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Explanatory notes to accompany the Groundwater Vulnerability Index GIS for Stirling Council

Groundwater Systems and Water Quality Programme

A report for Stirling Council

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Explanatory notes to accompany the Groundwater Vulnerability Index GIS for Stirling Council

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1 Introduction

These notes are designed to accompany the ArcView geographical information system (GIS) format groundwater vulnerability index maps produced by the British Geological Survey (BGS) for Stirling Council. The maps are based on digital geological information for both bedrock and superficial deposits: they do not take account of soil cover. They cover the whole of the Stirling Council area plus a 2 km 'buffer zone' around the area to account for peripheral data and allow for more meaningful interpretation at Council boundaries.

The purpose of the GIS maps is to show, in broad terms, the vulnerability of groundwater to pollution. Groundwater is contained within aquifers of various types. Abstractions from these aquifers provide water for potable supplies and various domestic, industrial and agricultural uses. Some highly permeable aquifers are very productive and of regional importance as sources for public water supply, while less permeable formations are still of local importance. Groundwater also provides the baseflow to surface watercourses. Groundwater is typically of high quality and often requires little treatment before use. However, it is vulnerable to contamination from both diffuse and point source pollutants, from direct discharges into groundwater and indirect discharges into and onto land. Aquifer remediation is difficult, prolonged and expensive, and, therefore, the prevention of pollution is important.

The approach and classifications used in the production of the groundwater vulnerability index GIS can also be used in the assessment of specific land use practices, proposed developments and land use changes over aquifers where these could have an impact on groundwater quality. More detailed site specific assessment of vulnerability will be required where it is considered that development may have an impact on groundwater quality.

This GIS and printed maps are a compromise between the representation of natural complexity and the simplicity of interpretation at a scale of 1:50,000. This places limitations on the resolution and precision of map information. In this case, there is a wide variety of geological strata and potential pollutants, and the classification used is, of necessity, generalised. Individual sites and circumstances will always require further and more detailed assessment to determine the specific impact on groundwater resources. The map coverages in the GIS only represent geological conditions (bedrock or superficial) at their upper surface. Where these formations have been disturbed or removed, for example, during mineral extraction, the vulnerability class may have been changed. Hence, where there is evidence of disturbance, site specific data need to be used to determine the vulnerability of the groundwater.

The methodology used has not included consideration of the soils. The overall permeability of each geological unit has been interpreted, enabling an assessment of the vulnerability of groundwater occurring under the Stirling area. The vulnerability classification does not follow the methodology devised for published groundwater vulnerability maps used by the Scottish Environment Protection Agency (SEPA). The latter methodology includes a system in which superficial geology and soil data are used to produce a series of detailed vulnerability classifications. The current methodology, however, provides a broad-based view of both the vulnerability of groundwater and the location of the more permeable aquifers under the Stirling area.

The data used for the compilation of the vulnerability GIS use part of the 1:50,000 DigMap solid and drift geology coverage. The 'thick drift' polygons found in the GIS were interpreted and drawn based on BGS borehole records. The GIS and associated maps should not be used at scales larger than 1:50,000.

There are three themes within the GIS: Solid Geology Permeability, Drift Geology Permeability and Aquifer Vulnerability, formed by combining solid and drift geology permeability.

2 Overview of solid and drift geology

The oldest rocks in the district are Precambrian metamorphosed sedimentary rocks to the north of the Highland Boundary Fault. These were originally deposited in a large, rapidly sinking basin and later subjected to powerful tectonic movements during the Caledonian orogeny in early Palaeozoic times, during which they were deformed, metamorphosed and uplifted to form high mountains.

By Devonian times, the Highland area in the north of the Stirling district comprised an almost peneplained mountainous tract bounded to the south by the subsiding trough of the Midland Valley. A sequence many thousands of metres thick of Devonian sedimentary and volcanic rocks accumulated in this trough, the former largely derived by erosion of distant Scandanavian mountains. This sedimentary phase was interrupted by further tectonic disturbance, which caused deformation of older Devonian rocks. Further deposition after this deformation period laid down Upper Devonian sandstones and cornstones and Lower Carboniferous sedimentary sequences. Carboniferous rocks are largely cyclic, with repeating units dominated by sandstones and shales with subordinate limestone and coal beds. Volcanic activity during the Carboniferous resulted in the creation of basaltic lavas and doleritic intrusive sills, and volcanic agglomerates.

Following the Carboniferous no rock formations survived erosion until Quaternary times, when glacial and post-glacial activity resulted in the deposition of extensive glacial till (boulder clay) and glaciofluvial sands and gravels, and in some areas, raised marine deposits associated with higher sea levels. Since glaciation, deposition has been largely confined to river valleys where extensive alluvial deposits have accumulated, and to the accumulation of peat across much of the southern part of the district.

3 Aquifer permeability and vulnerability

The permeability of a geological unit determines the ease with which groundwater can flow through it. In sedimentary rocks such as sandstone, groundwater flows along intergranular flowpaths between individual sand grains as well as through fractures and other voids. Sandstones can vary greatly in permeability but are often among the most highly permeable and porous (able to store groundwater) rock units. In limestones, groundwater flow and storage is almost entirely within fractures. The rock units with the highest permeability in the Stirling district are Devonian sedimentary sequences (largely sandstone, but also mixed sequences of sandstone with subordinate siltstone and mudstone) and the Carboniferous Passage and Upper Limestone formations, which contain a number of thicker sandstone units.

Apart from these two, Carboniferous sedimentary sequences in the region are considered to be moderately permeable, because sandstone units in the sequences are thinner and/or less abundant, and because mudstone bands are often more common, acting as barriers to vertical groundwater movement. Other rocks of moderate permeability in the district are Devonian conglomerates, and ancient Cambrian and Ordovician limestones and Precambrian metamorphosed limestones and calcareous pelites. Although ancient rocks are generally of low permeability, calcareous rocks such as these can develop significant secondary permeability.

Most of the low permeability geological units in the region are metamorphic and igneous rocks, which have little or no primary (intergranular) permeability, and in which groundwater storage and flow is confined to thin and limited weathered zones and/or fractures, which makes these rocks poor aquifers. Examples in the Stirling district are Precambrian metasediments and metamorphosed igneous rocks, and varied igneous rocks ranging from Ordovician to Devonian in age. Other low permeability rocks in the Stirling district are Carboniferous mudstones, including the Ballagan Formation.

Superficial deposits vary in permeability from coarse gravels and blown sand, which are highly permeable, to sandy silts, which may have moderate permeability, to virtually impermeable lacustrine, marine or glacial clays. Much of the southern part of the district is covered by glacial till, often infilling deep ancient valleys or forming characteristic 'hummocky ground' or drumlins on lower ground, and which generally acts to impede groundwater recharge. Patterns of modern and post-glacial drainage are picked out in the distribution of highly permeable alluvial and glaciofluvial sequences, dominated by sand and gravel with subordinate silts and clays. In the southeastern part of the district, are small outcrops of similarly highly permeable raised marine deposits. The northern part of the district is dominated by mixed glacial deposits, which generally have a large proportion of sand and gravel interbedded with clay, resulting in overall moderately permeable sequences.

The groundwater vulnerability index map is based on the general assumption that where more highly permeable formations crop out at the ground surface, water can infiltrate at a faster rate to the water table compared to less permeable formations. Where less permeable formations crop out at the surface, such as clayey drift deposits or crystalline igneous or metamorphic bedrock, a larger proportion of the rainfall falling on the ground will flow directly to surface watercourses instead of soaking into the ground. More permeable formations are, therefore, more vulnerable to contamination. Permeable drift formations can act both as aquifers in their own right, and as pathways for groundwater to reach underlying bedrock (solid) aquifers. Areas where high permeability drift overlies low or moderate permeability bedrock; where high permeability drift overlies high permeability bedrock, and where high permeability bedrock outcrops at the surface, are, therefore, treated as equally vulnerable on the vulnerability map.

Where a thick clayey drift deposit overlies a permeable aquifer, the clay can act to impede the downward movement of pollutants, and thus as a protective cover. However, where there are relatively thin sandy clay layers (generally less than 5 metres), a certain amount of recharge to deeper aquifers will occur. The GIS distinguishes where low permeability drift (generally till but also peat and marine clays) overlies bedrock aquifers, shown in pink, but it should not be assumed that this low permeability drift layer always acts as an effective barrier, as there may be significant variations in the thickness of the drift.

The detailed identification, location, thickness and extent of any clayey deposits can be difficult due to a lack of data. However, an interrogation of BGS borehole records has been made and these records interpreted to show where there is a strong probability that there is greater than 5 metres thickness of clay in the drift sequence. This is shown on the maps as a transparent hatched overlay. This information is limited only to where borehole geological data are present, and, therefore, represents the likely minimum extent of thick clayey drift, and not the complete picture.

3.1 SOLID GEOLOGY PERMEABILITY

The solid bedrock has been divided into three major groups based on permeability (High, Moderate and Low), shown on the map in Figure 2. There is a fourth category to cover two small areas in the northeast of the district where solid bedrock is classed as 'unknown' on the 1:50,000 digital geology coverage. The major groups include the following rock units:

High Permeability:

(Red on GIS)

- Devonian sandstones (e.g. Kinnesswood and Teith Sandstone Formations)
- Carboniferous cyclic sedimentary rocks (largely sandstone) (e.g. Passage and Upper Limestone Formations)

Moderate Permeability:

(Yellow on GIS)

- Carboniferous limestones and cyclic sedimentary rocks (mixed sequences of limestone, sandstone and siltstone) (e.g. Limestone Coal and Lower Limestone Formations and numerous individually named limestone formations)
- Lower Devonian conglomerates (e.g. Craig of Monievreckie Conglomerate)
- Precambrian metalimestones (e.g. Loch Tay Limestone Formation)

Low Permeability:

(Green on GIS)

- Carboniferous basalts, dolerites and volcanic agglomerates (e.g. Clyde Plateau Volcanic Formation)
- Precambrian metamorphosed sedimentary rocks (e.g. Ben Lawers Schist, Ben Lui Schist and Ben Ledi Grit Formations)
- Carboniferous and Lower Devonian mudstones and siltstones (e.g. Cromlix Mudstone and Ballagan Formations)

3.2 DRIFT GEOLOGY PERMEABILITY

Drift deposits are also divided into three main groups according to permeability (High, Moderate and Low), shown on the map in Figure 3. A fourth category covers a number of very small areas in the south of the district where drift geology is classed as 'unknown' on the 1:50,000 digital geology coverage. There are two parts of the district, on the eastern and western edges, where drift geology remains largely unmapped, and these are indicated by a 'stipple' overlay on the GIS maps. Areas uncoloured on the drift geology permeability map are those areas with no drift cover.

The drift coverage in the Stirling district is highly variable, and some of the drift mapping is relatively old and does not account for recent advances in drift typology. Many of the drift units are internally heterogeneous, often composed of sands, gravels, silts and clays in varying amounts at different locations, but mapped as a single unit. Parts of such a unit may, therefore, be relatively permeable, while other parts are largely impermeable. The classifications used in the groundwater vulnerability GIS and map and described below represent the best attempt at interpreting such drift units in terms of their overall permeability. In most cases this has been done using a precautionary principle, so that, for example, hummocky glacial deposits comprising a mixture of diamicton[1] with subordinate sand and gravel, which are considered as a whole to have generally low permeability but which may be dominated by sand and gravel at certain locations, are classified as having moderate permeability. Another example is alluvial sands or gravels with silts and clays, thought to be largely moderately permeable but with pockets of highly permeable sands or gravels, which are classified as having overall high permeability.

[1] A general term for any unsorted, unstratified sediment regardless of its genesis. Diamicts may be formed in various situations: glaciation, mudflow, landslide, avalanche, and turbidity current. Till is a special kind of diamicton that was formed directly from glacier ice. The terms diamictite and tillite are used for the ancient, consolidated equivalents of diamicton and till sediments.

The groups include the following units:

High permeability:

(Red on GIS)

- Alluvial, glaciofluvial, raised marine and river terrace deposits - sands and gravels, and mixed sequences of dominantly sand and gravel with subordinate silts and clays

Moderate permeability:

(Yellow on GIS)

- Hummocky glacial deposits, ice contact deposits and glacial till/moraine deposits – mixed sequences of diamicton, sand and gravel

Low permeability:

(Green on GIS)

- Glacial till (boulder clay)
- Glaciolacustrine, lacustrine, intertidal, raised marine and alluvial clays and silts
- Peat

4 The groundwater vulnerability index map

The basic assumption made in defining the three vulnerability index categories shown in the GIS and printed map (see Figure 4) is that that high aquifer permeability equates with a high groundwater vulnerability index: i.e. pollutants at ground level are able to migrate downwards more easily and in greater volume where permeable material such as gravel or sandstone is present. Formations of this type are, therefore, more vulnerable than others.

The vulnerability map incorporates both the solid and drift permeability classifications previously described to produce twelve combinations of solid and drift permeability. These combinations are referred to by two-letter codes: 'HH', 'HM', etc. The letters are as follows:

H High permeability
M Moderate permeability
L Low permeability
N No drift cover present over the bedrock formation
U Where geology is classified as unknown on the digital geology coverage

The first letter in the code refers to the solid (bedrock) permeability and the second letter to the drift permeability. For example, 'HM' refers to High Permeability Solid rock overlain by Moderate Permeability Drift.

These twelve combinations have then been grouped into three main categories of groundwater vulnerability labelled 'High' (red on map), 'Moderate' (yellow) and 'Low' (green). A sub-category, (pink on map), shows areas where a highly permeable bedrock aquifer is covered by low permeability drift (till/boulder clay or other clayey drift). It should be noted that the thickness, and therefore the effectiveness, of this clay as a barrier to pollution is uncertain.

The vulnerability categories are summarised in Figure 1. Anywhere in the Stirling area where there is a highly permeable aquifer present beneath the ground surface, either bedrock or drift, the map is coloured red or pink to denote high vulnerability. Aquifers (bedrock or drift) of moderate permeability are coloured yellow to indicate an overall moderate vulnerability (except where a moderately permeable aquifer is combined with a highly permeable aquifer). Areas where low permeability formations (bedrock or drift) occur, where groundwater is least vulnerable, are coloured green. There still remains a risk of groundwater pollution within areas classified as moderate or low vulnerability, but owing to reduced permeability, the risk, and therefore vulnerability of groundwater, is considered to be lower.

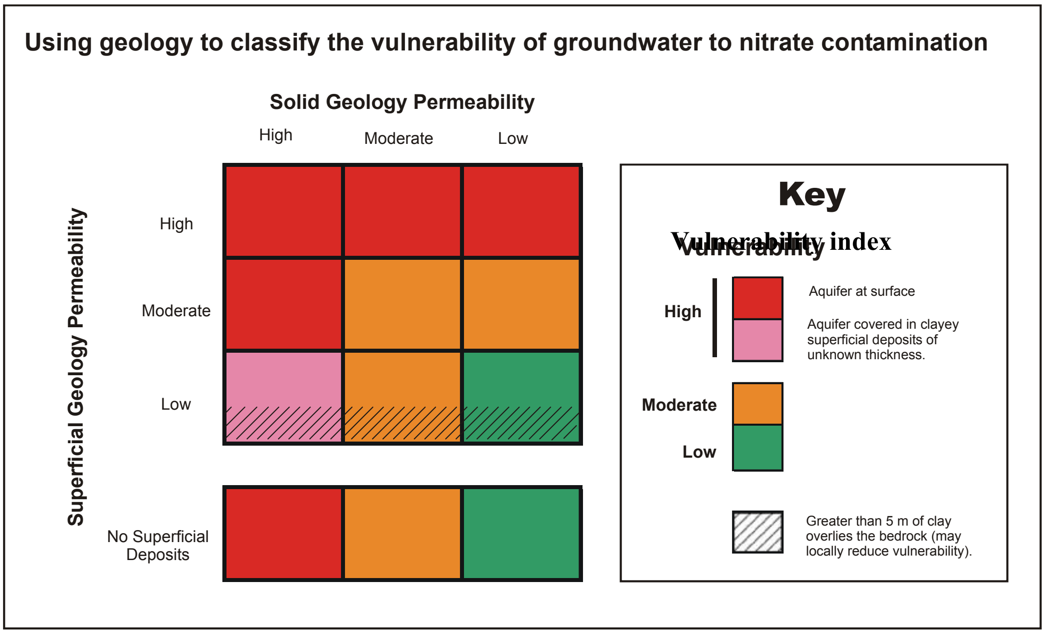


Figure 1 **Illustration of groundwater vulnerability index categories based on solid and drift geology**

There are a number of small areas where drift geology is unknown (see section 3.2). These areas are distinguished on the groundwater vulnerability index map because it is impossible to determine groundwater vulnerability (in either solid or drift aquifers) without taking drift permeability into account. There are also a few very small areas where solid geology is unknown (see section 3.1).

5 Drift Thickness

The final overlay, shown on the GIS maps as a transparent hatching, shows where there is a strong probability that a cumulative thickness of 5 metres or more of clay is present in the drift sequence. Because the drift sequence can be highly heterogenous, high permeability sands and gravels may crop out at the surface while at depth there is a thick sequence of till or lacustrine clays. Any bedrock aquifers beneath these areas will receive a certain amount of protection from the clay layer in the drift, which will inhibit recharge to the bedrock aquifer. The information to create this overlay is derived from BGS borehole archives. It should be noted that where no hatching is present it does not necessarily mean that there is less than 5 metres thickness of clayey drift. In many areas a lack of borehole records may make it impossible at present to identify the presence of clays. In addition, even where a total of 5 metres or more of clay is present in the drift sequence, not all drift aquifers will necessarily receive protection, as they may overlie much or all of the clay.

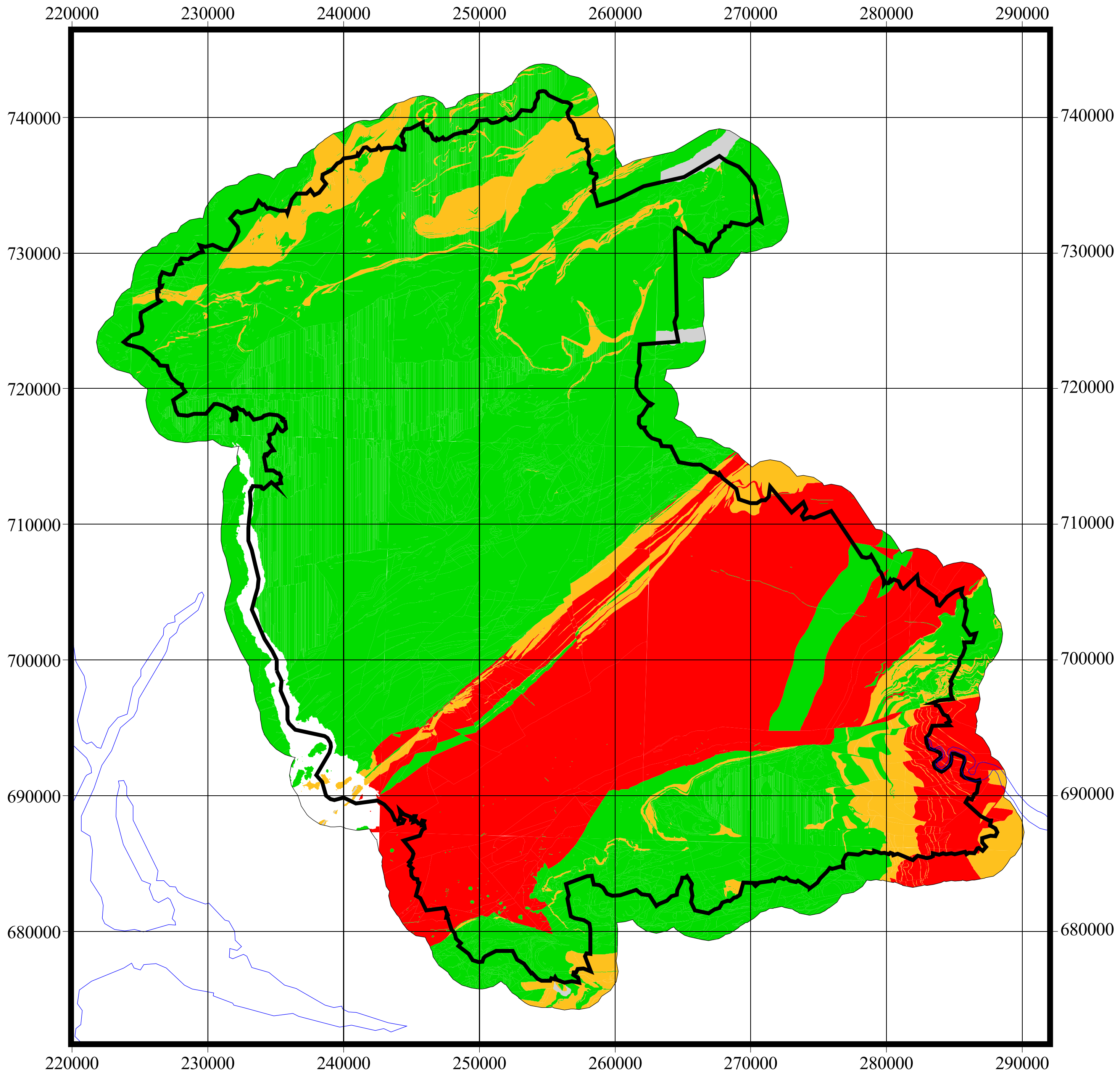
6 Water Boreholes

The GIS also contains a shapefile showing the locations of known water boreholes in the Stirling district taken from the British Geological Survey Scottish Water Borehole database (Figure 5).

7 Copyright

References

FRANCIS E H, FORSYTHE I H, READ W A AND ARMSTRONG M. 1970. The Geology of the Stirling District: Memoirs of the Geological Survey of Great Britain (Scotland). British Geological Survey.



Legend

Coastline

County boundary

Solid geology permeability

High

Moderate

Low

Unknown Geology

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Figure 2 Stirling Bedrock Geology Permeability

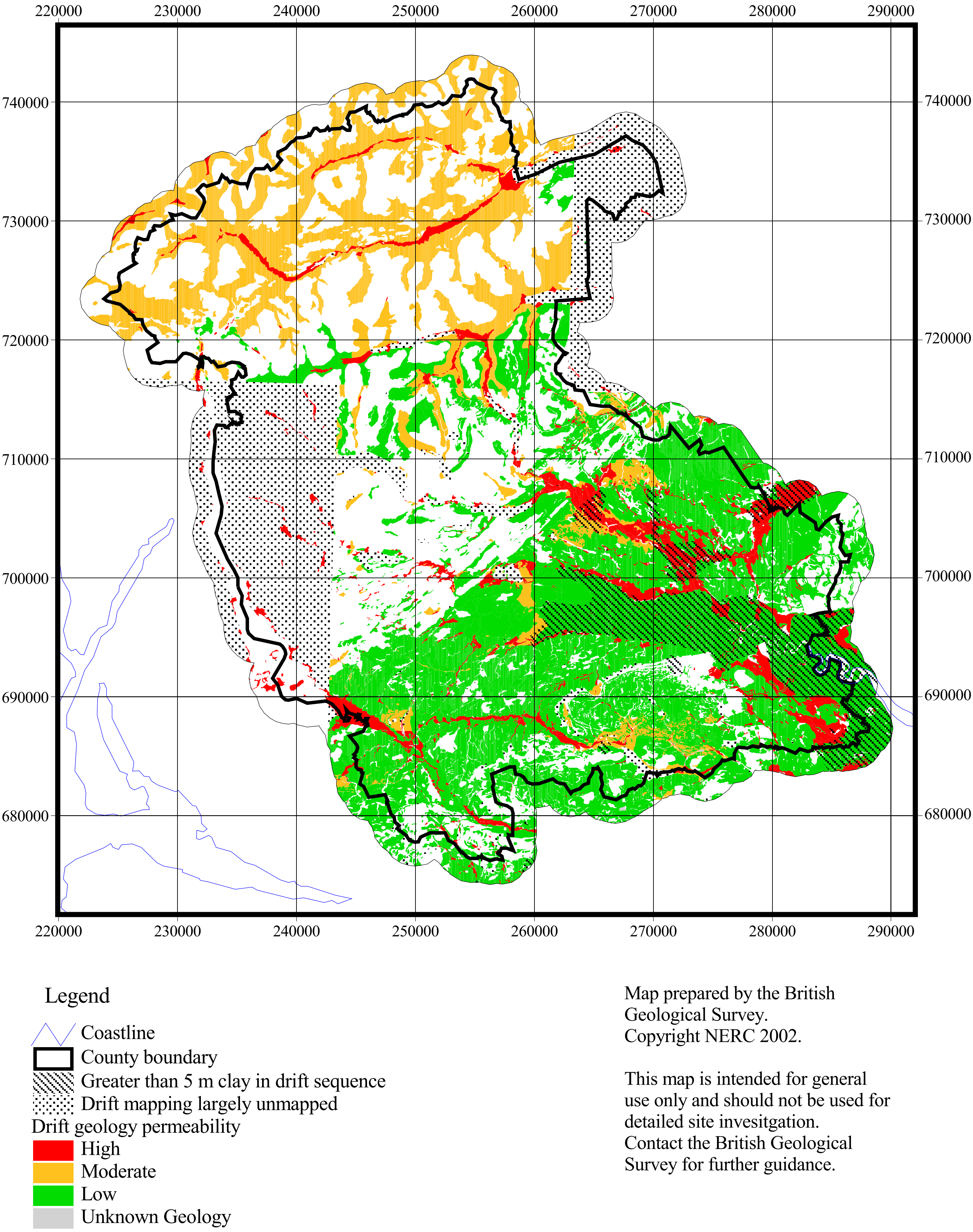

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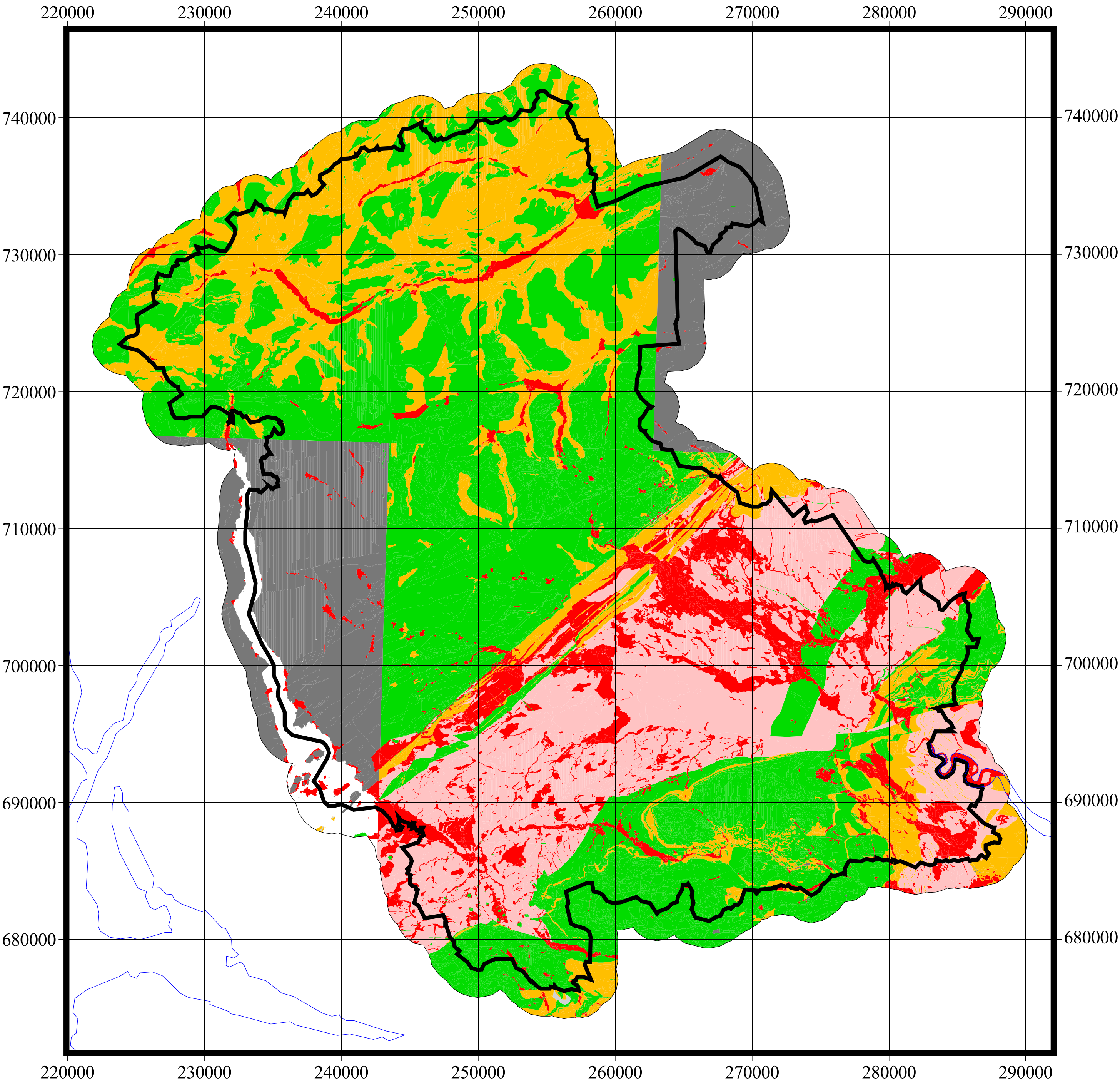
Figure 3 Stirling Superficial Geology Permeability



Legend

Groundwater Vulnerability Index

- HH HM HN HU LH MH
- HL
- MM MN ML LM
- LL LN
- UH UN UL
- MU LU UU

Coastline

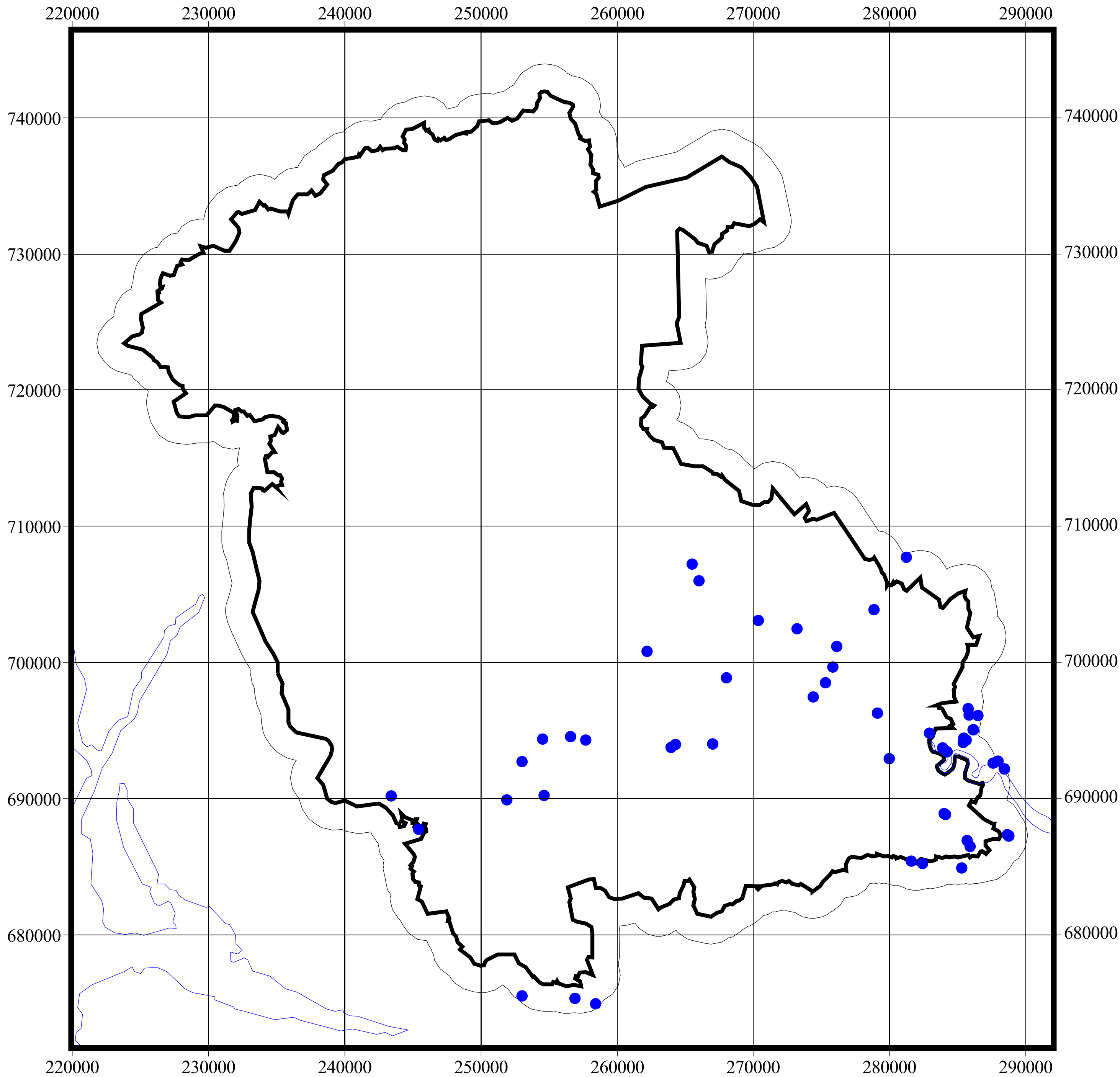
County boundary

This map is intended for general use only and should not be used for detailed site investigation. Contact the British Geological Survey for further guidance.

The first letter in the vulnerability combination corresponds with Solid Geology Permeability. The second letter corresponds with Drift Geology Permeability.

H = High
M = Moderate
L = Low
U = Unknown Geology (generally areas where drift mapping is unavailable at 1:50,000 scale)

Figure 4 Stirling Groundwater Vulnerability Index



Legend

Coastline

Boreholes from Scottish Water Boreholes Database

County boundary

Map prepared by the British Geological Survey.

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Figure 5 Known Water Boreholes in the Stirling District