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Saline intrusion: a screening tool for the assessment of risk to coastal aquifers in Scotland

Groundwater Management Programme

Commissioned Report CR/06/025N

BRITISH GEOLOGICAL SURVEY

GROUNDWATER MANAGEMENT PROGRAMME

COMMISSIONED REPORT CR/06/025N

Saline intrusion: a screening tool for the assessment of risk to coastal aquifers in Scotland

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Foreword

This report is the published product of work commissioned by the Scottish Environment Protection Agency (SEPA) to indicate the degree of risk to coastal aquifers from new and proposed abstraction groundwater boreholes in Scotland.

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Summary

A simple methodology has been devised for use by SEPA non-technical staff in Scotland for use in the initial assessment of the risk to aquifers of seawater intrusion caused by the construction of a new abstraction borehole close to the coast. The methodology has been translated into a GIS-based format.

The methodology is not intended to provide all the answers as to whether there is a risk from seawater intrusion. Rather, it provides a screening tool to omit all new sources that will not be at risk, whilst allowing those that are perceived to be at risk to be assessed individually by SEPA hydrogeologists using other, more detailed, datasets.

The methodology assumes that no intrusion will take place at distances greater than 4 km from the coast. All bedrock aquifers are assumed to depend on fracture-flow and to have an equal risk potential. Where low volume coastal abstraction takes place fractured bedrock is at greater risk of pulling in sea water than are intergranular media such as Quaternary sands. This is due to the focussed conduit flow in fractures compared to the diffuse transport in porous media.

The variables taken into consideration in the risk tables are: distance from the coast, dynamic gradient and proposed abstraction rate from new boreholes.

It must be emphasised that this methodology is not intended to be the complete assessment for risk of seawater intrusion. It is to be used as an *initial* screening by administrative staff when processing applications for new water abstraction boreholes and utilises only very basic level information. It is to distinguish between, for example, single cottage supplies located 3.5 km from the coast from larger abstractions intended for locations closer to the sea. For the latter, more detailed investigations will be carried out using detailed data within a more complex methodology.

1 Introduction

Implementation of the Water Framework Directive (WFD) in Scotland includes the assessment of the impact on aquifers of new groundwater abstractions. For new sources in coastal areas, the assessment is to include an initial, basic, screening tool to aid non-technical staff in SEPA to make decisions as to whether an application warrants further assessment by a hydrogeologist. This report and accompanying GIS-based map of Scotland are intended to provide administrative staff with the means to make the initial screening of applications with regard to saline intrusion risk.

SEPA commissioned BGS, as part of the 2005-06 Secondment contract, to devise a basic methodology which would indicate the risk to aquifers from abstractions of varying size on GIS-based maps. This short report provides an explanation of the principles behind the GIS maps, and includes some examples from the Isle of Arran.

The maps are not intended to provide the final judgement as to whether a new borehole will pose a threat by the introduction of seawater to coastal aquifers, but to indicate, in broad terms, which boreholes can clearly be excluded from any further investigation. Therefore, they should help to minimise the amount of time specialist hydrogeologists have to spend on routine abstraction applications. The maps will allow, for example, the construction of a lower-yielding source such as single cottage supply borehole located 3.5 km from the coast, but require high-yielding sources to undergo a more detailed assessment.

2 Seawater intrusion: theory and reality

Classic studies on the relationship between seawater and freshwater aquifers were made by Ghyben and Herzberg in the late nineteenth Century. They assumed simple hydrostatic conditions in a homogeneous, unconfined aquifer (Freeze and Cherry, 1979). They used the difference in density between the two types of water to predict the depth to the interface. The formula devised for this was:

$$D_{sw} = \frac{Den_{fw}}{Den_{sw} - Den_{fw}} \times WT_{el}$$

where:	D_{sw}	=	depth to the salt water interface below sea level at location x
	Den_{fw}	=	density of fresh water
	Den_{sw}	=	density of sea water
	WT_{el}	=	elevation of the water table above sea level at location x

Using the actual densities of freshwater (1.000 g/cm^3) and sea water (1.025 g/cm^3), the theoretical depth to the saline interface is 40 times the elevation of the water table above sea level. Therefore, if the water table in an unconfined coastal aquifer is lowered by 1 m, the interface will rise by 40 m. However, it being a dynamic interface, the calculation is very approximate.

The depth to the interface can be deeper than predicted using the Gyben-Herzberg formula, as demonstrated by Hubbert (1940) who used graphical flow-nets to show steady-state seaward flow.

In reality, complex geological structures affect the nature of the saline interface, homogeneous aquifers being rarely present in Scotland. Where raised marine superficial deposits overlie fractured bedrock, or where igneous intrusion and faults present barriers to groundwater flow, the saline front may be affected. Within low-permeability fractured rock and within superficial deposits that contain thin lenses of high-permeability material, preferential movement of saline water inland can take place near abstraction boreholes, leading to a derogation of water quality at rates more rapid than predicted by the standard formulae.

The paucity of data on aquifer properties and hydraulic gradients for Scottish aquifers means that it is not possible to construct meaningful maps of saline risk for the whole coastline, based on classic formulae. As an alternative, more basic maps have been produced that assume all bedrock aquifers are fractured and that hydraulic gradients are steeper where higher ground is close to the coast. The maps indicate where, for certain ranges of abstraction, the hydraulic gradient may be reversed to cause intrusion of sweater and are based largely on experience of Scottish conditions.

3 Seawater intrusion in Scotland

3.1 EXAMPLES OF POSSIBLE SEAWATER INTRUSION IN SCOTLAND

Figure 1 shows the locations of sites on the Scottish coast where saline intrusion may have occurred. There are not always hard, reliable data available for each site and some are founded largely on historical evidence. There is a need to investigate many of these sites more fully to ascertain the situation.

3.2 FRESH GROUNDWATER NEAR THE COAST

There are a small number of sites in Scotland where drilling has taken place very close to the coast. Sea water intrusion, a likelihood in these localities, is not present.

Annan – A deep borehole (90 m) was drilled near the beach head at a large industrial complex by the Solway Firth and was expected to show the presence of brackish water. However, below 70 m depth, the groundwater SEC became progressively lower, indicating that ‘fresh’ groundwater in the Permian sandstone aquifer may be present under the tidal Solway Firth. No signs of sea water intrusion were observed in the bedrock aquifer, although there was some indication of intrusion within the raised marine sands close to the mouth of the River Annan.

Orkney - A small borehole supply on the island of Rousay was used to supply a seafood processing plant. The borehole, although located very close to a low cliff at the beach head, abstracted good quality water from the Devonian flagstones. The absence of seawater entering this borehole may have been due to the steep hydraulic gradient and the barrier effect of a dyke that intruded the flagstones at the site in a parallel alignment to the coast.

East Lothian – a borehole drilled to 142 m depth at Catcraig, near Dunbar, in 1910 was located close to the beach head. Artesian conditions were encountered in the lower Limestone Formation and the borehole has produced fresh groundwater under natural artesian conditions to the present day.

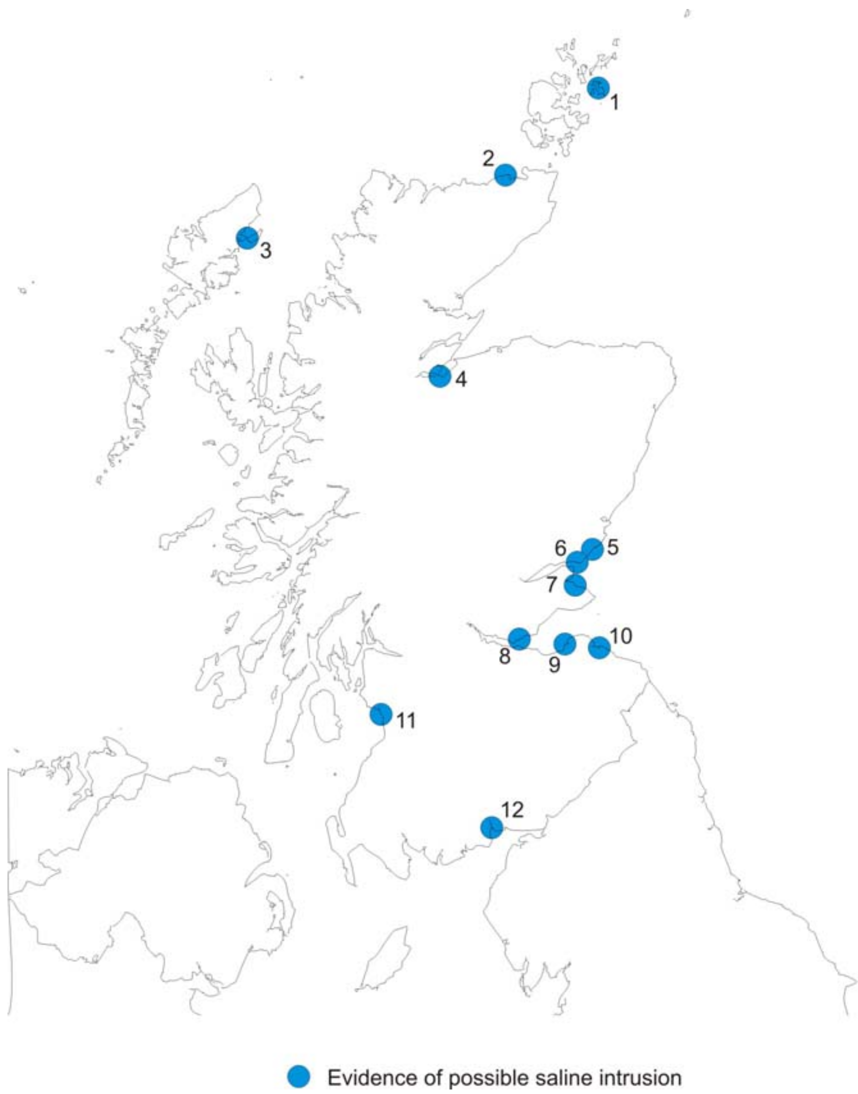


Figure 1 Possible sites where seawater intrusion may have taken place

1. Stronsay - slight increase in electrical conductivity (SEC) in a borehole 120 m from the sea. Drilled in Devonian Flagstone. (Distance from coast - 100 m, aquifer – flagstones)
2. Thurso - possible intrusion in flagstones (Distance from coast - unknown, aquifer - flagstones)
3. Stornoway - raised marine sands overlie Permian sandstone with elevated SEC (Distance from coast - <1 km, aquifer, superficial over Permian sandstone).
4. Industrial estate, Inverness - brackish water in 90 m-deep borehole in glacial gravel (Distance from coast - 500 m, aquifer - Holocene gravel).
5. Arbroath - evidence of seawater in golf club and other industrial boreholes (Distance from coast - <1 km, aquifer - Lower Devonian).
6. Carnoustie - possible contamination in industrial borehole within Devonian sandstone (Distance from coast - 1.5 km, aquifer - Lower Devonian).

7. St. Andrews - irrigation boreholes show increased salinity (Distance from coast - <1 km, aquifer - Lower Carboniferous).

8. Burntisland - over-pumping in borehole located very close to the coast leads to increased SEC (Distance from coast - <1 km, aquifer - Lower Carboniferous).

9. Aberlady - possible salinity in Carboniferous irrigation borehole (Distance from coast - 1.1 km, aquifer - Lower Carboniferous).

10. Near Dunbar - possible seawater intrusion in Devonian rocks (Distance from coast - <1 km, aquifer - Lower Carboniferous).

11. Irvine - high SEC in both raised marine sands and deep Carboniferous aquifer (Distance from coast - <1 km, aquifer - superficial over Coal Measures).

12. Sandhead, Dumfries - possible increase in salinity in borehole close to the estuary (Distance from coast - <0.5 km, aquifer - superficial over Permian sandstone).

4 The principles behind the maps

Two sets of maps have been produced, according to the nature of the aquifer to be exploited by the new borehole. The map sets distinguish between fracture-flow/dominantly fracture-flow aquifers (Table 1) and purely intergranular-flow aquifers (Table 2), and, therefore, effectively separate bedrock aquifers from superficial aquifers. It is anticipated that over 90% of abstraction applications will be for boreholes to be drilled into bedrock aquifers, and so the base table (Table 1) will be the most used by SEPA administration staff. For more detailed risk assessments, as required by the matrices in Tables 1 and 2, the rate of recharge to the aquifer, the transmissivity and the hydraulic gradient must be taken into account when assessing the likelihood of saline intrsuion.

In order to maintain consistency in processing borehole applications, a simple method was required that relied upon GIS-based information available for the whole of the coastal areas of Scotland. The paucity of data on porosity, permeability and fracture patterns in coastal areas meant that a sophisticated method could not be used where aquifers can be classified according to these factors. Therefore, all bedrock aquifers have been grouped in one table, with an additional table for superficial aquifers. The factors used in the risk assessment tables are:

Bedrock/superficial aquifers – this distinction was made in order to distinguish between dominantly fracture flow and intergranular flow aquifers.

Ground elevation – the 30 m contour has been used to distinguish between high and low ground.

Abstraction rate – higher rates mean a greater risk.

Distance to coast – in general terms, greater distances mean lesser risks for similar abstraction rates. However, in fractured aquifers, distant boreholes linked by well-developed fracture systems may be at a higher risk than sources located closer to the coast where there may be no such connections present.

4.1 BEDROCK AND SUPERFICIAL AQUIFERS

Scottish bedrock aquifers are almost all fracture-dominated. This can lead to relatively rapid transit times for groundwater within a generally low-storage medium where values for transmissivity are low. For boreholes located close to the coast, there is the potential for fractures to link the borehole directly to the margins of the freshwater aquifer, possibly leading to rapid penetration of low-quality brackish groundwater along specific, narrow, pathways to the abstraction source.

Groundwater in unconsolidated, sandy or gravelly superficial aquifers moves entirely by intergranular means. Interconnected porosity tends to be higher than in bedrock aquifers and the volume of groundwater held in storage per unit volume of aquifer is normally higher. This characteristic will, in general terms and for equivalent abstraction rates, prevent the rapid penetration of saline water towards a borehole, resulting in a slightly lower risk to the aquifer. It is possible that the risk factor between bedrock and superficial aquifers could narrow where very thin, highly permeable, gravel beds are present that will tend to act in a similar way to fractures. In general terms, however, at low abstraction rates, there is less risk to superficial aquifers of saline intrusion compared to fractured bedrock.

4.2 HYDRAULIC GRADIENT

Steep hydraulic gradients towards the coast from inland lessen the risk of seawater intrusion. Flatter gradients tend to be found under low-lying ground, such as raised beaches and adjacent to estuaries.

Inadequate data are available to produce meaningful maps of groundwater gradients in Scotland. Therefore, as a proxy for this, the elevation of the ground surface has been used to identify those sites where there is likely to be a steeper hydraulic gradient present, close to the coast. Digital elevation maps were used to mark out the 30 m elevation contour. This value was used to distinguish between low and high ground.

4.3 ABSTRACTION RATE

The principle behind using abstraction rate in the Tables is that a high rate of groundwater abstraction from a particular borehole will result in:

- More water being drawn from the aquifer
- A steepening hydraulic gradient from the coast to inland, leading to a greater risk of sea water intrusion.

Abstraction rates of <50, 50-100, 100-500 and >500 m^3/day have been chosen to be consistent with SEPA abstraction licensing regulations.

4.4 DISTANCE FROM THE COAST

In general terms, the greater the distance from the coast, the lesser the risk of seawater intrusion for boreholes that have similar-sized yields.

It has been assumed that no seawater intrusion will occur if the source is located more than 4 km from the coast. There is no evidence in Scotland of intrusion having taken place at these distances.

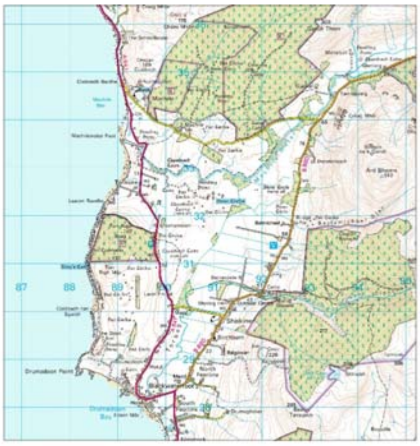
There are five distance groups in the tables: <100, 100-200, 200-500, 500-1000 and 1000-4000 m.

4.5 THE MAPS

The GIS layer was constructed for use with ArcMap 8. Metadata are provided in Appendix 1.

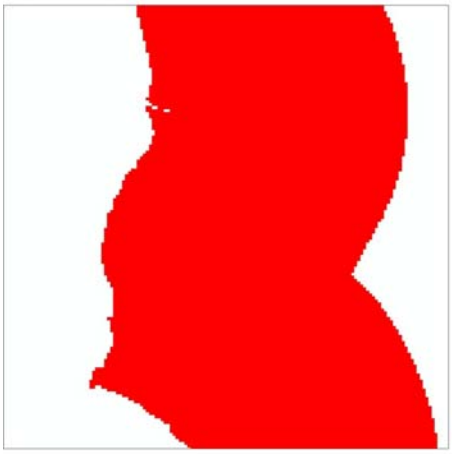
To create the layers, all data was reduced to a 50 m grid. The location of the 30 m elevation contour was, therefore, reduced to the accuracy of the 50 m grid. There are no geological data used in the layers. In the case of the main bedrock Table, all bedrock for this initial screening tool is treated as having the same characteristics. Therefore, the inclusion of bedrock lines is not necessary. In the case of superficial aquifers, because there is a lack of knowledge on the thickness and nature of superficial deposits around the coast, it was concluded that the GIS layers should not be used as an indication of where the aquifers actually existed. Therefore, risk layers have been produced for the whole of the coastline, irrespective of where superficial deposits are actually present. Wherever a superficial aquifer is encountered and an application for abstraction made, the risk layers can then be used.

Figures 2 and 3 provide examples of the GIS maps for part of the west coast of Arran. This area was chosen to demonstrate the influence of low-lying ground on risk, compared to where high cliffs border the coast. The Figures show that, for large abstractions, the risk zone extends inland by 4 km, but, for smaller abstractions, the influence of the 30 m contour is evident and areas of low-lying ground adjacent to bays are highlighted. The latter are at higher risk of seawater intrusion because of the presumed lower hydraulic gradient below flatter land.

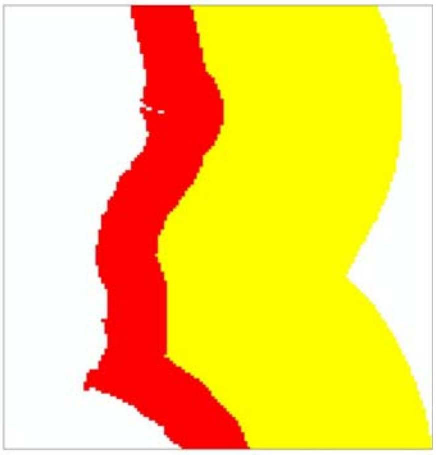


Base map: Machrie coast of Arran

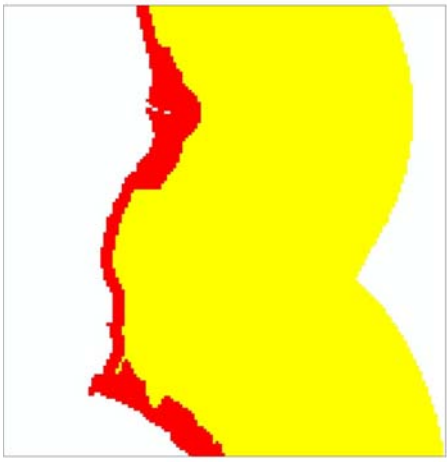
For bedrock aquifers



Abstraction >500 m³/day



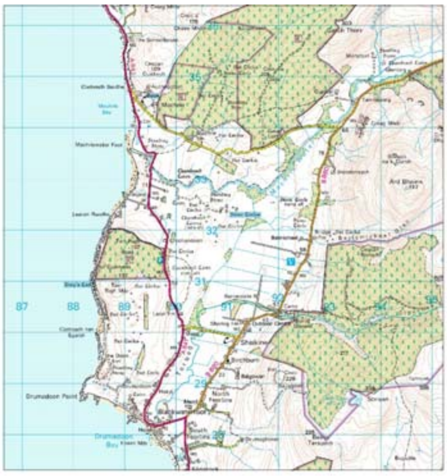
Abstraction 100-500 m³/day



Abstraction 50-100 m³/day

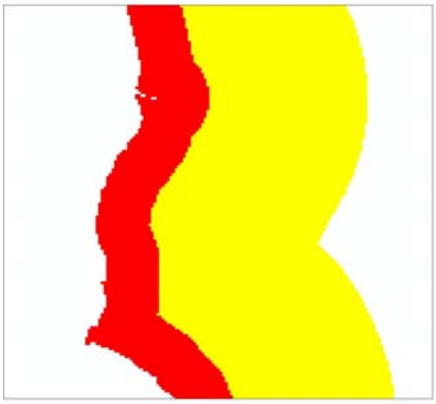
Abstraction <50 m³/day

Figure 2 Maps based on Table 1 (fracture-flow aquifers). The Arran coast includes high cliffs in the southern part, with a small area of low ground in the northern part where the Machrie Water meets the sea.

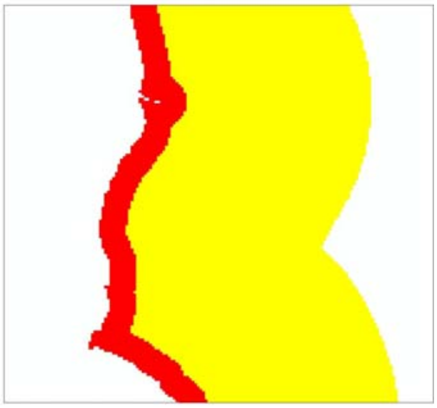


Base map: Machrie coast of Arran

For superficial aquifers



Abstraction >500 m^3/day



Abstraction 100-500 m^3/day

Abstraction 50-100 m^3/day

Abstraction <50 m^3/day

Figure 3 Maps based on Table 2 (intergranular-flow aquifers)

5 Saline Intrusion Risk Charts

5.1 VARIABLES USED IN THE RISK ASSESSMENT

- ***Aquifer Groupings:*** Table 1: Base Table for all bedrock aquifers.
  Table 2: Where a superficial aquifer is the target aquifer.
- ***Distance from Coast:*** Five bands up to 4 km from the coast (<100 m, 100 – 200, 200 – 500, 500 - 1000 and 1000 – 4000 m)
- ***Elevation:*** Subdivided into 0–30m (low ground) and >30m OD (high ground).
- ***Abstraction Rate:*** Subdivided into <50, 50-100, 100-500 and >500 m^3/day.

Table 1 Base Table: for all new boreholes, except where it is known that a superficial aquifer is the target

Abstraction rate (m^3/day)	Distance from coast (m)									
	<100		100-200		200-500		500-1000		1000 - 4000	
	Low Ground	High Ground	Low Ground	High Ground	Low Ground	High Ground	Low Ground	High Ground	Low Ground	High Ground
<50	Risk	Risk	Risk	No Risk	No Risk	No Risk	No Risk	No Risk	No Risk	No Risk
50 – 100	Risk	Risk	Risk	Risk	Risk	No Risk	No Risk	No Risk	No Risk	No Risk
100 – 500	Risk	Risk	Risk	Risk	Risk	Risk	Risk	Risk	No Risk	No Risk
>500	Risk	Risk	Risk	Risk	Risk	Risk	Risk	Risk	Risk	Risk

Table 2 For superficial aquifers: where boreholes are to be drilled into shallow sand and gravel aquifers only

Abstraction rate (m^3/day)	Distance from coast (m)									
	<100		100-200		200-500		500-1000		1000 - 4000	
	Low Ground	High Ground	Low Ground	High Ground	Low Ground	High Ground	Low Ground	High Ground	Low Ground	High Ground
<50	Risk	No Risk	No Risk	No Risk	No Risk	No Risk	No Risk	No Risk	No Risk	No Risk
50 – 100	Risk	Risk	Risk	No Risk	No Risk	No Risk	No Risk	No Risk	No Risk	No Risk
100 – 500	Risk	Risk	Risk	Risk	Risk	Risk	No Risk	No Risk	No Risk	No Risk
>500	Risk	Risk	Risk	Risk	Risk	Risk	Risk	Risk	No Risk	No Risk

References

Freeze, R.A. and J.A. Cherry. 1979. *Groundwater*. Prentice-Hall, Inc., Englewood Cliffs, NJ, 604 pp.

Hubbert, M.K. 1940. The theory of groundwater motion. *Journal of Geology* 48: 785-944.

Appendix 1 METADATA

METADATA FOR GIS

Coastline: Owner - SEPA

Elevation data: Ordnance Survey DTM provided by SEPA