Chapter 18 The role of geology in developing places

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Keywords: places, development planning, resilience, infrastructure water management.

Geology has played, and continues to play, a significant role in how places in Scotland have developed. This influence of geology is wide reaching. It has underpinned the creation and availability of natural resources that have had a large role in guiding how and where settlements develop and economic growth (Smith et al. 2023, Ch. 17, this volume). Geology has also shaped the physical appearance of our present-day landscape – different rock types weathering and eroding in response to successive glaciations and long-term geomorphological processes (Press and Siever 1998) – and it underpins the diversity and richness of derived soils and biodiversity in Scotland (Dobbie et al. 2011). All of these have shaped Scotland's development through time and how people live and connect across the country today. The distribution of agriculture, farming and forestry, for example, all primarily reflect the underlying capability of soil and water resources, whilst the industrial development of the Midland Valley in the 18th century was a direct result of the accessibility of mineral resources and adjacent natural trading ports. Similarly, from the second half of the 20th century, the exploitation of North Sea oil resources has had a major impact on the economy and development of former market/fishing port settlements in Shetland, Easter Ross, Angus and Aberdeen and the oil refining plants at Grangemouth, Stirlingshire and Mossmorran in Fife.

As a result, geology not only underpins Scotland's natural environment and heritage, but it has also strongly influenced how places and communities have developed and the nation's social heritage. This pervasive influence of geology was recognised as early as 1882 by Archibald Geikie in his work *Geological Sketches* where he states, "probably few readers realise to how large an extent the events of history have been influenced by the geological structure of the ground whereon they have been enacted". Geikie makes the point that geology provides not only a physical framework of natural resources and landscape development, but it is also a key influence in determining how humans interact with places.

This chapter provides a series of examples as to how geology has influenced the development of places in Scotland and continues to do so. In particular, the chapter looks at the contribution of geology to the development and population growth of the Midland Valley through the industrial revolution, and the imprint this has had on the present-day environment. The second part of the chapter explores some of the emerging ways that geology can help build resilient places and infrastructure under climate change.

The role of geology in past and present development of the Midland Valley

Industrial development of the region

Central Scotland today is home to ca. 3-4 million people – holding the majority of the nation's population (Scottish Government 2020$_a$), in part due to the growth and wealth from its former industrial development. In geological terms, the Midland Valley of Scotland comprises the relatively low-lying part of central Scotland and is bounded to the north and south by the Highland Boundary Fault and Southern Upland Fault, respectively (Cameron and Stephenson 1985). Carboniferous aged rocks, comprising of repeating sequences of mudstone, siltstone, sandstone and limestone, with coal, ironstone and seatearths underlie a major part of the Midland Valley (see Chapter 10 this volume) including Ayrshire, Glasgow, Lanarkshire, the Lothians and parts of Fife and Stirlingshire. Superficial deposits of glacial and marine, estuarine, deltaic and alluvial origin overlie these rocks across the region to varying extent and thicknesses, reflecting a range of glacial and post-glacial depositional processes (Browne and McMillan 1989).

These rocks played a fundamental role in the industrial development and population growth of the region, providing accessible resources of coal, ironstone, oil shale and limestone as well as building stone. Superficial deposits across the region have been heavily exploited by excavation of brick pits and sand and gravel pits. The development of iron and steel production and subsequent heavy engineering industries in central Scotland during the 18th and 19th centuries were in large part due to the existence of these resources (Smith et al. 2023, Ch. 17, this volume). At their peak, Scottish coal fields within the Midland Valley produced approximately 44 million tonnes annually (Younger 2001).

The major oil extraction and refining industry developed in the central Midland Valley in the 1850s to produce oil and paraffin wax from the West Lothian Oil Shale Formation reaching its peak in 1913 and producing 27.5 million barrels of crude oil. This led to huge increases in the population (up to 900%) of some West Lothian villages. The industry gradually declined after the First World War and closed in 1963. The red shale waste heaps (or bings) remain a striking part of the West Lothian landscape today, creating specialist ecological habitats and many have been repurposed for recreational activities (Harvie 2005; Almond Valley Heritage Trust 2021).

These industries and the mining of the Carboniferous geology, were for many decades the backbone of Scotland's economic development until as recently as the middle of the 20th century. The premier example of this is Glasgow. The development of the Glasgow conurbation and its prominence as an industrial city in Scotland was based largely on the combination of: (1) the proximity of the River Clyde offering easy transport; and (2) mineral extraction from numerous and easily accessible coal and ironstone seams of the Carboniferous geology. By the 18th Century, Glasgow became the third most important port in the UK, after London and Liverpool, with imports of tobacco, cotton, coffee, rum and sugar (Glasgow City Council 2014). From 1732 onwards, the establishment of ironworks and forges, predominately in the East End of the city, increased the local demand for coal and ironstone at the expense of the export trade. Modification of the River Clyde throughout the 18th and 19th centuries enabled it to become deep enough to accommodate the largest commercial vessels thus allowing easy import of raw materials and export of finished goods (Bowie 1975). In this period, Glasgow became a centre of heavy industry renowned for ship building (based on the River Clyde), railway engineering, iron and steel manufacture and cotton spinning. At one time, the world's largest cyanide and chromium works were located in Glasgow. By 1800, the population of Glasgow had grown to 84,000; reflecting the gathering momentum of the industrial revolution (Browne et al. 1986). Across the whole Glasgow conurbation, the trend of increasing population and commercial success continued well into the 20th Century.

Similar industrial growth was seen across the River Clyde catchment and wider parts of the Midland Valley through the 18th and 19th centuries with the advent of the railways, which enabled transport of raw materials to the ports. Motherwell, for example, remained a small hamlet to the southeast of Glasgow until it became a railway junction with a direct link to Glasgow. The creation of excellent transport routes led to the development of a number of major iron and steel works in the town, and a wide range of other heavy engineering in the area, building everything from munitions, to bridge components, and trams. Similarly, Coatbridge emerged as a settlement following the construction of the Monklands Canal in 1788 to transport coal from the North Lanarkshire coalfield to Glasgow. By 1869, the Gartsherrie Ironworks at Coatbridge had become the largest in Scotland at that time, employing 3,200 people. The arrival of the Forth and Clyde canal in 1788, and then the railways in the 1820s transformed the towns of Kirkintilloch and Wishaw, respectively, into centres of cotton weaving, iron working and boat building (East Dunbartonshire Council 2014; Lanarkshire Communities 2014).

With the advent of increased globalisation during the 20th century, heavy industry and mining in central Scotland declined between the 1950s and 1980s. Since then, the regeneration of many former heavily industrialised areas in the Midland Valley has taken place, and is ongoing, with light industry and housing.

Modern day impacts of this development

The industrial development in the Midland Valley has left a legacy of modified landscape and watercourses, abandoned mines, infilled quarries, industrial waste and contamination; all of which influence land and water quality across the region as well as wider Scotland. This modified landscape and the underpinning geology and ground conditions play a strong role in modern development of the region, influencing building design, preferred location of development and required remediation of land areas amongst other things. Each of these are discussed in more detail in the following sections. The requirement for geological understanding and ground characterisation in development approaches is growing, with sites that once would have been considered too complex and uneconomic to consider redevelopment, are increasingly being brought forward for new uses. This is due to several drivers, including land pressure, regeneration policies and preference to develop brownfield sites over greenfield sites under Scottish Planning Policy (Scottish Government 2014). This development planning approach aims to improve urban environmental quality and create more cohesive towns and cities without tracts of disused land. The brownfield legacy of sites can; however, pose individual challenges for present day development which requires a detailed understanding of ground conditions to be made early on in development considerations (see Topic Box 18).

Mining and subsidence

As a result of the industrial development of the region, most of the Midland Valley and central Scotland is now underlain by extensive former mining operations (Younger 2001). An immediate challenge for any development work is that much of the mining legacy predated accurate record keeping. It was not until the late 19th century that it become a legal requirement to record the extent of mine workings on abandonment plans when a mine closed. For example, Glasgow City Council has approximately 1,000 records of abandoned mineshafts within its administrative area, which are believed to be around one third of the true number. Recently, extensive effort has also gone into digitising available mine abandonment plans across the UK and Scotland. These data are published and available from The Coal Authority (2022).

Much of the shallow mining in the Midland Valley was carried out by partial extraction methods; bell pits; stoop and room; and longwall mining. These leave a risk of collapse of the mine workings, possible subsidence or crown hole development at the surface (Fig. 18.1a), depending on the depth of the workings, the thickness of coherent rock strata above the workings, and the dip of the geological strata.

Stoop and room mining was the principal method in the Midland Valley until the middle of the 20th Century (Younger et al. 2002), with mineral resources being extracted in a grid like pattern – Fig. 18.1b. Miners dug straight tunnels into the mineral seam, often parallel and perpendicular to seam dip, and extracted the desired mineral as they moved forward. To prevent the collapse of the mine, roof pillars (or 'stoops') of the seam were left in-situ. These pillars created avenues and roadways that could either be left open once the mineral had been worked, or in some instances once the miners had reached the maximum extent of the workings, they would work backwards removing the pillars as they moved out of the mine to obtain total abstraction.

As part of any development consideration in the present day, it is vital sites are carefully assessed to determine the risk of ground movements from collapsing historic mine workings and mineshafts. Site investigation programmes require to establish the depth of mine workings present below rockhead and the ability of the overlying strata to hold the additional weight of a new building or structure (Chiverrell 2019). A detailed appraisal of ground conditions, must also be given when constructing piled structures in areas where mine workings are present - the toe of foundation piles can impose a point load on rock, causing penetration of the workings (BSI 8004:2015+A1:2020). Consideration is also required relative to historic mineshaft locations and risks associated with mineshaft collapse under development proposals. The Construction Industry Research and Information Association (CIRIA) abandoned mine workings manual (C758D) provides a risk-based approach for all investigation in mining legacy issues, mitigation and remediation (Chiverrell 2019).

The effect of these ground conditions is seen today in issues of subsidence and the programme of works often required to stabilise significant areas. Glasgow began to respond to the challenges of abandoned shallow mining in the 1980s by instituting a programme of site investigation and infill grouting of shallow workings. This was principally designed to preserve the built heritage of typical tenements; but has since extended to other areas and building types that are underlain by the shallow mine workings of coal and ironstone, but also in limestone, sandstone, fireclay and alum shale. This has led to an extensive programme of grouting across parts of the city – Fig. 18.2. Angled holes designed in a grid target the underlying geological seam and inject a grout mix comprising pulverised fuel ash, cement and sometimes sand under low pressure to fill the voids in the abandoned workings. The grout, when set, has no great strength, but acts as a void filler to prevent the roof material in the workings from collapsing. Recently, expanding grouts – foamed concrete and polymer resin – have been utilised to prevent flow down open roadways, and in one case, actually lift a damaged building structure back nearer to original level. This latter effect is only possible where the workings are very shallow (less than 2m below foundation level), and for a rigid building structure.

Landfill, mine and ground gas

The potential for ground gas is another factor which has resulted from the history of exploitation of superficial deposits and mining operations through the Midland Valley.

Assessing the potential for ground gas is a key component of ground investigation and geological considerations in any development works in the Midland Valley, as well as across many other regions of Scotland. The former mining and quarrying activities across the Midland Valley left a network of abandoned underground features. Historically these were often used for the direct disposal of various wastes and by-products from the industrial processes; and there are now significant volumes of made ground across the region of unrecorded provenance; and also, as a direct result of general upfilling of land as part of development phases. Other post-industrial features such as disused former railway cuttings or quarry features were also commonly infilled and utilised for waste disposal purposes too.

All of these features and processes require to be regarded as potential sources of landfill or ground gas such methane (CH_4), carbon dioxide (CO_2) and hydrogen sulphide (H_2S); which can also be found in organic rich soils (peat) and rocks.

The term ‘mine gas’ is used specifically to refer to methane, hydrogen sulphide, carbon dioxide and carbon monoxide gases released from coal seams and the surrounding bedrock. Changes in oxidation state of the coal seam and strata, lead to the stored gas desorbing into the air or groundwater within surrounding fractures or voids spaces within the rock. This happens when the coal is mined, or a borehole or foundation solution is advanced into an intact seam. It can also occur when unworked seams above and below a worked seam are disturbed by ground movements; or when the mine workings are dewatered leading to a change in oxidation state. Abandoned mines can continue to release mine gases such as methane until the workings are completely flooded or the gas reserve is depleted (Department of Energy and Climate Change 2011).

Landfill, ground and mine gases can be harmful to human health in specific circumstances if they reach the ground surface and accumulate in insufficiently ventilated or protected buildings. This was evidenced in the Gorebridge incident in Midlothian within central Scotland in 2013-14, where gas ingress from mine workings occurred to residential buildings and caused demonstratable health effects (National Health Service (NHS) Lothian 2017; RSK-Scottish Government 2019; BSI 8485:2015+A1:2019).

As part of site development considerations, it is vital that risks from ground and mine gas are well understood. Depleted oxygen levels should also be considered in the context of ground and mine gas. This involves understanding the geological conditions of a site and made ground presence, the nature of the coal seams present, any contamination present; expected changes in groundwater level and climate change influences; and how the development proposals could influence conditions and potentially create pathways. If a risk from ground or mine gas is identified, risk assessments may be undertaken as part of a ground investigation approach; this may include ground gas monitoring. There is much published guidance on this subject; however common approaches that follow a multiple lines of evidence approach are outlined in CIRIA C665 (Wilson et al. 2007), BSI 8485:2015+A1:2019 and BSI 8576:2013 and specific to mine gas as set out by CL:AIRE (Contaminated Land: Applications in Real Environments) (2021). This enables the level of risk, and any remedial or counter measures required to manage the risk, to be well understood and designed appropriately for the proposed development scenario (Card et al. 2019).

Soil and Land Contamination

Soil is a vital part of a sustainable environment. It underpins a wide range of essential environmental, social and economic functions from the growth of food, to supporting forestry and controlling the quality and quantity of water flow (Dobbie et al. 2011). It can also be an important store of carbon and underpin a number of internationally important habitats in

Scotland. Soil quality is defined as the ability of soil to carry out these functions (Dobbie et al. 2011).

Soil is primarily composed of decomposed vegetative matter; weathered material derived from the underlying geological bedrock; and superficial materials deposited by rivers or glaciers over millennia. The chemical composition of soil is ultimately determined by these and other factors such as topography, climate, biological action and atmospheric deposition (McBride 1994, Dobbie et al. 2011).

As soil parent material, geology plays an important role in determining soil geochemistry (Rawlins et al. 2003). However, in urban and developed environments, the concentrations of chemical substances are often elevated as a result of atmospheric and terrestrial urban pollution, transport, industry and the nature of urban ground, which is typically disturbed and in-filled and bears little relation to the soil of the surrounding rural environment (Birke and Rauch 2000; Mielke et al. 2000; Fordyce et al. 2005; Johnson et al. 2011). Hence, urban soil chemistry is a combination of the natural soil composition plus the anthropogenic (human-made) contribution (Johnson and Ander 2008).

In Scotland, the industrial history of the Midland Valley is imprinted on the environmental quality of soils in the region and also the chemistry of groundwater and surface water bodies in some areas. A recent study by the BGS demonstrates the combined contribution of geology, urbanisation and industry to soil chemistry in the River Clyde catchment in the Midland Valley (Fordyce et al. 2017; 2019). Systematic surveying of topsoil (0 – 20 cm) across the region revealed that median chromium concentrations (Cr, 102 mg kg^{-1}) in Glasgow were higher than in many other UK cities due to the presence of volcanic bedrock in the area, as well as the history of chromite metal ore processing in the city, as follows.

In rural parts of the Clyde catchment, higher Cr concentrations (> 166 mg kg^{-1}) in topsoil are associated with the outcrop of the Silurian–Devonian mafic volcanic rocks in the south-east of the catchment and with the more mafic components of the Clyde Plateau Volcanic Formation to the south-west of Glasgow (Fig. 18.4). This is because in the natural environment, Cr is typically associated with mafic and ultramafic igneous rocks, and concentrations are commonly higher in organic-rich rocks such as black shale and coal than in other sedimentary lithologies (Gonnelli and Renella 2013). Higher values of Cr (> 144 mg kg^{-1}) are also present in the south-east of the Clyde catchment associated with coniferous forestry and opencast coal mining; and correspond to high-manganese (Mn) soil, suggesting retention of chromium in secondary Mn-oxides in this low-pH environment.

By contrast, within the urban areas of the Clyde catchment, anthropogenic activities have had a significant influence on the present-day geochemistry of the soils. High topsoil Cr values (> 173 mg kg^{-1}) are associated with made ground and industrial sites in Milngavie and Renfrew–Paisley–Johnstone; with the Moffat Mills distillery/former paper mill in Airdrie; the former iron pit/works at Calderbank in Coatbridge and at Beith. Elevated values are reported also at Ravenscraig, Motherwell, which was the largest steel mill in Europe until it closed in 1992 (Fig. 18.4). Rutherglen in south-east Glasgow was home to the world's largest chromite ore processing plant during the 19th Century, which operated until 1968. Chromite ore processing residues (COPR) were extensively used as landfill material around south-east Glasgow, and it is estimated that 2,500,000 tons (dry weight) were deposited in the area during the lifetime of the factory (Farmer et al. 1999). Consequently, Cr concentrations are significantly elevated (> 173–4286 mg kg^{-1}) in topsoil in these parts of the city (Fig. 18.4).

Efforts to remediate the COPR-waste sites in Glasgow have been extensive in recent years, and are ongoing; including the lining and diverting of water courses away from the known areas of waste deposition, in-situ chemical treatments with calcium polysulphide and capping/containment of the waste materials to reduce infiltration and mitigate the impacts on soil and water quality and human interaction, as part of major urban regeneration programmes in the East End of Glasgow (Bewley & Sojka 2013) (Fig. 18.5).

Overall, the results of the BGS geochemical survey show that the concentrations of several chemical substances are elevated (1.1–2.1 times, based on median values) in urban soil relative to the rural background, as a result of the long history of urbanisation and industrialisation in the region. These include arsenic (As), copper (Cu), chromium (Cr), molybdenum (Mo), nickel (Ni), lead (Pb), antimony (Sb), vanadium (V) and zinc (Zn) (Fig. 18.6). In addition, higher soil calcium (Ca) and pH in urban areas, relative to rural soil, is indicative of the presence of building rubble, slag and made-ground materials such as concrete in city soil, which is generally calcareous in nature (Fig. 18.6). This is a typical indicator suite of parameters that is symptomatic of urban anthropogenic pollution, found not only in Glasgow and the Clyde catchment, but in other cities in the UK and elsewhere (Birke and Rauch 2000; Fordyce et al. 2012). This demonstrates that even 40 years after the decline in major industry in Scotland, understanding and managing the legacy of urban/industrial pollution remains key a key component to planning future places.

Indeed, land can be contaminated by a variety of substances that pose immediate or long-term risks to human health and the environment. Contaminants can range from asbestos, polycyclic aromatic hydrocarbons (PAHs), solvents, oil, petrol and heavy metals to radioactive substances. The sources of contaminants are not just restricted to industrial processes: others may include agricultural activities, inadequate waste management and disposal, deposition from the atmosphere and everyday activities such as petrol distribution and dry cleaning (Scottish Environment Protection Agency 2022$_a$).

Today, there is a much greater appreciation of the environmental impacts of industry and these are monitored, controlled and regulated by a comprehensive collection of legislation - including the Controlled Activities Regulations and the Environmental Liability Regulations (Scottish Environment Protection Agency 2009) and the Pollution Prevention and Control (Scotland) Regulations 2012. The contaminated land regime, implementing the provisions of Part IIA of the United Kingdom Environmental Protection Act 1990 came into force in 2000 in Scotland (Contaminated Land (Scotland) Regulations, 2000). This provides a framework to inform policies, procedures and decisions around the management and remediation of contaminated land (Scottish Executive 2006). Under Part IIA contaminated land is defined as ‘any land which appears to be in such a condition, by reason of substances in, on or under the land, that either significant harm is being caused or there is a significant possibility of harm being caused to human health or the environment’. In total across the whole of Scotland, it is estimated that approximately 67,000 sites (82,034 hectares) could be affected by land contamination, and so require inspection under Part IIA regulation or alternatively to be dealt with as part of the planning system (Scottish Environment Protection Agency 2009).

The contaminated land regime follows the “suitable for use” approach as the most appropriate way to deal with the legacy of contaminated land, recognising that the risks from contamination are site specific and depend greatly on the proposed usage of the site, as well as many other factors including underling geology (Scottish Executive 2006). Risk exists when a source (a contaminant) and a receptor (e.g. people, groundwater, rivers, ecology or the wider environment) both exist at a site with a pathway linking the two; termed a pollutant linkage. This site-specific risk assessment approach requires a comprehensive understanding of the geology and unique conditions at a development site to best understand the source(s), pathway(s) and receptors(s) and extent of remedial treatment required to ensure that human health and the environment are no longer at risk. Therefore, these assessments often involve environmental geoscience expertise to ascertain natural and anthropogenic influences on land quality and likely contaminant behaviour and mobility.

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Surface water and groundwater quality

Surface and groundwater resources are, like soils, key components of a resilient and sustainable environment, and they underpin ecosystems and a range of industries in Scotland. During the former industrial development of the Midland Valley abstraction of groundwater was extensive; this dewatering enabled the mineral seams to be worked. One estimate puts the total volume of groundwater being pumped from mines in the lower Clyde catchment alone around 1950 at 215 ML per day (Ó Dochartaigh et al. 2007). Groundwater in the Midland Valley today is used mainly for agriculture. In Fife and East Lothian this is largely for irrigation, and in the south and west of the Midland Valley largely for sheep and cattle (Ó Dochartaigh et al. 2011). Groundwater abstraction for dairy farming is particularly widespread in Ayrshire.

The natural groundwater quality in the Carboniferous aquifers is generally good where it doesn’t intercept mine workings (Ó Dochartaigh et al. 2011). However, in areas close to mine workings or former direct disposal of industrial waste, the natural baseline chemistry of groundwater and surface water resource is often altered. For example, in Glasgow the presence of COPR has led to observation of Cr concentrations in surface water up to 6.7 mg L^{-1} and in groundwater up to 169 mg L^{-1} in some cases (Whalley et al. 1999; Farmer et al. 2002, Palumbo-Roe et al. 2017). Existing UK Environmental Quality Standards for freshwater receiving waters range from 0.0081 mg L^{-1} (surface water) to 0.0375 mg L^{-1} (groundwater) for total dissolved Cr for ‘good’ environmental status (Scottish Environment Protection Agency 2014; 2019). River-bed sediments are also shown to have been affected by pollution in the region - a regional geochemical survey of the Clyde catchment finding up to 3561 mg kg^{-1} Cr in urban stream-bed sediments in Glasgow (Fordyce et al. 2004).

Although all deep mining in the region has now ceased, it continues to be the biggest influence on the hydrogeology of the Carboniferous aquifers in the Midland Valley (Ó Dochartaigh et al. 2011). Ferruginous mine waters are the most common source of pollution, and these are predominantly associated with flooded deep mine workings, particularly coal mines, in the Carboniferous aquifers of the Midland Valley (Younger 2001; Smith et al. 2023, Chap. 17, this volume). The lowering of water levels and exposure of rock strata to air during mine dewatering meant iron pyrites and marcasite, both sulphides of iron, which are present in the Carboniferous strata, could be oxidised to form ferric and ferrous sulphates, sulphuric acid and ferric oxide. A systematic survey of baseline groundwater chemistry in Scotland undertaken between 2005 and 2011 by the BGS and the Scottish Environment Protection Agency (SEPA), showed the occurrence of this ferruginous groundwater chemistry in the Midland Valley aquifers, particularly from the Coal Measures and Clackmannan Groups, where the groundwaters are suspected to intercept abandoned mine workings. These groundwaters are generally low in dissolved oxygen and show high concentrations of bicarbonate (HCO_3), Calcium (Ca), sulfate (SO_4), iron (Fe) and manganese (Mn) with evidence of pyrite oxidation within the mined areas (Ó Dochartaigh et al. 2011; MacDonald et al. 2017).

Monitoring of water levels has occurred in many mines since dewatering was stopped in Scotland, particularly since the early 1990s. Groundwater rebound occurs over decades; the rates decreasing over time after initially very high rates. At Polkemmet Colliery in West Lothian, groundwater rebound was estimated to still be occurring at up to 10 m per year some ten years after dewatering stopped in 1984 (Chen et al. 1999). There are now around 150 abandoned mines where mine water is still pumped or, more commonly, discharged by gravity flow to the surface in Scotland (Ó Dochartaigh et al. 2011), and 13 treatment centres where mine water discharge is treated (The Coal Authority 2020). Most of the flows are now small, less than 5 L per second, however the ongoing management and treatment centres required highlights the ongoing influence of the geology and former development to the groundwater chemistry in the area and how the resource is now used and managed regionally (Smith et al. 2023, Chap. 17, this volume). A database of these mines is maintained by the Coal Authority (Environment Agency 2021).

Topic box 18. Regeneration of vacant and derelict land – the role of geological expertise and research

The legacy of Scotland's industrial past means that today almost a third of the Scottish population lives within 500 meters of a derelict site (Scottish Vacant and Derelict Land Survey 2019). In deprived communities the figure increases to 55%. Scotland's National Planning Framework promotes re-use of brownfield land in preference to greenfield sites; with the planning system having a key role in tackling land contamination across Scotland (Scottish Government 2014; 2018$_a$). The benefits of redeveloping vacant and derelict land are multi-fold, as it helps to: improve environmental quality through remediation of any legacy contamination; develop more compact future urban forms with shorter travel distances and lowered transport emissions; healthier and spatially better-connected communities, which can attract further investment; and restoration of urban biodiversity. For example, the conversion of former claypits on the banks of the Forth and Clyde Canal in North Glasgow, Hamilton hill to a Local Nature Reserve, now provides accessible green space for recreation and biodiversity in an inner-city area (Scottish Canals 2022). However, the development of brownfield sites is complex and extensive investment in remediation of the sites is often required before construction and new development can begin.

Analysis of the take-up of vacant and derelict land gives an indication of the size of the challenge of brownfield development in places such as Glasgow. Around 939 hectares, or 0.54%, of the total available land in Glasgow is classed as vacant or derelict (Scottish Vacant and Derelict Land Survey 2019). In recent years an average of 30-40 hectares of vacant and derelict land were reclaimed and brought back into use in Glasgow. Across the whole of Scotland, vacant and derelict land still extends to some 11,037 hectares (Scottish Vacant and Derelict Land Survey 2019). Bringing this land across Scotland back into use for environmental, social and economic benefits, takes significant technical expertise. Understanding the geology, ground conditions, gassing regime and any contamination present (soil, ground, surface water) is pivotal. Geological and geotechnical expertise is essential to be able to appropriately assess ground-related risks (e.g. contamination, ground movement, ground gas, etc.) and inform appropriate building design and ground remediation or protection measures. Looking ahead, geologists will also increasingly need to be able to identify how changes in climate will alter these risks and the mitigation and engineering approaches required.

The Sighthill Transformation Regeneration Area (TRA) in Glasgow City (one of five TRAs currently in the city) is a ready example of the level of geological expertise and input required in developing these sites. Sighthill is one of the largest brownfield development projects happening in the UK, and it will provide around 1000 new homes, a new park, education centre, businesses and a local community centre – Fig. 18.7. Redeveloping this 50-hectare site will cost in total around £250 million once both the required ground remediation work and new infrastructure are complete (Glasgow City Council 2022). Several phases of ground investigation and input of geological expertise were required to develop a sufficiently detailed appreciation of the geological constraints of the site for the development proposals and the contamination source-pathway-receptor relationships. This site characterisation was then used to design effective remedial solutions across the site which were suitable for use planning requirements. Multiple lines of evidence, including drilling new boreholes, soil and water sampling, groundwater and ground gas monitoring have been required. The first phase of remediation of the site involved managing around 1 million cubic metres of soil material whilst remediation and stabilisation of residual waste chemicals and hydrocarbons at the site were completed (Glasgow City Council 2022).

The role of geology in future opportunities for low carbon places

The role of geology in influencing the development of Scotland is clear – from industrial growth, to the challenges in the modern-day development within the country. In the Midland Valley in particular, geology will undoubtedly continue to influence the development of this region – not only through complex ground conditions which have resulted from the former mining in the region, but the geology and industrial legacy also offer potential opportunities for the future in developing new low carbon technology. There will be a continued need for geological expertise and new research to harness these opportunities and inform appropriate regulation.

Going forward, legacy mine workings and the circulating groundwater resource could offer a potential resource for heat recovery and storage in central Scotland, coinciding with areas of greatest population density and existing fuel poverty. Mine water heat schemes can be feasible for groups of homes, or large industrial buildings, if high flow rates can be sustained – depending on the permeability and transmissivity created by the old mine workings and the surrounding strata. Smith *et al*. (2023, Ch. 17, this volume) provides more discussion of the potential for this heat resource and storage within Scotland. Shallow geothermal energy, which is based on heat derived from both deep (< 200 m) within the earth and from solar energy absorbed by the ground, and then distributed via groundwater systems is another potential source of renewable energy for the future. A range of shallow geothermal technologies are being developed to extract and transfer this heat energy for use in homes and businesses which could be applicable in Scotland. In most cases, this involves use of boreholes or an underground closed loop, plus a heat pump. Other, wider, low carbon approaches and opportunities which are enabled by geology, exist in Scotland such as the potential use of former oil field infrastructure and geological reservoirs in the North Sea to support Carbon Capture, Utilisation and Storage (CCUS) technologies.

These illustrate a few of the ways in which geology is likely to continue to play an important influence in how society interacts with places.

Geology will be an important part of how we develop a low carbon economy going forward and significant research is ongoing to better understand these opportunities.

The role of geology in building resilience to climate change

As well as having been a significant influence on development and industry, geology makes a substantial contribution to how we can build resilience to climate change. This is an area of growing research in order for key geological controls and processes to be better understood. This section of the chapter explores in more detail some of the emerging and increasing ways that geological inputs are considered in environmental management and infrastructure design.

Infrastructure resilience

Slope Instability

During the glaciations of the Quaternary Period, glacial erosion in upland areas of Scotland steepened and lengthened slopes; while retreating ice deposited a mantle of sediment on valley sides. These processes resulted in many slopes in Scotland being left in an unstable state, and the resulting mass movement processes have affected both rock slopes (in the form of rock slides, mountain slope deformation, and rockfall) and sediment covered hillsides (predominantly as debris flows). Dating of large rock slides and rock falls show that the majority occurred within a few millennia of local deglaciation (Ballantyne 2019). Most rock slopes today are largely stable, although intermittent small rockfall events are still recorded, such as on Lochnagar in April 2000 (Watson et al. 2001). Debris flows are also far less frequent now than in immediate post glacial times; however, they remain a relatively common occurrence on steep upland slopes and understanding debris flow risk is a key part of infrastructure resilience in Scotland, particularly in relation to transport and cabling.

The conditions that influence current debris flow activity are slope angle (generally >30°); the presence of source sediment (glacial sediments, talus slopes, regolith, or material accumulated in gullies); and saturation of sediments, usually by prolonged and / or intense rain, leading to a reduction in effective stress and resulting instability. Milne et al. (2015) observed that factors such as slope length and sediment texture (e.g. a greater proportion of coarse sandy material) influences the magnitude and spatial frequency of debris flows in Scotland.

Impact to infrastructure

A large proportion of the debris flow events in Scotland occur in remote areas away from large settlements and built-up areas. Reports of housing or buildings being affected are rare, although there are exceptions. A rainfall-induced debris flow caused structural damage to a house in the Ochil Hills in November 1984 (Jenkins et al.1988), and one of a series of debris flows in August 2004 had a substantial impact on a residential property in Cairndow, Argyll (Winter et al. 2006). More recently, houses in Glengyle were evacuated when a number of damaging debris flows affected the area around Loch Katrine in August 2019.

The energy and transport infrastructure that connects Scotland's communities frequently has to pass through steep terrain, and therefore includes segments with greater exposure to debris flow hazard. The Scottish debris flow events of August 2004 are a particularly notable example of the impact on road infrastructure. During that month intense and long-lasting rainfall, which in places reached 300% of the 30-year average for August, resulted in a large number of debris flows in the Scottish hills, including a small number that intersected the trunk (strategic) road network (Winter et al. 2005; 2006). The intense rain generated 31 individual debris flows in Glen Ogle, Stirlingshire on the 18th August; of which two traversed the A85 road, trapping 20 vehicles and resulting in helicopter airlift rescue of 57 motorists and passengers (Milne et al. 2009) (Fig. 18.8). Debris flows also blocked the A83 at Glen Kinglas and Cairndow in Argyll on the 9th August, and the A9 north of Dunkeld on the 11th August.

The events of August 2004 prompted the Scottish Road Network Landslides Study (Winter et al. 2005; 2009). This body of work included a GIS-based hazard assessment (incorporating analyses of geological, topographical and land use datasets), from which a hazard ranking exercise was undertaken to identify sites where measures to reduce exposure and / or hazard should be prioritised. One of highest-ranking sites identified in the study is the A83 at the Rest and Be Thankful in Glen Croe – a glacially breached valley where glaciogenic sediment on steep slopes contributes to ongoing slope activity (Finlayson 2020). Debris flows have caused road closures at this site on multiple occasions over the past 15 years. While there have been no major injuries, these road closures have been associated with considerable economic impacts in the area because of the large vulnerability shadow (geographical area over which impacts are experienced) that is cast when the route is not passable (Winter et al. 2018). For example, the losses associated with a debris flow event in 2007 were estimated to be in the region of £80,000 per day, totalling £1.2 million over the 15-day closure. Measures to reduce exposure and hazard at the Rest and Be Thankful have included: advisory leaflets in the local area; ‘wig wag’ warning signs (where flashing lights are activated during forecast or actual heavy rain); installation of debris flow fences; and temporary use of a relief road (the Old Military Road) (Winter 2016). Debris flow catch pits have also been installed, and in 2020 Transport Scotland initiated a review to assess different options to improve the longer-term resilience of the A83 Rest and Be Thankful route.

Events related to rainfall-induced slope activity have also had severe impact on rail infrastructure. Tragically, one incident led to three fatalities when gravel from a crest drain system, together with eroded debris from surrounding ground, was washed onto the track by a cutting near Carmont, Aberdeenshire in August 2020, causing a train to derail (Rail Accident Investigation Branch 2021). Other derailments have occurred where trains have struck rainfall-induced debris flows sourced from natural slopes above the tracks on Stob Coire Sgriodian by Loch Treig in June 2012, and at Loch Eilt near Glenfinnan in 2018 (Rail Accident Investigation Branch 2018; Freeborough et al. 2019).

Although Britain’s railway network is reported as one of the safest in Europe many of the earthworks and drainage were designed and constructed in a different time (up to 150 years previously), and have become subject to increased frequency and severity of extreme weather events in recent years (Haines 2020; Hearn 2021). With many thousands of kilometres of track, this presents a significant challenge for asset managers. Additionally, a number of Rail Accident Investigation Branch (RAIB) reports have identified that landslide material affecting tracks originates from slopes outside the Network Rail boundary (Rail Accident Investigation Branch 2014). These slopes, known as Outside Party Slopes (OPS), can include cuttings, embankments, and natural slopes and are owned or managed by an external party. One approach to help give a national overview of the potential landslide hazard originating from OPS has been the development of a landslide susceptibility model for the entire railway network in Great Britain (Freeborough et al. 2016; 2019).

Future resilience and approaches

Climate projections suggest that Scotland will see an increase in the frequency and intensity of heavy rainfall events (UK Climate Projections 2018). Such changes are likely to influence the frequency and distribution of debris flow events. Improved understanding of the nature and distribution of sediment on slopes will be important in future hazard assessments. This is highlighted by a damaging debris flow that occurred at Loch Ailort in August 2016, where local ‘pockets’ of sediment in generally ice-scoured terrain provided source material for the failure (Palamakumbura et al. 2021). New mapping approaches employing geoanalytical and geostatistical techniques alongside remote sensing datasets and field observations provide one possible solution to improving our understanding of spatial sediment distribution on such hillslopes (e.g. Williams et al. 2020). At the same time, new strategies for detecting early signs of slope instability are being developed, such as terrestrial laser scanning (Sparkes et al. 2018). One approach that has shown particular promise at the A83 Rest and Be Thankful site, is the use of vector tracking analysis on live-streamed time-lapse imagery; which picked up precursor slope movement from images prior to a larger debris flow event (Khan et al. 2021).

In addition to onshore slope instability, recent multibeam surveys of Scottish sea lochs have identified a number of subaqueous mass movements (Stoker et al. 2010; Carter et al. 2020) (Fig. 18.9). The sea lochs of western Scotland have similarities with the fjords of Norway, Alaska and Canada where submarine landslides have led to loss of life and damage to infrastructure (such as cables and pipelines) (Longva at al. 2003; Carter et al. 2014). There is uncertainty surrounding the triggers for the subaqueous mass flow events identified so far in Scottish sea lochs, although factors such as glacier retreat, degassing of biogenic sediments, and anthropogenic activity have been discussed (Carter et al. 2020). Currently, the small database limits our understanding of the extent and nature of subaqueous landslides in the near-shore environment, although new surveying will improve this picture.

Water management and resilience

Managing water in a changing environment

The management of surface water in Scotland, including flooding, is a significant and well-known challenge for responsible authorities. Scotland’s climate has already changed over the last century, and it now has drier summers and wetter winters (Critchlow-Watton et al. 2014). The future projected climate changes and intensification of rainfall patterns will further extend these challenges (UK Climate Projections 2018). Development in the future will increasingly need to find ways to mitigate and adapt to climate change. The latest National Flood Risk Assessment carried out by SEPA in 2018 predicts the number of properties exposed to surface water flooding will increase from 210,000 to 270,000 by 2080 under a 1:200 year event scenario (Scottish Environment Protection Agency 2018, Scottish Government 2021$_a$). Therefore, climate change is driving an increased exposure in flood risk.

Changes in how we use land and how we manage it, will also have an important role in determining water resilience and how we need to manage water resources (Critchlow-Watton et al. 2014). The densification of towns and cities (see Topic Box 18) is, for example, adding to pressure on surface water drainage systems that are already at capacity (Scottish Environment Protection Agency 2021). As result, urban areas in Scotland in particular face mounting challenges with surface water drainage and related flooding. Concerted effort across all sectors through the planning process will be required to ensure that new development is appropriately sited and designed in order to create future sustainable places (Scotland’s Infrastructure Commission 2020).

The Flood Risk Management (Scotland) Act 2009 has meant a lot of progress has been made in Scotland in understanding the impact of flooding and how it can be managed (Scottish Environment Protection Agency 2022$_b$). Integrated water management approaches at a catchment-level are supported by the development of Scotland's River Basin Management Plans under the Water Framework Directive (Water Environment and Water Services (Scotland) Act. 2003). Increasingly, stakeholders are looking at how blue-green infrastructure; and how natural flood management approaches can help support water management in Scotland and improve climate resilience (Scottish Government 2020$_b$; Scotland's Infrastructure Commission 2020; Scottish Environment Protection Agency 2021). Geology plays an important role in the effectiveness of these approaches, as discussed in the following sections of this chapter.

Sustainable drainage

Surface water drainage systems, also referred to as Sustainable Drainage Systems ('SuDS') or Blue Green Infrastructure, manage rain and surface water in a way that mimics natural drainage. In doing this, SuDS aim to reduce surface water flooding, improve water quality and protect and enhances both the built and natural environment (Scottish Government 2018$_b$). The systems achieve this by either storing or re-using surface water at source, or reducing flow rates to watercourses.

As a result of rising surface water management pressures, particularly in urban areas, SuDS schemes are now mandatory for managing surface water drainage from all new developments in Scotland (Water Environment and Water Services (Scotland) Act 2003). This helps support an approach of no new water (or surface water connections) draining into the combined sewers network (Scottish Water 2017).

SuDS come in a range of forms, including: retention systems or wetlands that delay the discharge of surface water; vegetated swales that remove pollutants from surface water prior to discharge to watercourses or aquifers; permeable pavements and green roofs; and infiltration trenches and soakaways that mimic natural recharge, allowing water to soak into the ground. Often a SuDS design will use several of these techniques in a management chain. Of the 767 SuDS sites in Scotland at the end of 2001, the most widely used were filter drains, infiltration trenches and permeable pavements (Wild et al. 2002) and this persists to present day (McDonald 2018).

Infiltration SuDS are encouraged by authorities in Scotland where there will be no adverse impact on water quality and where local ground conditions allow. These drainage systems directly infiltrate surface water to the subsurface, giving the overall advantage of reducing the amount of surface water to be managed. However, it is important the systems do not inadvertently lead to an increased risk of groundwater flooding, negatively impact water quality, or incur ground instability issues. For example, within post-industrial brownfield sites, which many development proposals relate to, there is a risk of mobilising contaminants still present in the ground to groundwater or surface water through the drainage design, which requires detailed consideration. Site investigation and site-specific risk assessment help identify the risks associated with this; and whether remediation and/or a modified SuDS design is required as part of development proposals (Woods-Ballard et al. 2015).

Contaminated runoff from certain land-uses can also cause water pollution through drainage schemes without appropriate mitigation; for example, hydrocarbons present in runoff from lorry parks or chemical usage within industrial settings could cause contamination of underlying groundwater. The SEPA assess acceptability of pollution risk from SuDS through the authorisation process under the 2011 Water Environment (Controlled Activities) (Scotland) Regulations (CAR).

The geology and setting of any site need to be understood, in order to ensure infiltration drainage systems are implemented only where the ground conditions are appropriate, and in which the systems can perform well and can be easily maintained (British Geological Survey 2015; Woods-Ballard et al. 2015). For example, to reduce groundwater flooding risks, infiltration-based schemes should not be installed where the groundwater level is within a metre of the base of the infiltration component, even after periods of prolonged wet weather. For infiltration-based SuDS to work effectively, the topsoil and the underlying geology need to be free draining. If they are used on less suitable, lower permeability ground, this can result in failure of the system causing it to flood and removing any benefits from pollution attenuation (Wild et al. 2002). Geotechnical engineers and engineering geologists often support drainage specialists in considering site constraints such as ground stability and the infiltration capacity of the subsurface. An important consideration in the Midland Valley area due to the mining legacy, is also the potential or SuDS schemes to increase the rate of rise in mine water levels and stability implications.

Natural flood risk management

With growing recognition of the limitations and costs of traditional flood management approaches in the face of climate change, ‘Natural’ flood risk management (NFM) is another approach in which there has been interest and application over the last decade. NFM promotes a catchment-wide approach to interventions aimed at reducing surface runoff (e.g. tree planting), and slowing the flow of water in rivers (e.g. re-meandering). Policies such as the European Union (EU) Water Framework Directive and the Flood Risk Management (Scotland) Act 2009 have driven these new approaches across the UK (Rouillard et al. 2015), along with guidance on implementation (e.g. Scottish Environment Protection Agency 2015).

There are now over 94 NFM projects in the UK, but evidence for NFM effectiveness remains low (Dadson et al. 2017) given uncertainties in quantifying the impacts of interventions at large scales and how catchments respond under different conditions. Overcoming these challenges will require a better understanding of both surface and sub-surface hydrological processes at the catchment scale, and how these respond to human pressures such as land use change and climate change.

Geology plays a fundamental role in controlling catchment hydrological processes, influencing the evolution of soils, how catchments store and release water, and the geometry of river networks. While NFM interventions such as tree planting cannot significantly alter these geological controls, understanding how they interact, and which controls dominate where, is a key question for NFM implementation. The efficacy of tree planting or other changes in land management to control runoff generation is likely to be highly dependent on soil type and underlying geology. Recent efforts to produce NFM ‘opportunity maps’ have therefore drawn on geological information to assist with broad scale NFM planning (Environment Agency 2018), although at relatively low resolution.

These interactions between catchment land use change and geology are being explored in the Eddleston experimental NFM catchment located in the Scottish Borders. This is one of the UK’s largest and longest running NFM pilot sites where interventions including tree planting, river re-meandering, holding ponds and in-stream woody debris dams have been put in place (Black et al. 2021). Research in the catchment has demonstrated the importance of geology in controlling catchment runoff mechanisms and the implications this has for NFM implementation. At the catchment scale, experiments using tracers to investigate the sources of water in rivers during storm events have highlighted the importance of water already stored in the catchment (within soils and rocks) in storm runoff, and suggest that soils and geology have greater influence than forest cover on the fraction of rapid runoff (Fig. 18.10) (Peskett et al. 2021). These findings correspond with work in other

Scottish catchments suggesting that soils and underlying superficial deposits are the dominant control on the time taken for water to reach rivers, even in areas with steep slopes (Soulsby et al. 2006; Tetzlaff et al. 2007).

At the site level, experiments in Eddleston have shown that while trees have impacts on infiltration, their impacts on water storage and groundwater dynamics are small and sensitive to the underlying soil type and geology (Peskett et al. 2020). Research in the catchment has also demonstrated how geological structure influences the interaction between hillslope runoff and floodplain groundwater dynamics, which is important for planning NFM interventions on flood plains (Ó Dochartaigh et al. 2018). These findings are particularly interesting in a Scottish context, given that they highlight the importance of sub-surface flow and groundwater even in catchments situated on poorly permeable bedrock that are common across Scotland. They also highlight the need to consider geological factors in other contemporary areas of Scottish policy, such as plans to increase tree planting to 18,000 ha per year in 2024-5 and new regional scale partnerships for integrated land use planning that help deliver national climate change targets (Scottish Government 2020$_c$).

Role of geology in sustainable future places

This chapter provides an illustration to some of the ways in which geology has, and continues to, play a significant role to the development of Scotland’s infrastructure, cities and catchments. It has also been a founding influence on our industries and cultural heritage.

Geologists provide an important contribution and knowledge base to informing future sustainable development. Reducing emissions and managing effects of climate change will require transformative approaches in how we plan future development and in how we manage the built and natural environment. To achieve vibrant low carbon places, Scotland’s national planning framework and local development plans will have to make complex choices over the next several decades around how we use resources (Scottish Government 2021$_b$).

Maintaining and improving environmental quality will be important for ensuring resilient ecosystems, communities and economies. How we use land will also be an important cause of environmental change. Scotland’s geology has underpinned the huge diversity of landscapes, soil, habitats and natural resources that we observe today. It will continue to play a significant role in creating future resilient and sustainable places.

END TEXT

Figures

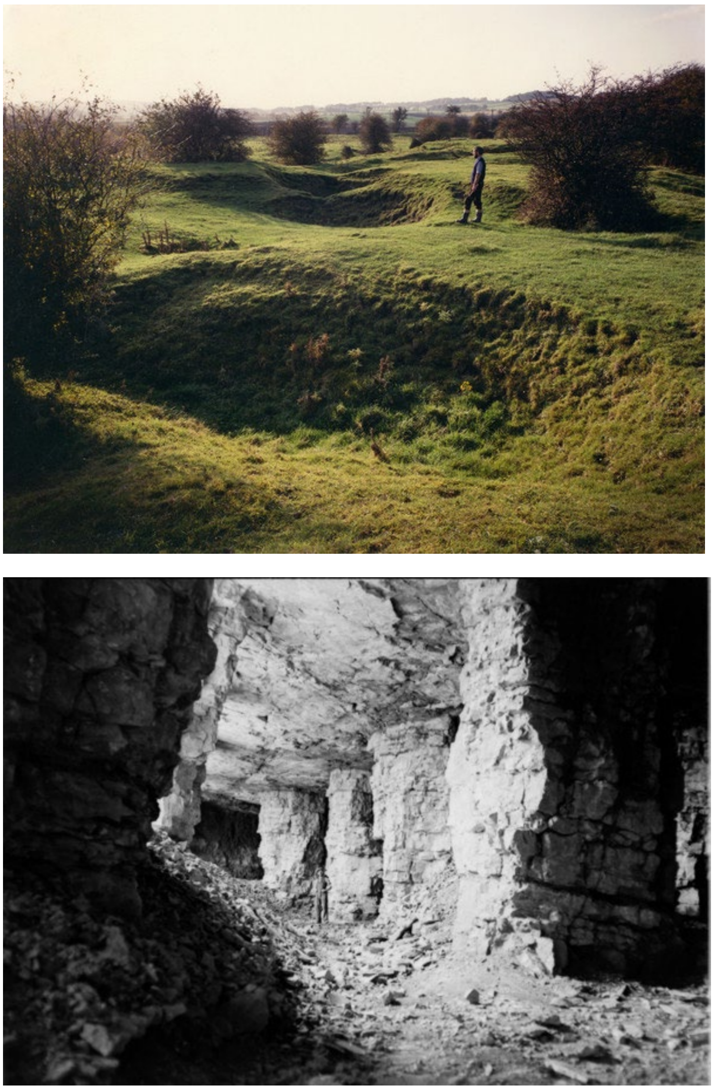
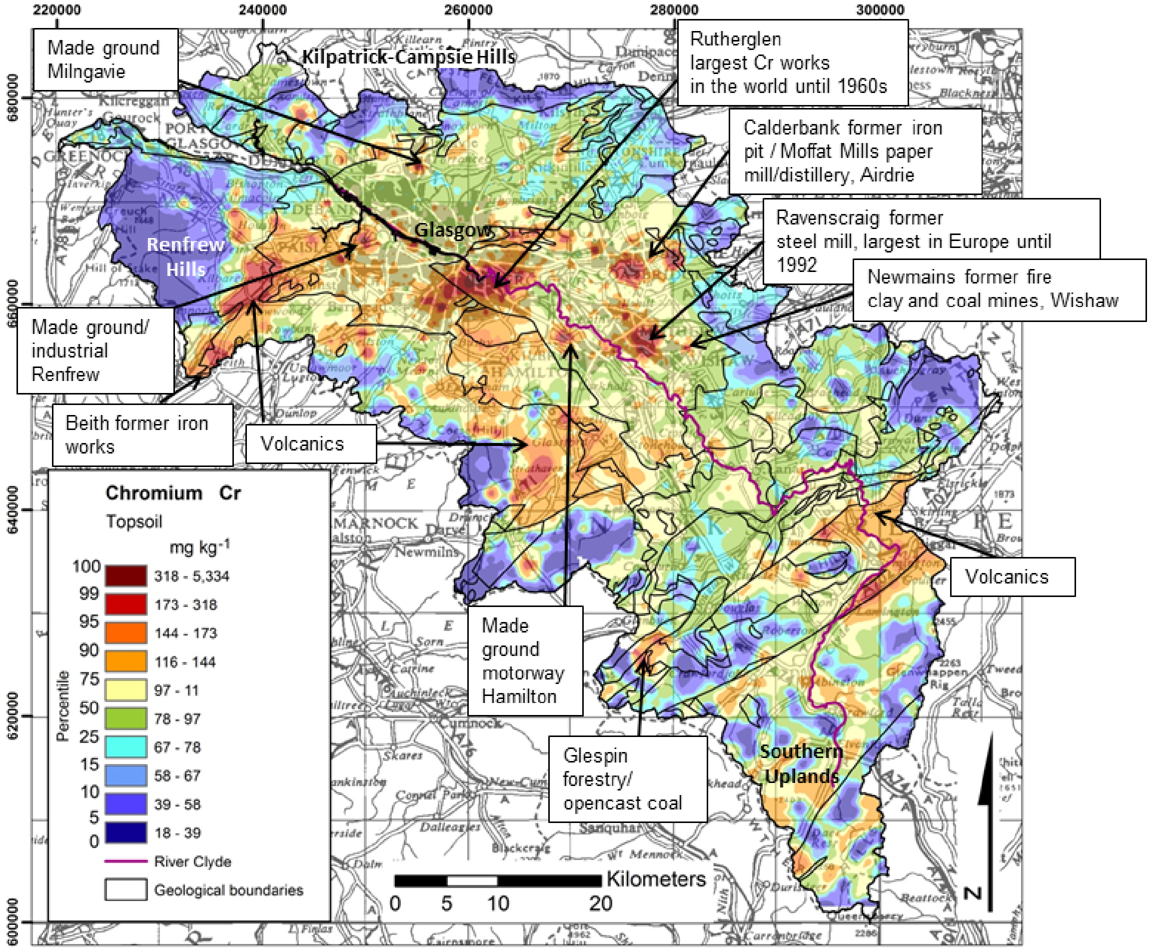


Figure 18.1a & b

Figure 18.2

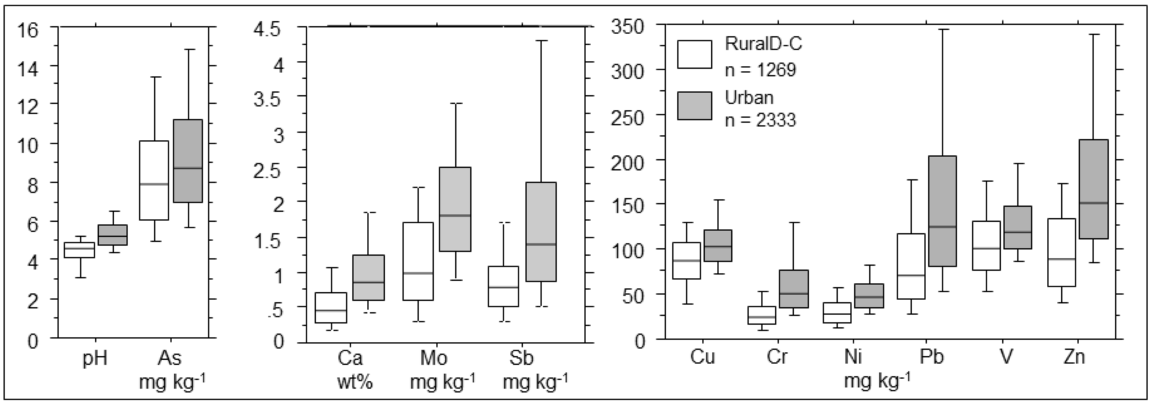
Fig 18.3



Soil Data BGS, © NERC, UKRI. Contains Ordnance Survey data © Crown Copyright and database rights 2021

Fig 18.4

Fig 18.5



Rural$_{D\text{-}C}$ = samples over Devonian and Carboniferous rock types as rural background

Fig 18.6

Fig 18.7

Fig 18.8

Fig 18.9

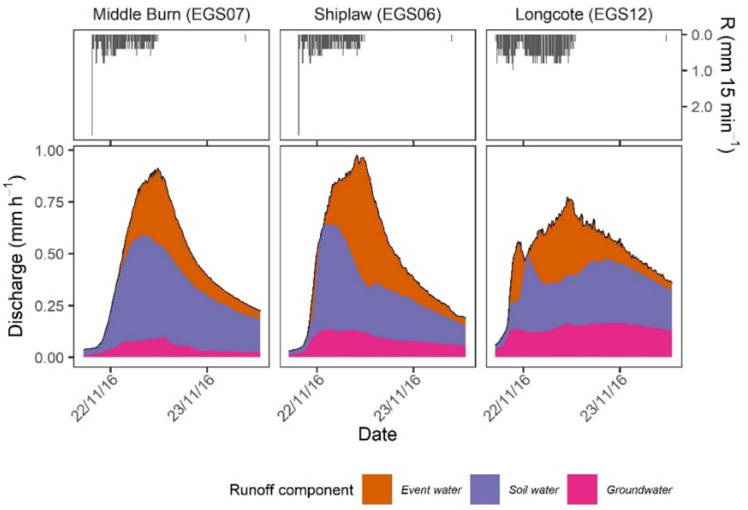


Fig 18.10

Acknowledgements

Figure captions

Fig. 18.1 – a: Areas of subsidence near Broxburn, West Lothian. These crown holes have been caused by strata collapsing into shallow ‘stoop and room’ workings in the Broxburn Shale (image UKRI © British Geological Survey); b: Stoop and room workings in limestone, Gorebridge, Mid Lothian (image UKRI © British Geological Survey).

Fig. 18.2 – A programme of drilling and grout filling shallow mine workings in a residential area of Glasgow City (image © Glasgow City Council).

Fig. 18.3 – Soil sampling is used to inform management and remediation design strategies for contaminated land (image © Scottish Environment Protection Agency).

Fig. 18.4 – Map of total chromium concentrations in the River Clyde catchment and Glasgow conurbation topsoil (from Fordyce et al., 2019, UKRI © British Geological Survey. Contains Ordnance Survey data © Crown copyright and database rights 2021. Ordnance Survey Licence No. 100021290).

Fig. 18.5 – Recent in-situ remediation soil washing and stabilisation works in the East End of Glasgow prior to new development on formerly impacted industrial sites (image © Glasgow City Council).

Fig. 18.6 – Box and whisker plots showing the 10th, 25th 50th 75th and 90th percentiles of parameter distributions in rural topsoil collected over Devonian–Carboniferous rock types and in the River Clyde catchment and Glasgow conurbation topsoil (Modified from Fordyce et al. 2019).

Fig. 18.7 – Aerial image of ongoing development works in 2021 at the Sighthill Transformation and Regeneration Area (TRA) in the centre of Glasgow City (image © Glasgow City Council).

Fig 18.8 – A photograph of one of the debris flows that trapped motorists on the A85 road in Glen Ogle in August 2004 (image UKRI © British Geological Survey).

Fig 18.9 – An image showing a subaqueous landslide in Holy Loch, western Scotland (image UKRI © British Geological Survey).

Fig 18.10 – The figure shows different runoff components (derived from isotope and geochemical tracer data) during a storm in streams from three contrasting sub-catchments in the Eddleston pilot. Middle Burn and Shiplaw are very similar, glacial till dominated, paired catchments, although Middle Burn has much higher forest cover. Longcote is a steeper catchment with very low forest cover, limited glacial till. Data from this storm and other storms sampled during the research suggested that forest cover has some impact on reducing rapid runoff of rainfall from storm events, but geology and associated overlying soils have a greater impact even in steep catchments on poorly permeable bedrock. (from Peskett et al. 2021).

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