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

Groundwater Systems and Water Quality Programme

A report for Fife Council

Research Report CR/03/031N

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Contents

1 Introduction

These notes are designed to accompany the ArcView geographical information system (GIS) format groundwater vulnerability index map produced by the British Geological Survey (BGS) for Fife Council. The map is based on digital geological information for both bedrock and superficial (drift) deposits. It covers the whole of the Fife Council area plus a 3 km ‘buffer zone’ around the landward boundaries to account for peripheral data and allow for more meaningful interpretation.

The purpose of the GIS map is to indicate, 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; other, less permeable formations, are of local importance for domestic, agricultural and industrial supplies. Groundwater also provides the baseflow to surface watercourses. Groundwater is typically of high quality and often requires little or no 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: therefore, the prevention of pollution is important.

The approach and classifications used in the production of the groundwater vulnerability index 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. There is a wide variety of geological strata and potential pollutants, and the vulnerability index classification 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) as mapped 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 collected and used to determine the vulnerability of the groundwater.

The overall permeability of each geological unit has been interpreted to produce an index of the vulnerability of groundwater occurring in Fife, and provides a broad-based view of both the vulnerability of groundwater and the location of the more permeable aquifers in Fife. The vulnerability index classification does not follow the methodology devised for an earlier published groundwater vulnerability map (NERC and MLURI 1998). The latter methodology includes an assessment of soil leaching potential, and combines data on superficial geology and soils to produce vulnerability classifications. The other main difference between the two maps is that the new GIS map gives equal weight to bedrock and drift aquifers, whereas on the earlier map the bedrock formation takes precedence if it is highly permeable.

The data used to interpret the groundwater vulnerability index are derived from the 1:50 000 DigMap bedrock and drift geology coverage. The GIS and associated maps should not therefore be used at scales larger than 1:50 000. Locations of thick clays have been interpreted and drawn based on BGS borehole records. Information on water boreholes is derived from the British Geological Survey Scottish Water Borehole database.

2 Overview of Bedrock and Drift geology

The oldest rocks that crop out in Fife are volcanic rocks, of Lower Devonian age, which are part of the Ochil Volcanic Formation. Earth movements later folded, faulted and uplifted these rocks, which were eroded to produce a subdued landscape. This was subsequently infilled by Upper Devonian sedimentary rocks, including fluvial sandstones of the Burnside and Glenvale formations and aeolian sandstones of the Knox Pulpit Formation.

Lower Carboniferous rocks were deposited in a low-lying alluvial coastal plain to marginal marine setting. They comprise sandstones, limestones and mudstones of the Kinnesswood, Ballagan and Clyde Sandstone formations. Above this, the Strathclyde Group comprises a cyclic sequence of mudstones, siltstones and sandstones with minor limestones and poor oil shales, formed by lacustrine-deltaic and fluvial depositional processes. During the remainder of the Upper Carboniferous, coal-forming swamp conditions were common, especially when the Limestone Coal Formation and Lower and Middle Coal Measures were laid down. Volcanic activity during the Carboniferous and early Permian resulted in the creation of lavas, intrusive sills, and volcaniclastic rocks.

During Quaternary glaciation, there was extensive deposition of glacial till: a stiff silty, occasionally sandy clay with numerous pebbles and boulders. During ice retreat, substantial volumes of glaciofluvial sands and gravels were deposited by meltwaters on top of the glacial till, and occasionally directly on bedrock. During this time, relative sea level was higher than today, and marine sediments were deposited over much of the Fife area, generally comprising a thin, discontinuous sheet of red clay. Thick deposits of glaciolacustrine clay also accumulated in Loch Leven after deglaciation. Since glaciation, deposition has been largely confined to river valleys where extensive alluvial deposits have accumulated, and to the accumulation of peat across the southern part of the district, although much of this has since been removed by human activity.

3 Aquifer Permeability and Groundwater 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. If these fractures are well developed, limestones can be highly permeable.

The rock units with the highest permeability in the Fife district are Upper Devonian sandstones, the Knox Pulpit, Glenvale and Burnside Formations; Lower Carboniferous sandstones of the Kinnesswood Formation; and Carboniferous sedimentary rocks (dominantly sandstones) of the Passage Formation.

All other Carboniferous sedimentary sequences in Fife are considered overall to be moderately permeable, although there can be significant variation in the aquifer properties of Carboniferous rocks, and some formations may show high permeability locally. These sequences often have thin or discontinuous sandstone units, and mudstone and siltstone bands are common, acting as barriers to vertical groundwater movement. Limestones within the sequences are often relatively hard and unfractured. Lower Devonian conglomerates are also classed as moderately permeable.

The Devonian and Carboniferous igneous rocks in Fife have little or no primary (intergranular) permeability, and groundwater storage and flow is confined to weathered zones and fractures. Locally, there may be small but rapid flow along these zones, but overall these rocks have low permeability. Lower Carboniferous mudstones and siltstones of the Ballagan Formation are also classed as having low permeability.

Drift deposits over most of Fife comprise low permeability glacial till. Around the coast there are small outcrops of low permeability marine silts and clays. On the northeast coast, beach and raised marine deposits comprising mixed sequences of clay, silt, sand and gravel are classified as moderately permeable. High permeability drift deposits comprise raised marine and beach sands and gravels around much of the coast; glaciofluvial sand and gravel; and alluvial deposits in river valleys which generally a large proportion of sand and gravel interbedded with small amounts of silt or clay, resulting in an overall moderately permeable sequence.

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 rapidly to the water table. Where less permeable formations, such as clayey drift deposits or crystalline igneous or metamorphic bedrock, crop out at the surface, 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 act 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 glacial till, but also marine clay and peat) 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, and it may be fractured in some areas.

The detailed identification, location, thickness and extent of 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, rather than a comprehensive coverage. Note that the printed map of groundwater vulnerability (NERC and MLURI 1998) also includes information on the presence and thickness of low permeability drift deposits, based on the same data.

3.1 BEDROCK GEOLOGY PERMEABILITY

The 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 a small area off the northeast coast where bedrock is classed as ‘unknown’ on the 1:50 000 digital geology coverage. Each bedrock unit has also been given a code signifying the level of confidence in the permeability classification, where 1 is most confident and 3 is least confident. Most units are coded 1 or 2. Lower confidence is given to bedrock units which are known to have varying permeability characteristics within the same unit. For example, igneous rocks overall have very low permeability, but fracturing within the rocks may create areas of locally higher permeability; similarly Carboniferous cyclic sedimentary rocks overall have moderate permeability, but within the sequence there are higher permeability sandstone and limestone beds and lower permeability siltstone beds.

The major groups include the following rock units:

High Permeability:

(Red on GIS)

- Upper Devonian sandstones (Burnside, Glenvale and Knox Pulpit Formations)
- Lower Carboniferous sandstones (Kinnesswood Formation)
- Carboniferous cyclic sedimentary rocks dominated by sandstone (Passage Formation)

Moderate Permeability:

(Yellow on GIS)

- Carboniferous limestones and cyclic sedimentary rocks (mixed sequences of limestone, sandstone and siltstone) (e.g. Strathclyde and Inverclyde Groups, Limestone Coal and Lower Limestone Formations and numerous individually named limestone formations)
- Lower Devonian conglomerates (Ochil Volcanic Formation conglomerate)

Low Permeability:

(Green on GIS)

- Carboniferous igneous rocks (e.g. Midland Valley Sill Compex, Kinghorn Volcanic Formation)
- Carboniferous mudstones and siltstones (Ballagan Formation)
- Lower Devonian igneous rocks (Ochil Volcanic Formation)

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 small areas, mostly in the southeast of the area, where drift geology is classed as 'unknown' on the 1:50 000 digital geology coverage. Areas uncoloured on the drift geology permeability map are those areas where no drift cover is mapped.

Drift coverage in Fife 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 index, 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.

Each drift unit has also been given a code signifying the level of confidence in the permeability classification, where 1 is most confident and 3 is least confident. Most units are coded 1 or 2. Lower confidence is given to drift units which are known to have varying 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.

characteristics within the same unit. For example, alluvium is a mixed deposit that can have high permeability overall, but also contains zones of lower permeability silts and clays.

The groups include the following units:

High permeability:

(Red on GIS)

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

Moderate permeability:

(Yellow on GIS)

- Hummocky glacial deposits, marine and beach deposits comprising mixed sequences of sand, gravel, silt and clay where it is believed that sand and gravel are not dominant

Low permeability:

(Green on GIS)

- Glacial till
- 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 index map incorporates both the bedrock and drift permeability classifications previously described to produce twelve combinations of bedrock 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 bedrock permeability and the second letter to the drift permeability. For example, ‘HM’ refers to High Permeability bedrock 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. For anywhere in the Fife 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 the overall low permeability this risk, and therefore the vulnerability of groundwater, is considered to be lower.

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 bedrock or drift aquifers) without taking drift permeability into account. There is also one area where bedrock geology is unknown (see section 3.1).

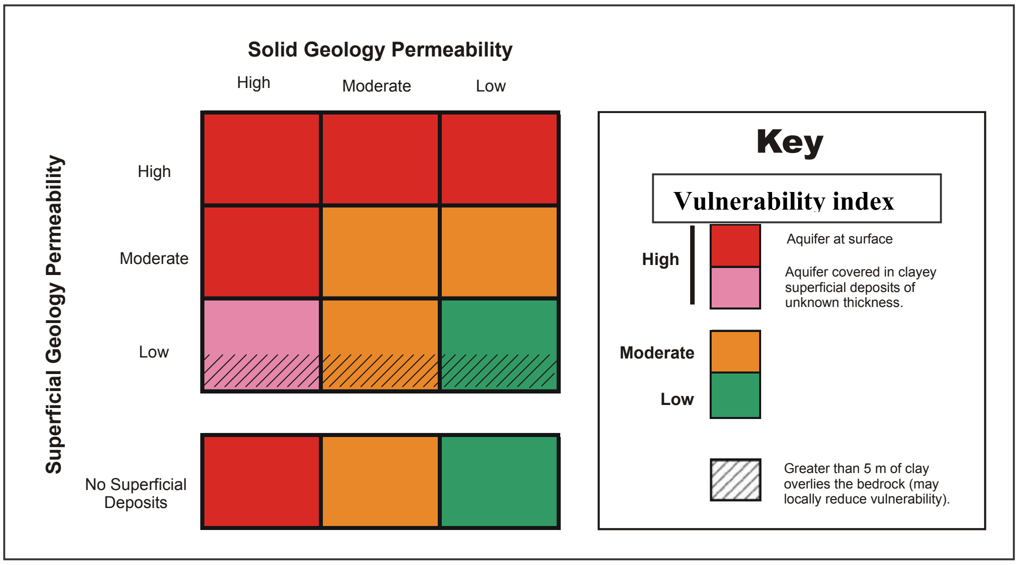

Figure 1 **Illustration of groundwater vulnerability index categories based on bedrock and drift geology**

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 heterogeneous, 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 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 Fife, taken from the British Geological Survey Scottish Water Borehole database (Figure 5).

7 Copyright

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NERC and MLURI. 1998. Groundwater vulnerability of Fife and surrounding area (1:100 000).

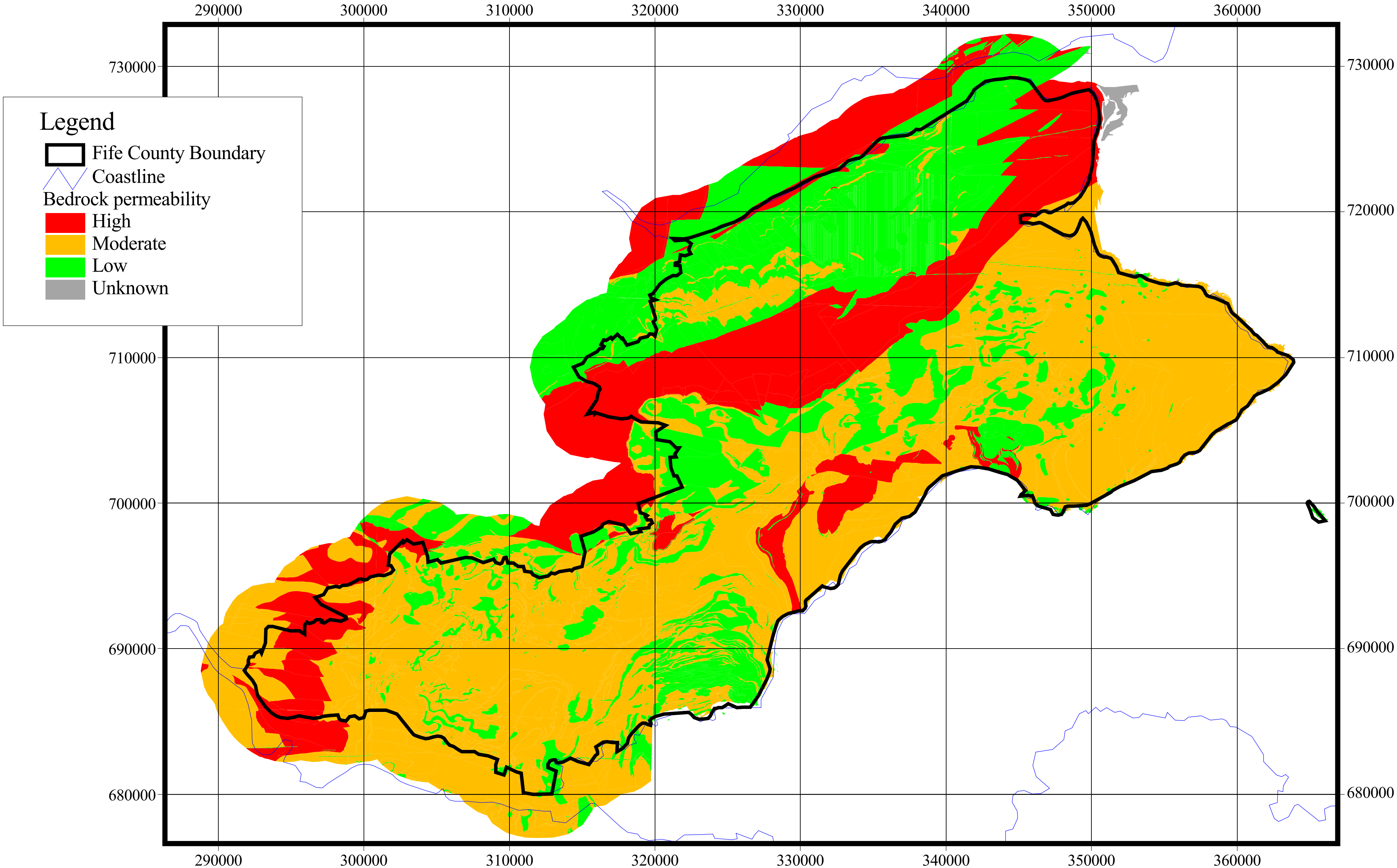

Figure 2 Fife - Bedrock Geology Permeability

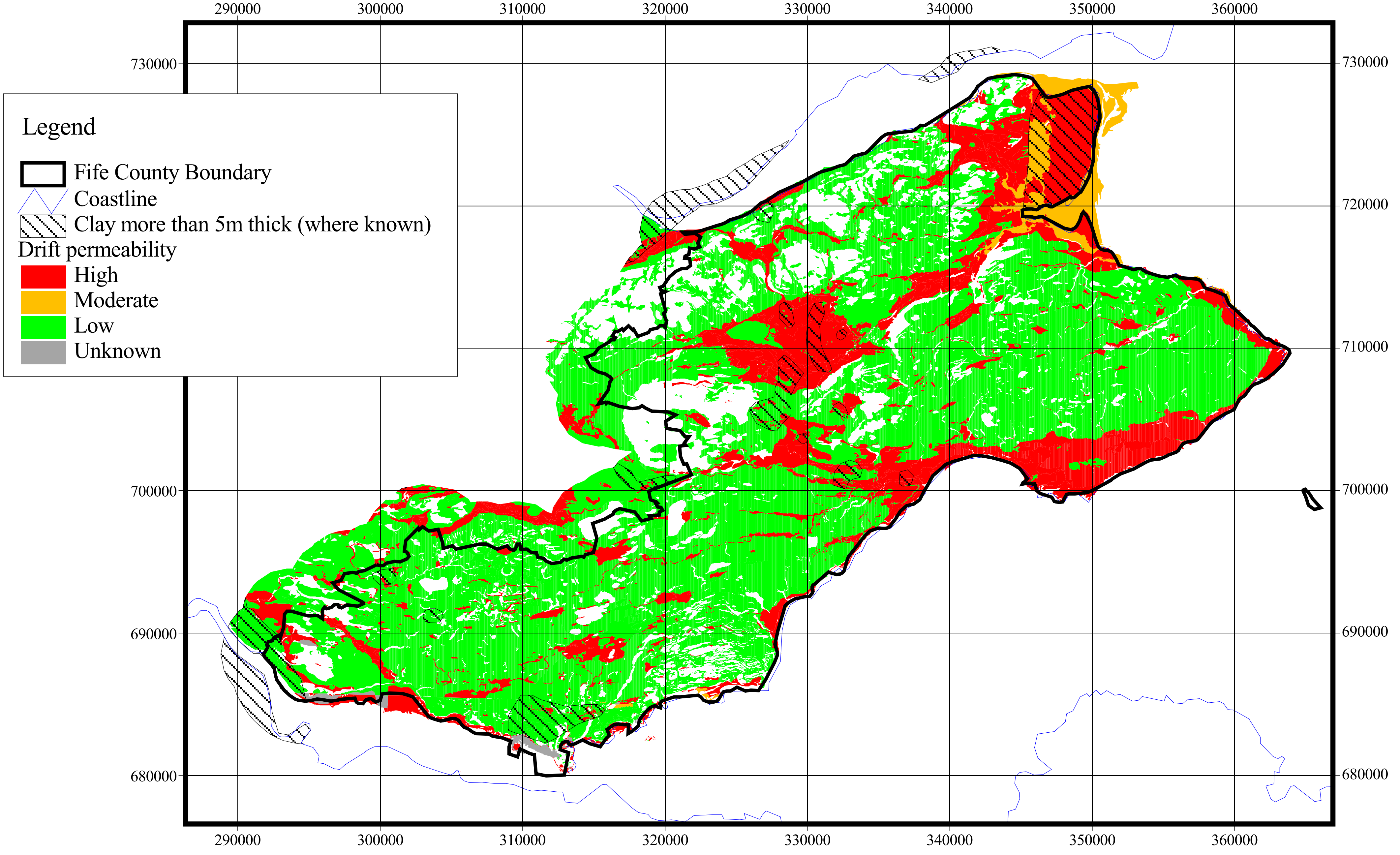

Figure 3 Fife - Drift Geology Permeability

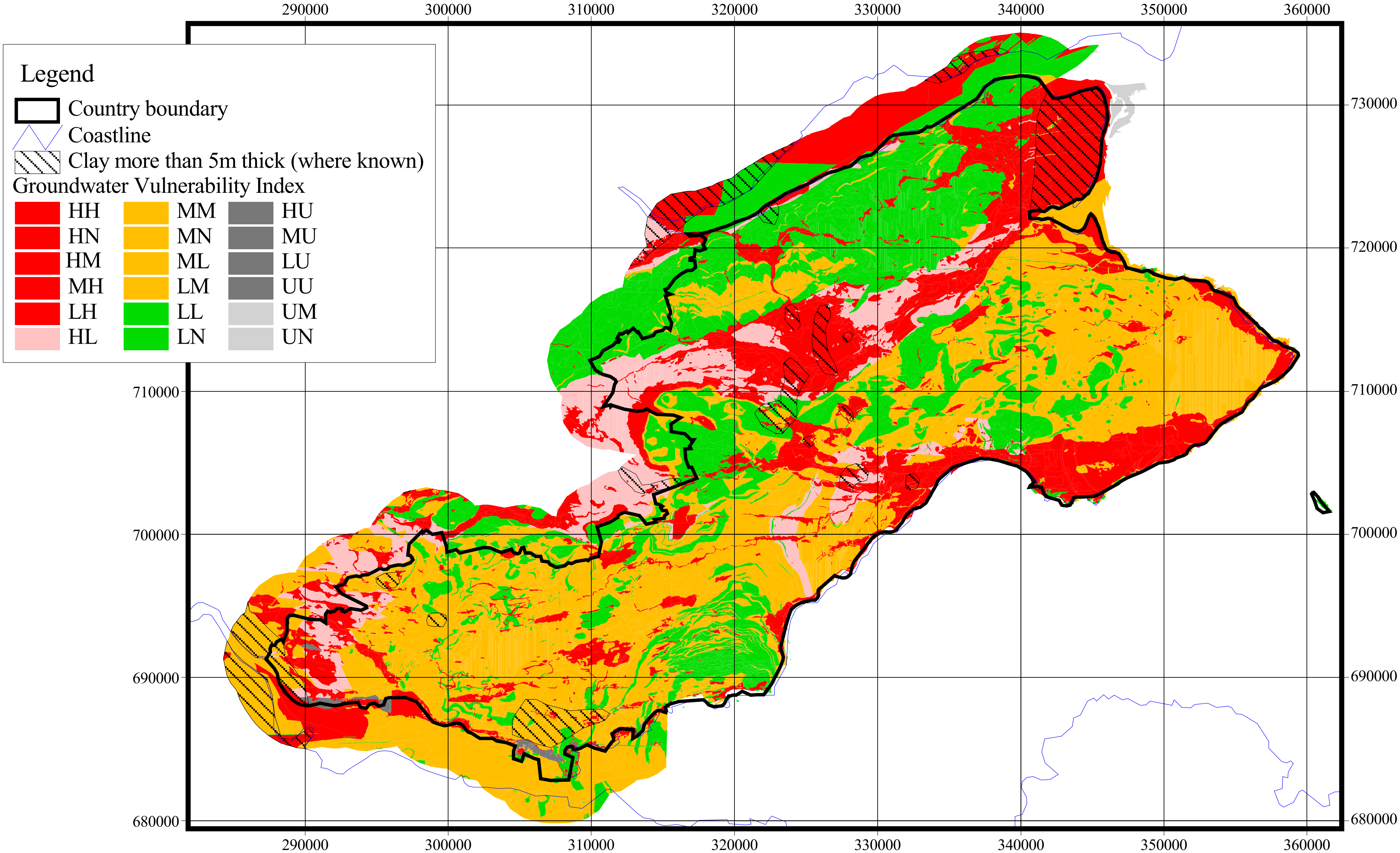

Figure 4 Fife - Groundwater Vulnerability Index

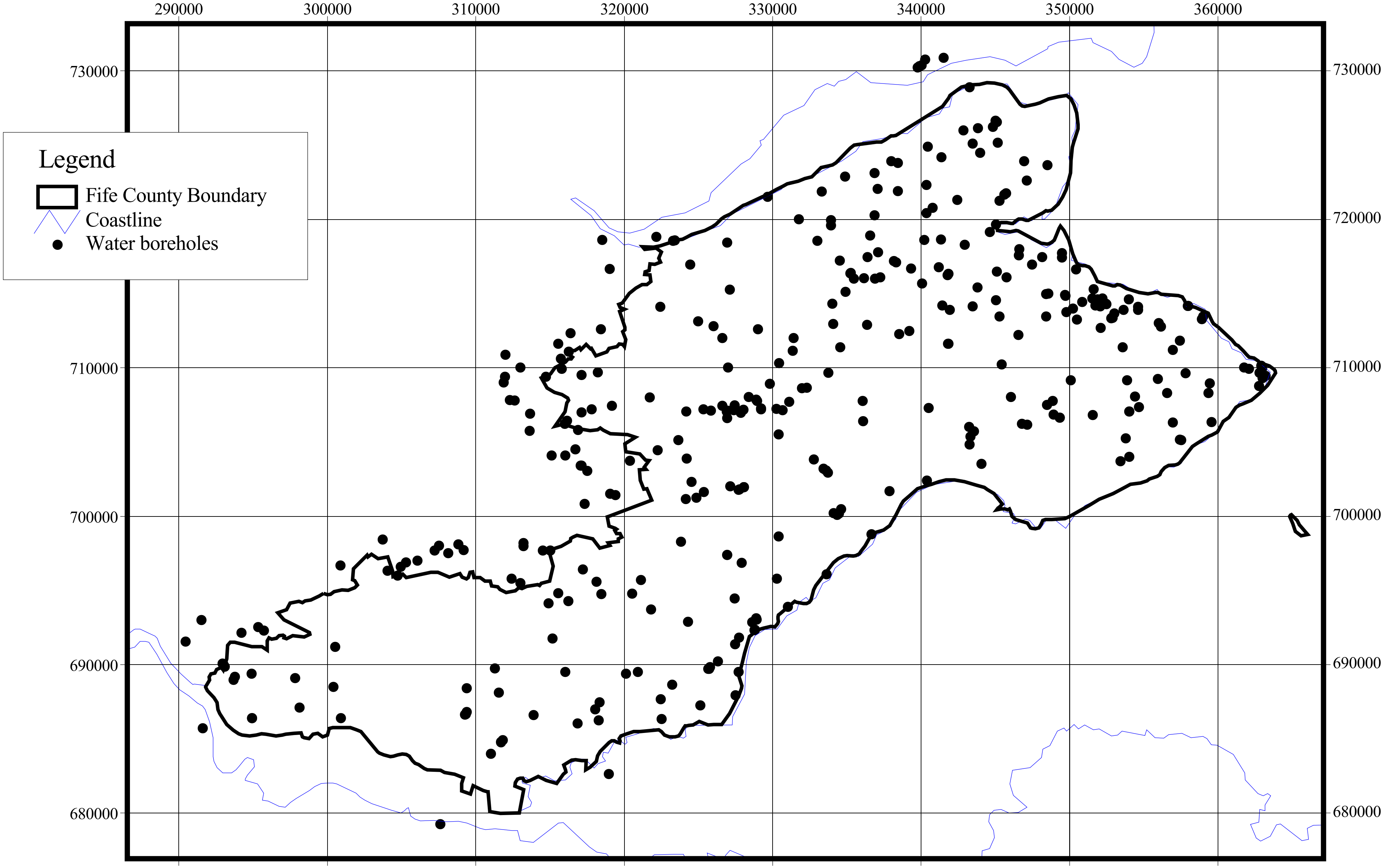

Figure 5 Fife - Water Boreholes