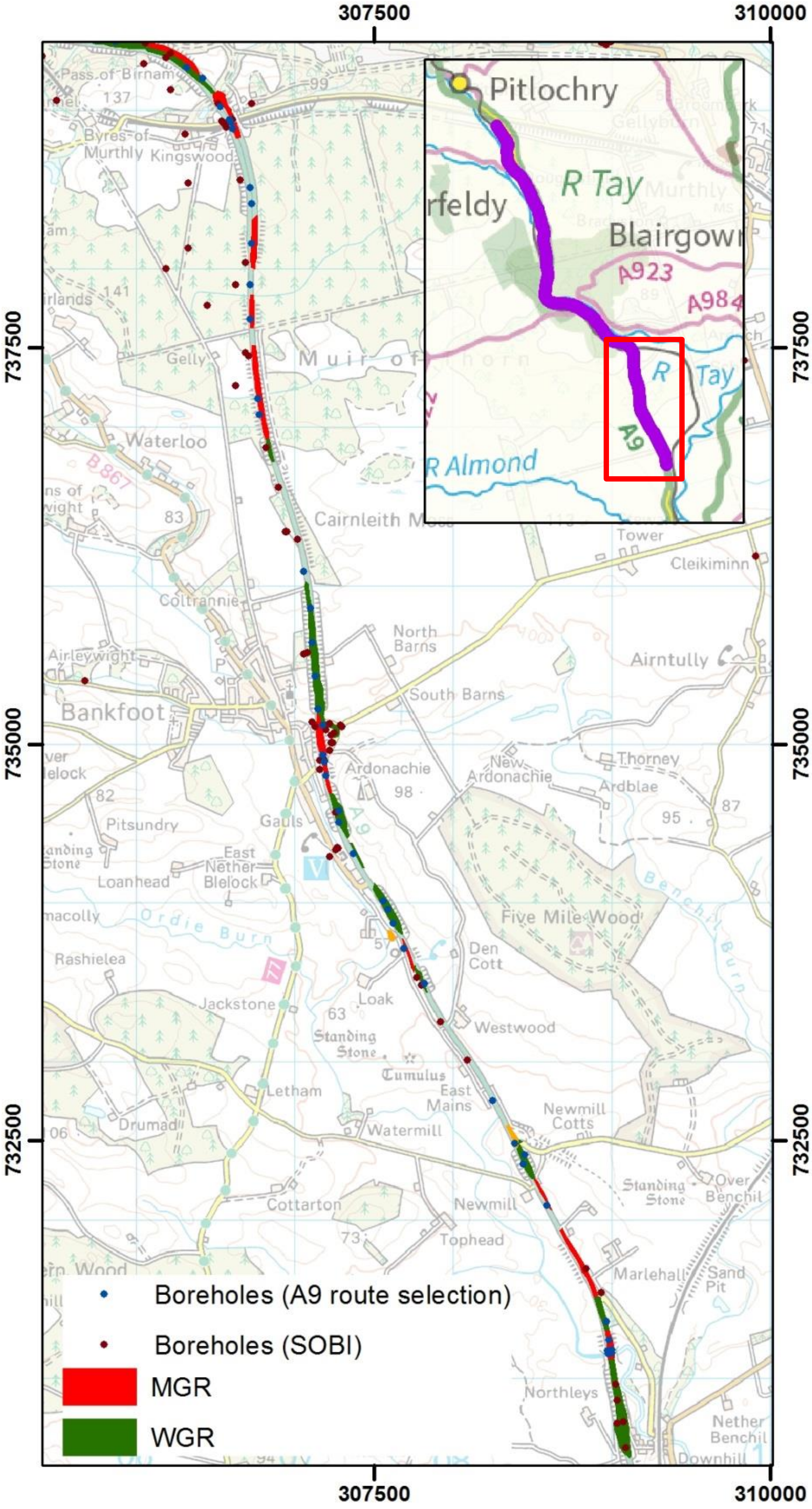

Figure A1-5 Map of the southern section of the Southern area (Dunkeld) showing the distribution of made ground and worked ground. The location of the main map is shown by the red box in the inset map. Contains Ordnance Survey Data © Crown copyright and database rights 2014.

Appendix 2 Interpolation functions

The interpolation functions used to derive a ‘pre-road’ DTM were Inverse Distance Weighting (IDW), spline and triangulation. Details of the functions are as follows:

Inverse Distance Weighting (IDW): attributes each target raster cell an elevation value based on a weighted combination the surrounding points; points at greater distance from the target have less influence on the value. The degree to which a point is influenced by surrounding points was modelled as a power function of the inverse of the distance from the point of interest using factors of 1.5, 2 and 3. A search radius of 12 surrounding points was used to calculate each output cell value.

Regularised spline: this process defines the surface elevation between known points using a mathematical function that minimises the surface curvature. A default weighting of 0.1 and a search radius of 12 points were used for local approximation.

Triangulation: this procedure defines a surface through linear triangulation between sets of three known points. Triangulation was done in GSI3D by generating an envelope of the DTM and using the ‘add scattered data points function’ prior to triangulating the 3D surface. GSI3D assumes that the surface is a geological unit and thus automatically calculates two surfaces representing the ‘top’ and ‘base’ of a geological unit during the triangulation. The top surface is clipped to the modern DTM and is therefore the triangulated representation of the modern ground surface. The base surface is not clipped to the DTM and represents the estimated pre-road ground surface.

Both the IDW and spline interpolations honour all the data present in the clipped DTM and therefore match the original DTM in the non-clipped areas. The re-interpolated DTMs were compared directly with the original DTM to estimate the ground surface change along the road route. For the triangulated DTM, the top and base TINs were exported from GSI3D as asci grids and compared against each other in ARC GIS.