



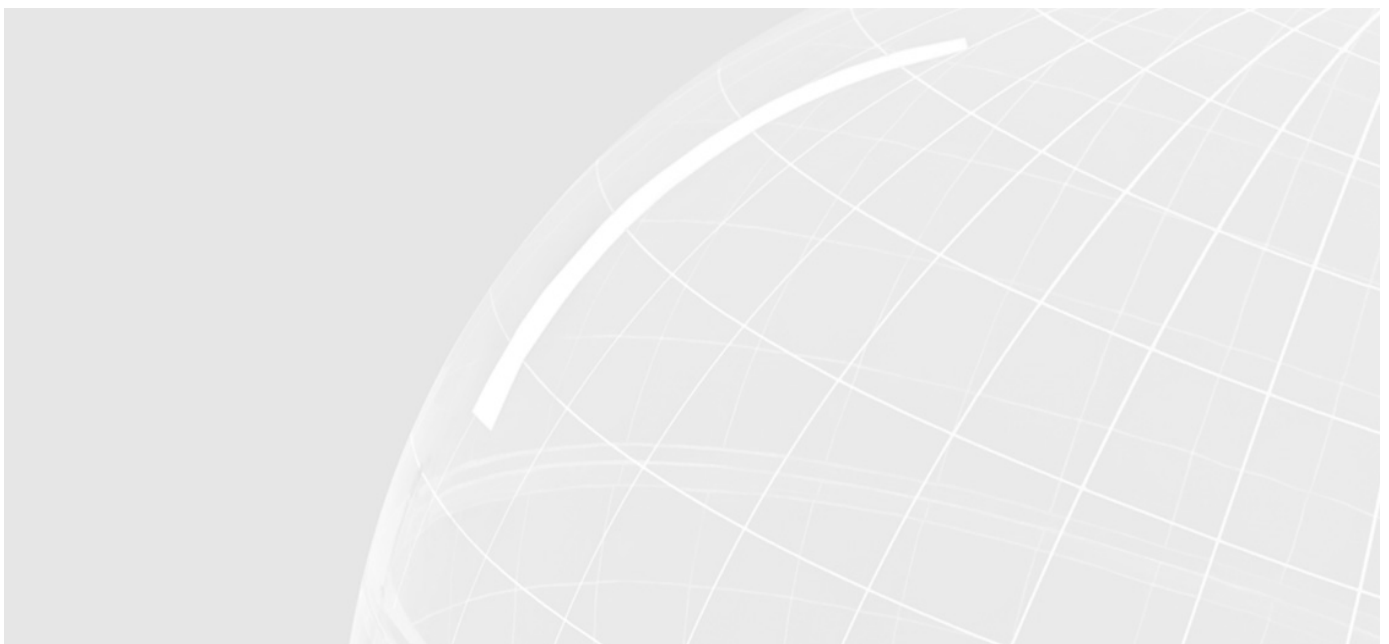
Musselburgh Flood Protection Scheme

East Lothian Council

Natural Flood-Risk Management Opportunities Study

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Musselburgh Flood Protection Scheme

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 Author: Rudi Barker
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Jacobs U.K. Limited

1 City Walk
 Leeds, West Yorkshire LS11 9DX
 United Kingdom
 T +44 (0)113 242 6771
 F +44 (0)113 389 1389
www.jacobs.com

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1. Introduction

Natural Flood-Risk Management (NFM) is the means of working with natural processes in order to manage the pathways and sources of flood waters across the catchment to benefit flood risk in other areas of the catchment (SEPA,2015)¹. NFM interventions aim to not only deliver flood risk management benefits but also societal, environmental and economical improvements by changing the way water moves through the landscape reinstating, mimicking and enhancing natural processes.

In Scotland, the need for delivering a more sustainable approach to flood risk management is underpinned in the Flood Risk Management (Scotland) Act 2009². Under this Act, SEPA works with local authorities and other responsible organisations to identify the most sustainable actions to manage flood risk, including the implementation of NFM techniques. The delivery of these actions, including more detailed assessments of the potential for NFM outcomes is the responsibility of the local authorities.

Musselburgh has been identified by East Lothian Council (ELC), within the Local Flood Risk Management Plan³, as a Potentially Vulnerable Area (PVA). Jacobs UK Ltd, have been commissioned by ELC to undertake a study with the aim to develop a flood protection scheme to provide a standard of protection⁴ equivalent to the 1 in 200-year flood event. As part of such studies, the Flood Risk Management (Scotland) Act 2009 requires the investigation for NFM to be used within the scheme. To fulfil this requirement, Jacobs have undertaken a high-level assessment of the River Esk catchment to understand where there is potential to implement changes that could reduce hydrological connectivity and thereby provide flood risk management benefits. This assessment provides an effective way of focussing attention on the areas of the catchment where flow interventions are most likely to have an impact upon hydrological connectivity that contribute to the flood peak at Musselburgh. NFM interventions can be put in place in conjunction with Sustainable Drainage Systems (SuDS), as such providing a multi-benefit approach.

An NFM opportunity tool developed by Durham University has been adopted for this study, SCIMAP-Flood_v2. The tool assesses hydrological connectivity at the catchment scale and the likelihood for this connectivity to contribute to flood risk at a downstream receptor, such as Musselburgh. This process therefore facilitates a qualitative assessment of the locations where interventions to slow the flow or provide attenuation could reduce flooding downstream. The outputs of this assessment can be taken forward and assessed, using a detailed hydrological model or other suitable approach, as to the feasibility of implementing NFM measures.

¹ SEPA Natural Flood Management: <https://www.sepa.org.uk/media/163560/sepa-natural-flood-management-handbook1.pdf>

² FRM Act 2009: <http://www.legislation.gov.uk/asp/2009/6/contents>

³ Strategic Flood Risk Assessment: https://www.eastlothian.gov.uk/downloads/file/27703/strategic_flood_risk_assessment_-_ldp_2018

⁴ Flood Risk Management Strategy Forth Estuary: http://apps.sepa.org.uk/FRMStrategies/pdf/ldp/LPD_10_FRMIS.pdf

2. Study Area

2.1 Location and Topography

Musselburgh is located approximately 8km to the east of the City of Edinburgh, on the coast of the Firth of Forth and is the largest town in East Lothian, Scotland, home to a population of approximately 21,900 people. Musselburgh lies on the River Esk which has a catchment area of approximately 322km². The Esk catchment is made up primarily of the North and South Esk which confluence at Dalkeith (Figure 2-1). Penicuik lies centrally within the North Esk which extends to the ridgeline adjacent the A701 which is the watershed with the South Esk. The South Esk extends from this ridgeline south towards the Moorfoot Hills and East to Middleton in the east of the catchment. The River Esk catchment is made up of two smaller catchments, the River North Esk and River South Esk.

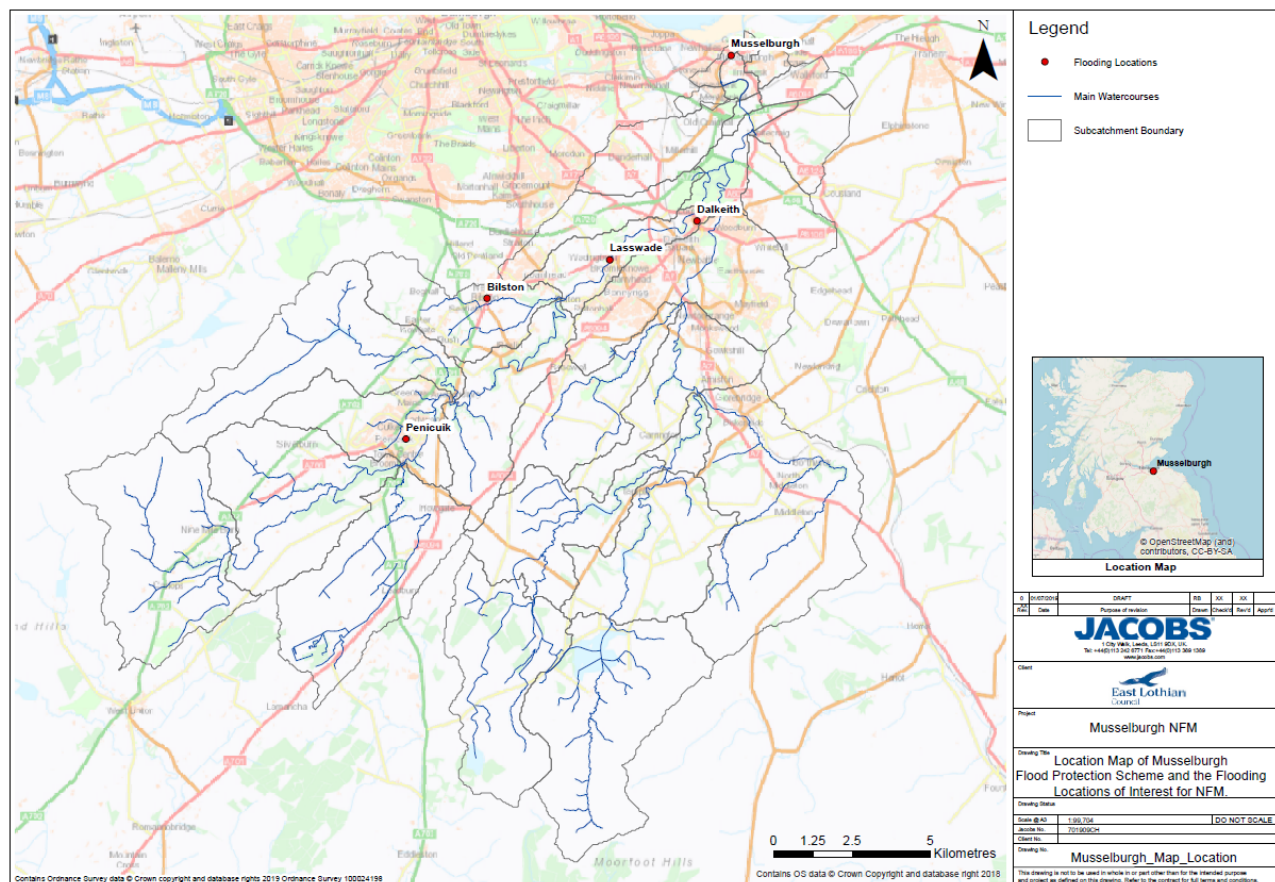


Figure 2-1: Location of Study Area and Flooding Locations of Interest.

The topography of the study area is varied, the northern extent of the catchment, of which sits around the town of Musselburgh is inherently flat due to its coastal location at the mouth of the River Esk. The catchment

becomes increasingly steeper as you move south past Lasswade and Penicuik towards the southern extent of the catchment. The southern extent of the catchment is characterised by rural areas and moorlands, with the Pentland Hills in the west, of which have a maximum elevation of 579m.

2.2 River Esk Hydrology

The River Esk drains in a Northerly direction towards the Firth of Forth, the catchment spans approximately 322km² and consists of predominately the River North Esk and River South Esk. In addition to this Loan Burn, Glencorse Burn and Bilston Burn are also notable tributaries within the River North Esk catchment (Appendix A.4). The confluence of the River North Esk and River South Esk sits approximately 3.5km upstream (south) of the town of Musselburgh, downstream (north) of the village of Dalkeith. Upstream of Dalkeith on the River North Esk lies Lasswade, Bilston and Penicuik. Loan Burn runs through the village of Penicuik and Bilston Burn flows through the village of Bilston. Both of which discharge into the River North Esk.

2.3 Soils and Geology

Soils across the catchment mainly comprise of freely draining brown soils and poorly drained mineral gleys as identified on the 1:25000 Soil Map⁵. Bands of alluvial soils also exist throughout the catchment, a key characteristic of river channels. The upland areas, such as the Pentland Hills, are predominately characterised with organic peat deposits.

A desk-based study using the British Geological Survey Mapping⁶ of the local geology showed the bedrock geology for the River Esk catchment to comprise predominately of Clackmann sedimentary rock and Scottish Coal Measures (mudstone, siltstone, sandstone, coal, ironstone and ferricrete). Superficial rock deposits are predominately made up of Diamicton (till), alongside patches of glacial sand and gravel.

2.4 Flood History

There have been several flood events over the years within the River Esk catchment. However, the two most significant events are those in October 1990 and August 1948 where Musselburgh had to be evacuated following the inundation of many areas of the town as a result of fluvial flooding from the River Esk⁷. These two events have been a major driver for ELC to implement a flood protection scheme.

In more recent years, since 2010, there have been three significant flood events in the Musselburgh area. In March 2010 a tidal surge coincided with the highest mean tides of the year⁸, resulting in extensive tidal flooding along the east coast of Scotland. In February 2011, another flood event occurred however there are limited

⁵ The James Hutton Institute – 1:25,000 Soil Map (partial Cover): http://map.environment.gov.scot/Soil_maps/?layer=1

⁶ British Geological survey: <http://mapapps.bgs.ac.uk/geologyofbritain/home.html>

⁷ October 1990 and August 1948 Flood: http://apps.sepa.org.uk/FRMStrategies/pdf/pva/PVA_10_21_Full.pdf

⁸ March 2010 Flood: http://apps.sepa.org.uk/FRMStrategies/pdf/pva/PVA_10_21_Full.pdf

details on this event, aside from a flood study report produced by Jacobs⁹ for Musselburgh of which stated a high flow event occurred on 7th February 2011, with an approximate peak flow of $67.05\text{m}^3\text{s}^{-1}$, and a peak river level of 4.84mAOD was recorded at Musselburgh Gauging Station. In July 2012 flooding was witnessed across Scotland with the River Esk breaking its banks¹⁰ and flooding Musselburgh, the source of flood event is not documented, however it is thought to be fluvial.

⁹ Musselburgh Flood Study Report, Jacobs 2012: https://www.eastlothian.gov.uk/download/downloads/id/28504/musselburgh_flood_study_report.pdf

¹⁰ BBC News: <https://www.bbc.co.uk/news/av/uk-scotland-18756046/parts-of-scotland-hit-by-flooding>

3. Natural Flood Risk Management Options

There are a wide range of NFM options that can be implemented in areas deemed to benefit from NFM. The various methods of NFM can be placed in the following categories, as detailed in the SEPA Natural Flood-Risk Management Handbook (2015):

- **Woodland Creation:** The planting and management of woodlands throughout the catchment. Over the last few decades woodlands have been subject to deforestation and thus our woodlands have become sparse. Woodland creation can help reduce runoff characteristics and increase water uptake. It can include floodplain woodlands, riparian woodlands and catchment woodlands.
- **Land Management:** Land management is the process of incorporating good practice into the management of the land for the purpose of increasing infiltration of water and sediments into soils and reducing surface runoff. Land management can take the following forms: land and soil management practices, agricultural and upland drainage modifications, non-floodplain wetlands and overland sediment traps.
- **River and Floodplain Restoration:** This is the process of the stabilisation of excessively eroding river banks/ beds in order to reduce deposition of sediment downstream. River and flood plain restoration can be achieved through: river bank restoration, river morphology and floodplain restoration, instream structures and washland and offline storage ponds

These NFM options are not exclusive of each other and can be implemented in combination. The CIRIA SuDS Manual (CIRIA C753, 2015)¹¹ provides a useful 'Source-Pathway-Receptor' conceptual model which can be used to locate interventions in their most effective locations:

- **Source Control:** Is the method of managing flows as close to the source as possible in order to reduce the volume of flow entering the drainage system/channel network, and/or delay its arrival into the network. As such, for the purposes of this investigation this includes measures that can be implemented across large areas such as woodland planting, soil aeration or infiltration improvements or changes to land management including measures such as grip blocking;
- **Conveyance/ Pathway:** Is the movement of flow from one place to another with management occurring within the network, across a site or the local area. Therefore, for the purposes of this investigation this includes riparian woodland intercepting overland flow, large woody debris structures in channel that spill water onto the floodplain, river restoration and swales;

¹¹ The SuDS Manual: <http://www.scotsnet.org.uk/documents/NRDG/CIRIA-report-C753-the-SuDS-manual-v6.pdf>

- **Receptor/ Attenuation:** Is the process of reducing the peak flow rate through the storage of runoff, resulting in the inflow rate being greater than the controlled outflow, this occurs at the downstream end of catchments for large contributing areas. For the purposes of this investigation this includes online and offline ponds, large woody debris structures that attenuate water and other flow control methods. To meet the aspirations of an NFM scheme the scale of these structures should be kept to a minimum. A risk-based approach should be used to determine feature size, large structures would pose a risk should they collapse and would also require an excessive amount of structural design and engineering.

4. Hydrological Connectivity Mapping Tool: SCIMAP-Flood

4.1 Introduction

NFM seeks to return the hydrological response of a catchment to rainfall, to that of natural conditions, thus resulting in a slower responding and lower peak flood event hydrograph at the downstream receptor. In order to identify suitable locations to implement NFM we have used SCIMAP-Flood, a hydrological connectivity mapping tool to quickly identify these locations. Figure 4-1 outlines the conceptual model¹² for the tool. SCIMAP-Flood applies a score to each cell throughout the catchment between 0 and 1 as to the magnitude of that cell contributing to the flood peak at downstream receptor for a given event. The higher weighted (weightings closest to 1) areas are those identified as having the greatest likelihood of contribution to the flood peak at the downstream receptor as a result of a combination of the following:

- Local flood risk generation - the likelihood of runoff forming and propagating;
- Hydrological connectivity - ability of runoff to connect into a watercourse;
- Incorporating travel times to the receptor (referred to as point of impact [POI]); and,
- Spatial pattern of the rainfall event.

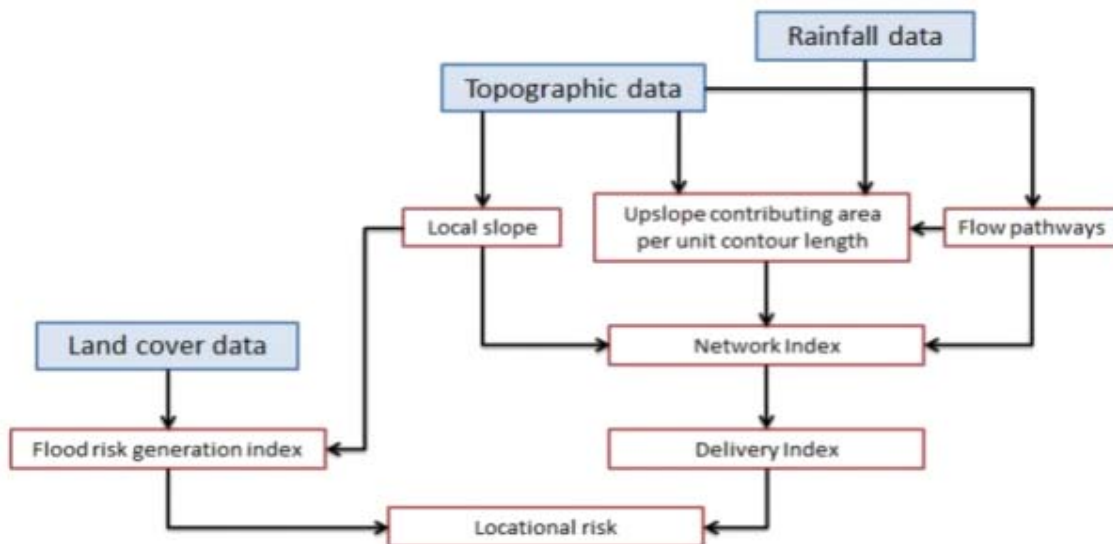


Figure 4-1 SCIMAP-Flood Conceptual Model (Fraser, 2019).

¹² Fraser, Alex, Rhys (2019) Modelling The Potential For Spatially Distributed, Natural Flood-Risk Management Techniques To Mitigate Flood Risk At The Catchment Scale For A UK Agricultural Catchment: http://etheses.dur.ac.uk/12980/1/AlexFraser_MScR_Thesis.pdf?DDD14+

The SCIMAP-Flood tool quickly identifies areas with a high-risk of generating overland flow that contributes to peak flow at a downstream point of impact. These areas can then be assessed further to consider the feasibility of implementing NFM measures in these locations. SCIMAP-Flood does this with minimal input data, based solely on the catchment routing via topography or channels alongside landcover and rainfall modules.

4.2 Input Data

In order for the SCIMAP-Flood tool to be able to weight cells based on potential for slowing the flow, the tool requires the following data:

- Centre for Ecology and Hydrology (CEH) Gridded Estimates Areal Rainfall (GEAR) dataset – 21 rainfall events selected based on peak flows at nearby river gauges, located on the River Esk in Dalkeith and Cowbridge. Events selected are detailed in Appendix A 1.1;
- Corine land cover map, shown in Appendix A 1.1;
- Runoff risk map (Standard Percentage Runoff [SPR]) based on 1:25,000 soil map produced by the James Hutton Institute¹³, shown in Appendix A 1.2; and,
- Time travel to POI – produced in SAGA (System for Automated Geoscientific Analyses), based on: receptor location and hydrological connectivity, shown in Appendix A 1.3.
- Hydrological connectivity – produced in SAGA, based on 5M DEM and channel network data, shown in Appendix A 1.5

All input sources are resampled to a 5m by 5m grid and reclassified to a scale between 0 and 1 in order to generate individual risk maps. Refer to Appendix A.1 for further details on the input data used.

4.3 Refinements

During the process of running the SCIMAP-Flood tool, one refinement was made to the Corine land cover data. This was the reclassification of Urban areas from 1 to 0. The default value of 1 skewed the results demonstrating the highest runoff potential was from urban areas which are not the subject of this study. As such the high weighting for urban areas was removed, thus refining the tool outputs.

Following a review of the outputs, an assessment on the moorland areas was also carried out, as the weighting suggested for moorland for the SCIMAP-Flood tool was 0.01, a very low risk/runoff weighting. Land management and drainage ditches on moorland can generate a rapid response to rainfall that could warrant

¹³ Lilly, A. and Baggaley N.J. 2018. Runoff risk map of Scotland (partial cover). James Hutton Institute, Aberdeen.

a higher risk rating. As such, random points were selected across the moorland areas and assessed using aerial imagery for any evidence of gripping and moorland drainage. The output of this assessment can be found in Appendix A.3, overall less than 50% of the points chosen showed evidence of gripping, and as such the weighting for moorland was left as being low. However, it should be noted that the assessment undertaken using aerial imagery was a very high-level assessment and could not consider subsurface drainage. Therefore, if there is requirement to build a hydrological model a more detailed assessment should be undertaken which could include drain surveys or Ground Penetrating Radar to determine under drainage.

Further refinements to the outputs of the tool include the inclusion of SPR data in the assessment. The instructions developed by Durham University for SCIMAP-Flood are to use landcover data, which enables the user to identify areas where land use contributes to a high risk of runoff. Utilising SPR data in place of land cover data allows the user to understand and identify areas where the soil properties of a given location could be contributing to high run-off, thus understanding what is underlying conditions are beneath the land cover. SPR provides information on the amount of runoff generated based on soil characteristics, i.e. runoff produced prior to any modifications to the land cover. Therefore, using both outputs it is feasible to see where a high-risk land use could be modified to realise the potential benefits available in areas where SPR would suggest low runoff generation would be likely.

5. Results

The tool outputs had two spatial targets, one set of outputs looked at Musselburgh as the sole point of impact (Appendix A 2.1). The second set of outputs looked at five points of impact as identified by the Forth Estuary Local District Plan¹⁴; Musselburgh, Dalkeith, Lasswade, Bilston and Penicuik (Appendix A 2.2). Focussing solely on Musselburgh as the sole point of impact could lead to the identification of high runoff areas that may increase flood risk elsewhere in the catchment if NFM measures were implemented. As such, the outputs for the latter identify areas where there is a high likelihood of contributing to peak flow in all locations, thereby indicating the areas where there would be the greatest potential to decrease flood generation that could benefit all five locations as opposed to just Musselburgh alone.

A key principle of NFM is providing a multi-benefit approach, protecting assets at a range of scales. Using multiple points of impact, it is possible to identify areas where there may be the potential to develop a scheme that protects multiple receptors. As a result of this, and from discussions at the NFM Project Scoping meeting in April 2019 the outputs that benefit multiple receptors (Appendix A 2.2) have been used to select locations to review those that have the greatest potential for interventions. Two areas (Area 1 and Area 2) have been identified due to their high potential for contributing to the flood peak, and therefore could be key target areas for slowing flows and reducing runoff. Both of these areas fall within the River North Esk catchment.

Potential multiple-benefit opportunities have also been discussed. This has been completed using Morphological Impact Assessment System (MImAS) datasets and the SEPA Water Classification Data¹⁵. By using these spatial datasets, it is possible to investigate where a change to the watercourse for environmental enhancement could be designed to provide flood risk management benefits.

5.1 Validation

Outputs from the tool were assessed against SEPA surface water flood mapping and NFM opportunity maps, in order to validate the tool outputs i.e. ensure they correlated with existing data. Whilst the two analysis methodologies differ from the SCIMAP-Flood tool, the governing processes within the tools would generate a spatial correlation, therefore using these two datasets for validation will provide a sense check of the outputs.

5.1.1 SEPA Surface Water Flood Mapping¹⁶

Figure 5-1 shows surface water flooding across the River Esk catchment, a rapid flood spreading model was used where a depression fills up and spills into a neighbouring depression is applied, this simplified approach

¹⁴ Forth Estuary Local District Plan: http://apps.sepa.org.uk/FRMStrategies/pdf/pva/PVA_10_22_Full.pdf

¹⁵ Water Classification Data: <https://www.sepa.org.uk/data-visualisation/water-classification-hub/>

¹⁶ SEPA Flooding Mapping: <http://map.sepa.org.uk/floodmap/map.htm>

means flow pathways are not accounted for¹⁷. The rainfall duration used in the SEPA report was the 1- and 3-hour durations meaning results are representative of the short duration high intensity storms therefore in some locations the 'critical storm' may not be represented in outputs¹⁷. To represent the differences between urban and rural runoff different rainfall response methodologies were applied. In rural areas percentage runoff of 50% for LiDAR areas and 55% for NEXTmap data was applied, with no allowance for drainage losses¹⁷. Within urban areas percentage runoff of 70% and losses of equivalent to the 5-year return period for LiDAR areas and 12mm/hr for NEXTmap areas was applied. Furthermore, areas with flood depths less than 0.1m were also removed due to the low risks associated with this shallow flow¹⁷.

The above methodology used to produce the SEPA Surface Water Flood Maps commonly mean that rural areas are not identified within the maps. Therefore, most of the surface water flooding displayed tends to align to watercourses and areas with flat floodplains. The high-risk locations within the surface water flood map (Figure 5-1) are proximal to those identified in SCIMAP-Flood in Appendix A 2.1 and 2.2. However, the function of floodplains is not built into SCIMAP-Flood, therefore floodplain locations with high risk of surface water flooding could be enhanced to provide additional storage or increase connectivity between the channel and floodplain.

Surface water flooding highlighted in and around the urban areas is not reflected in the refined SCIMAP-Flood outputs as these locations were recorded as low risk due to lack of NFM potential. This does not mean they are not likely to contribute to flood peak, simply that they are outside the scope of this work.

¹⁷ SEPA Surface Water Mapping Methodology: https://www.sepa.org.uk/media/163408/surface_water_summary.pdf

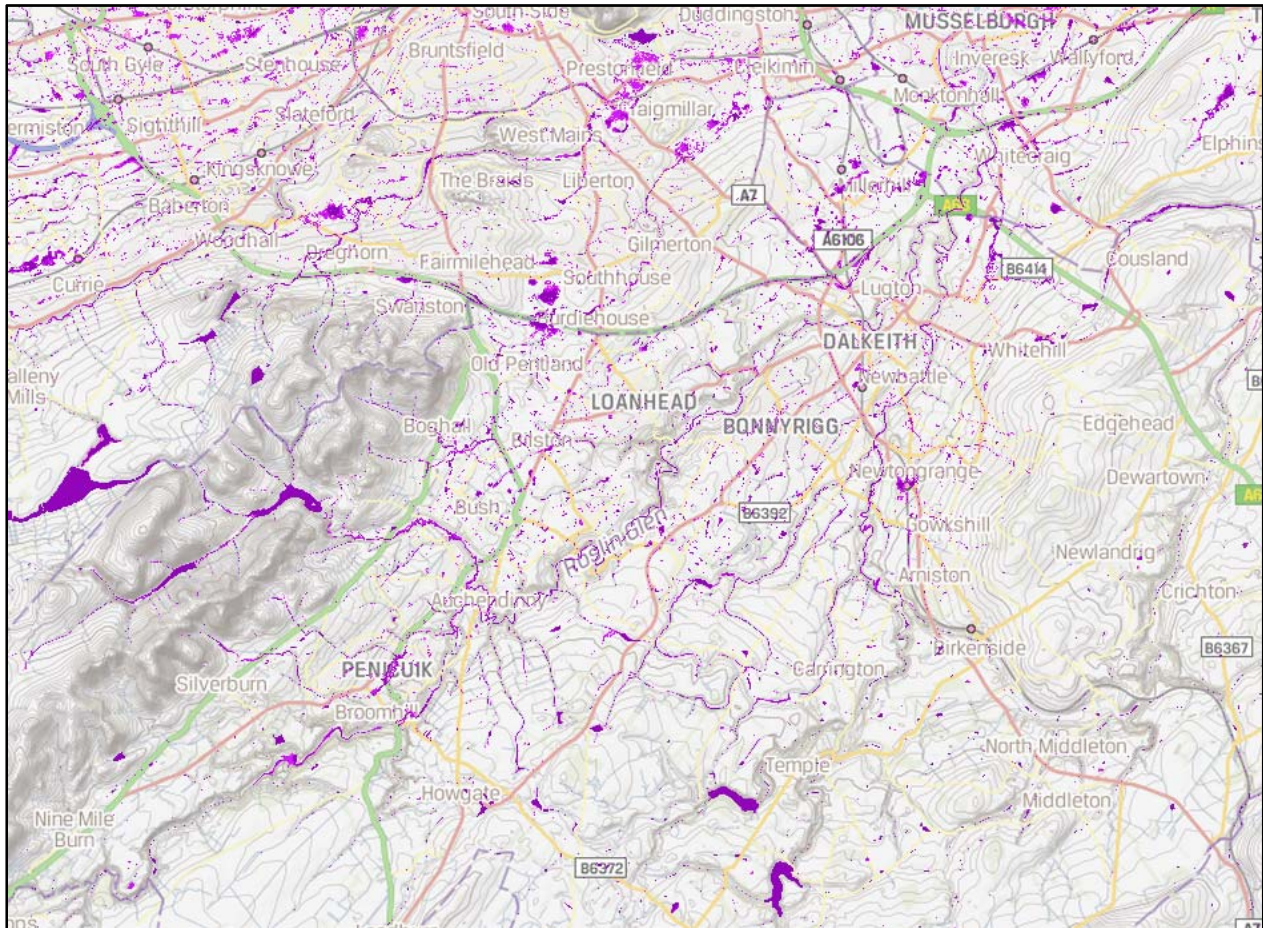


Figure 5-1: Surface Water Flood Map (SEPA, 2019).

5.1.2 SEPA Natural Flood Risk Management Opportunity Mapping¹⁸

The Natural Flood-Risk Management Opportunity areas mapping for runoff reduction and floodplain storage shown in Figure 5-2 and Figure 5-3, respectively, highlights several areas throughout the River Esk catchment. The largest collective area of interventions is located in the upper reaches of the River North Esk catchment in the Pentland Hills for runoff reduction. When compared to the outputs for both Corine land cover and SPR (Appendix A 2.1 and 2.2), it is evident that the maps do not entirely correlate with the SEPA NFM opportunity map. This is thought to be attributed to the following reasons:

Runoff Reduction

There are limited areas within the catchment identified as having opportunities for runoff reduction from the SEPA NFM opportunity mapping. This is to be expected given the maps are generated at a national scale and the runoff reduction areas are weighted towards areas with steep slopes and high annual average rainfall. The

¹⁸ SEPA Flooding Mapping: <http://map.sepa.org.uk/floodmap/map.htm>

weighting of the runoff reduction maps by SEPA means that within Scotland, there is a higher weighting for NFM opportunities in the uplands, particularly in the North and West of Scotland.

The outputs from SCIMAP-Flood consider hydrological connectivity and travel time to the points of impact for the target catchment only. This means that the risks are produced relative to the catchment and are not aggregated across the country. Simply put this means that the areas of greatest risk of contributing to peak flows can only be referenced as the greatest risk within this catchment and that there will always be a high and a low risk area irrespective of whether the area is actually a high risk nationally. There may be many more areas with higher risk characteristics outside of the catchment that are more nationally significant.

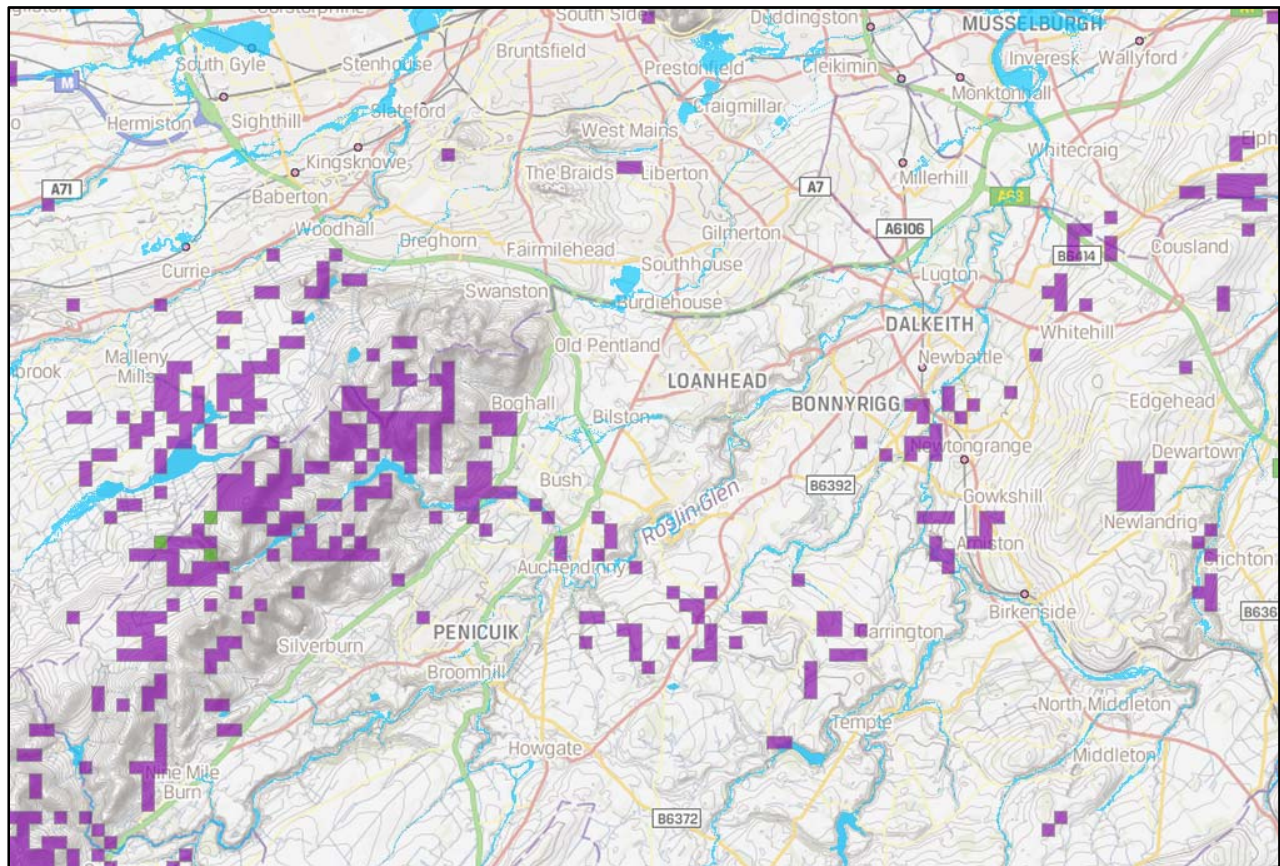


Figure 5-2: Natural Flood Risk Management Opportunity Mapping for Runoff Reduction, Highlighted in Purple (SEPA, 2019).

Floodplain Storage

There are very few areas within the catchment identified as having opportunities for floodplain storage from the SEPA NFM opportunity mapping. Like the runoff reduction mapping, this is to be expected given the maps are generated at a national scale. The floodplain storage mapping targets areas of gently sloping floodplain

and landcovers with good intervention potential. It is also worth noting that the mapping shows large bodies of water such as reservoirs and lochs to have potential for floodplain storage, however they are not suitable locations for NFM.

The SCIMAP-Flood methodology uses a slightly different risk weighting to that of the SEPA mapping, in particular, waterbodies are given a low weighting (Appendix A.1.2) and as such are not identified as areas of risk/opportunities. Similarly, the potential of floodplains is not numerically assessed as the tool finds the risk areas as a combination of high-risk land cover aligned with flow routing and timing. However, the process of reviewing spatial location of high risk and potential for floodplain attenuation could provide useful areas to consider mitigation downstream of locations at high risk of contributing to peak flows within the catchment.

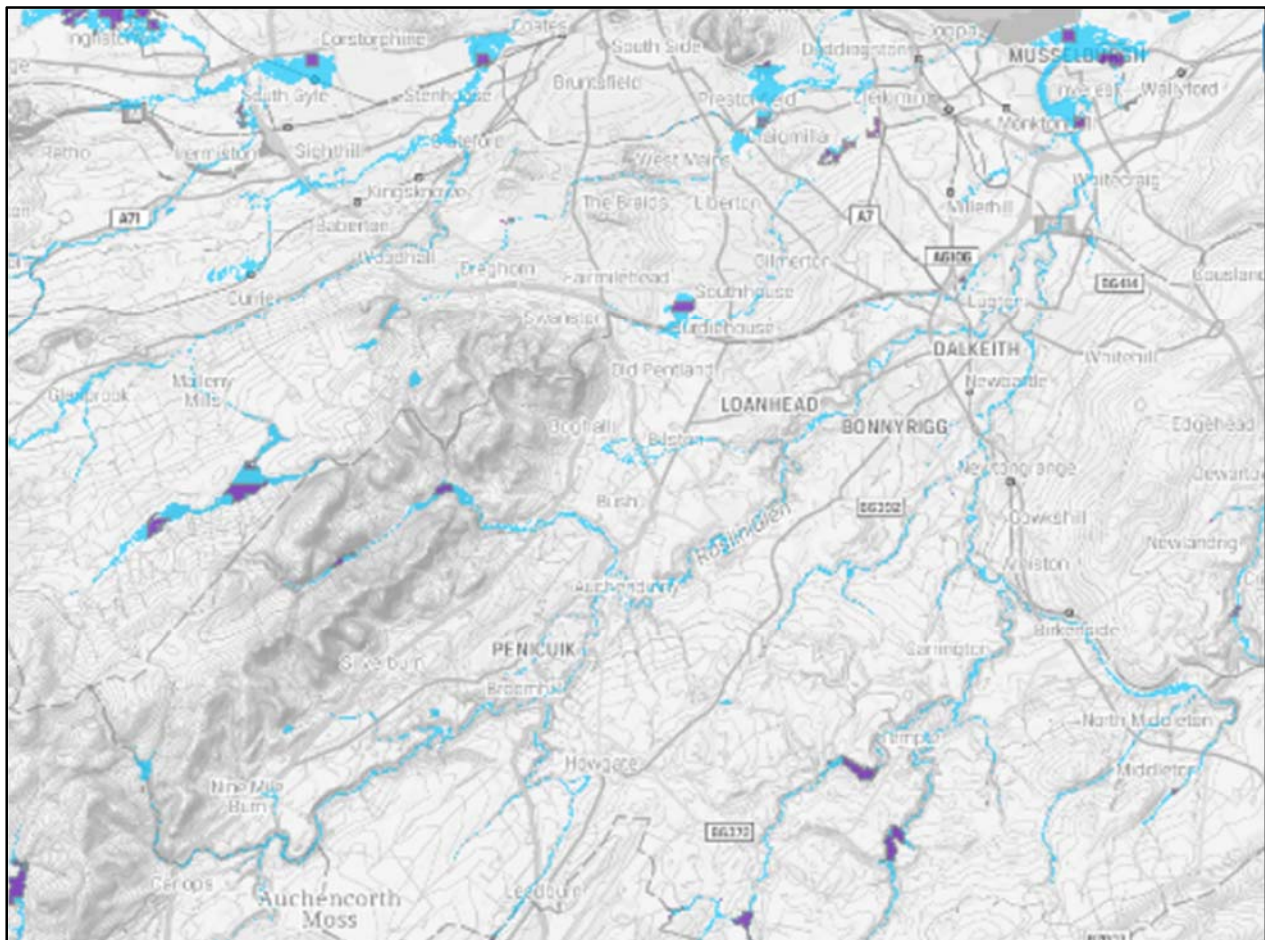


Figure 5-3: Natural Flood Risk Management Opportunity Mapping for Floodplain Storage, Highlighted in Purple (SEPA, 2019).

5.2 Area 1

Area 1 outlined in red in Figure 5-4 looks at a small subcatchment that lies within the upper reaches of the River North Esk catchment, Area 1 mainly comprises of the Lead Burn watercourse (Appendix A.4) and a number of smaller tributaries. The area surrounding Lead Burn is predominately improved grassland with moorland with several properties dispersed throughout the catchment, the A701 runs parallel to the watercourse, the hamlet of Lead Burn sits on the junction of the A701, A703 and A6094. There are many small strips of woodland adjacent to fields in the catchment as well as areas of conifer plantations.

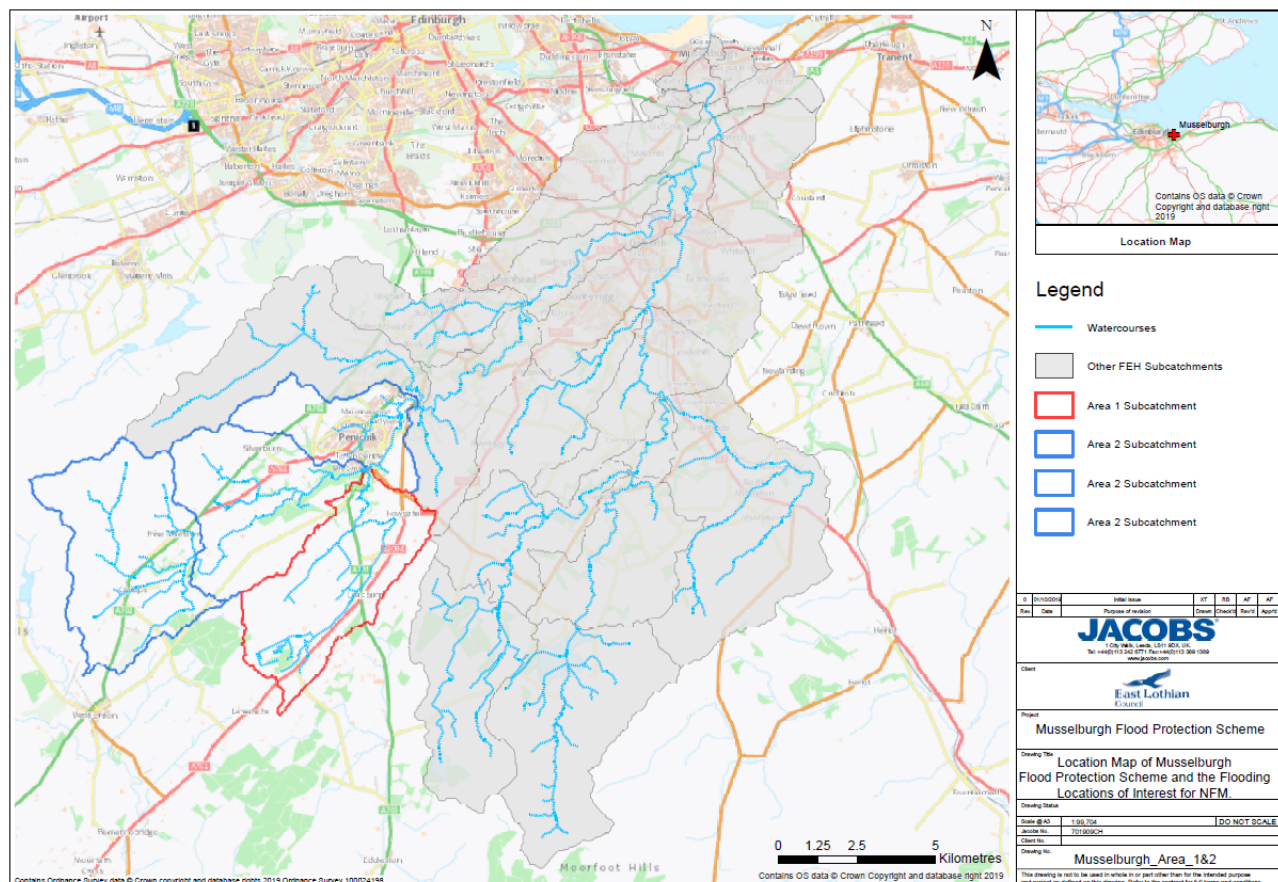


Figure 5-4 Location Map for Area 1 (Red Catchment).

5.2.1 SCIMAP-Flood High Risk Areas

The results of SCIMAP-Flood risk mapping show relatively high hydrological connectivity in the Lead burn catchment including its tributaries (Figure 5-5 and Figure 5-6). The results of SCIMAP-Flood produce a spatially variable risk rating within the catchment boundary. Risk ratings range from 0 at the lowest risk to 1 at the highest risk.

SCIMAP-Flood Using Corine Land Cover Mapping

Within this area runoff weightings are generally between 0.3 and 0.6, this means that cells have between a 30-60% likelihood of generating runoff that contributes to peak flows. There are also isolated areas weighted at 0.6-0.7 (shown in Figure 5-5). These locations are located on improved grassland with an elevated risk rating (0.3 weighting, from a 0-1 scale, Appendix 1.2). Runoff generation in this area is heavily influenced by the land cover as opposed to the slope, with the surrounding area sitting relatively flat, except where Lead Burn (Appendix A.4) flows. High runoff generation is particularly evident across the area of land that sits between the A6094 and A703, located in the north-eastern section of Area 1. NFM measures that can be considered in areas of high-risk land use includes land cover and land management changes, that seek to reduce runoff by reducing hydrological connectivity (Source changes as in the SuDS Conceptual Model).

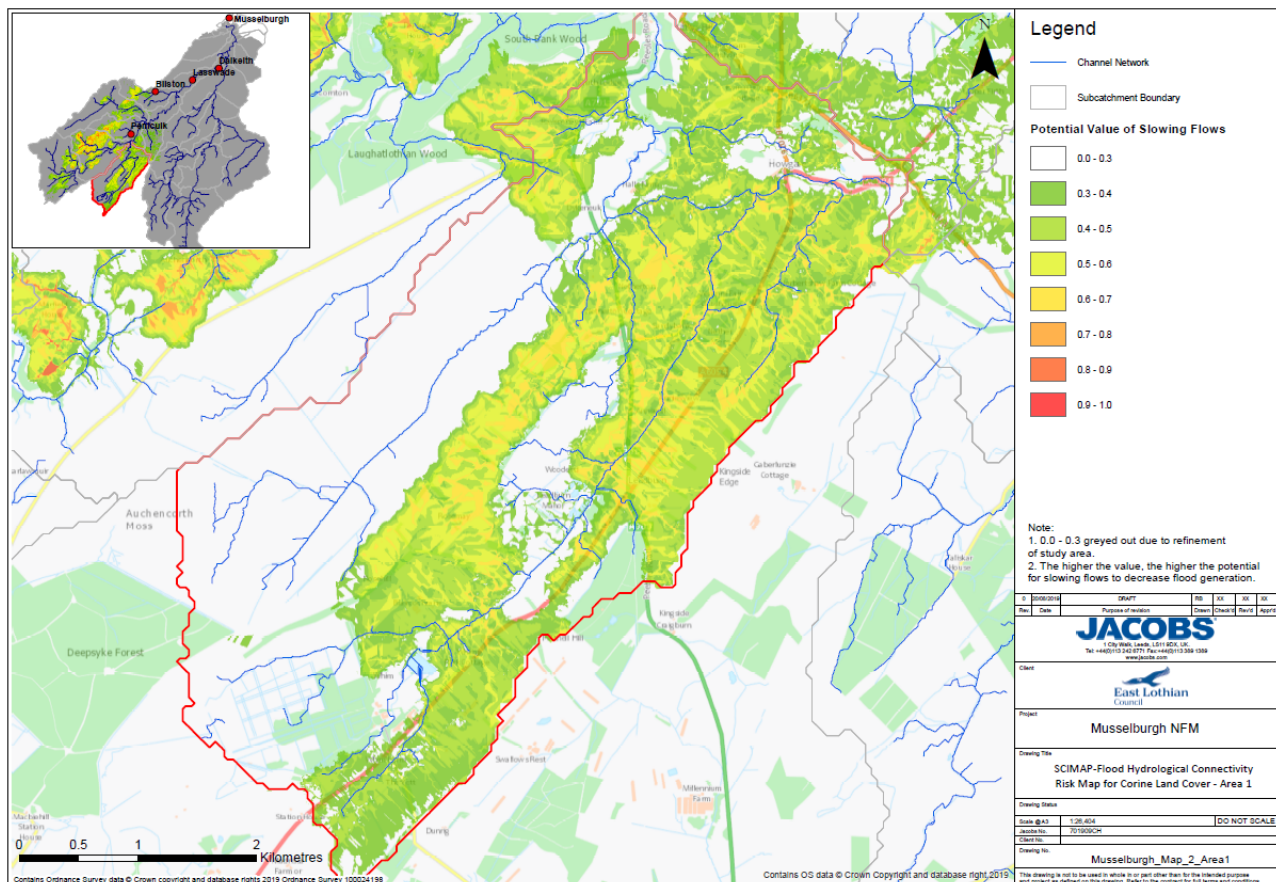


Figure 5-5: Hydrological Connectivity Risk Map for Corine Land Cover in Area 1.

SCIMAP-Flood Using SPR Mapping

It is important to consider with interventions such as land cover and land management changes whether there is potential for these changes to be effective. For example, mechanical improvements to improve infiltration

could be inhibited by underlying soil conditions that have low permeability. We therefore reviewed the SPR data to assess what would be the 'natural' baseline hydrological connectivity of the catchment. As shown in Figure 5-6 locations within Area 1 exhibit considerably greater risk scores for SPR than for land cover, with values sitting between 0.6 and 0.8. A sensitivity analysis has not been undertaken to determine whether the weightings applied are suitable, therefore, only the spatial location of these outputs should be used and not the scoring itself. The areas of highest potential (runoff) are located within the vicinity of a tributary of the Lead Burn and the Black Burn (Appendix A.4), as opposed to the Lead Burn itself when compared to the assessment being based on Corine land cover (Figure 5-5). This high runoff can be attributed to the high SPR (0.7) assigned to organic basin peat deposits in the soil runoff risk map produced by SEPA (Appendix A 1.3). The topography of the area is relatively flat, and as such it can be said that the major influencing factor for runoff generation in this area is the SPR. A result of this is that interventions in these locations should be targeted to changes to hydrological response using techniques such as increasing surface roughness or interventions in flow pathways such as runoff attenuation features or other conveyance approaches.

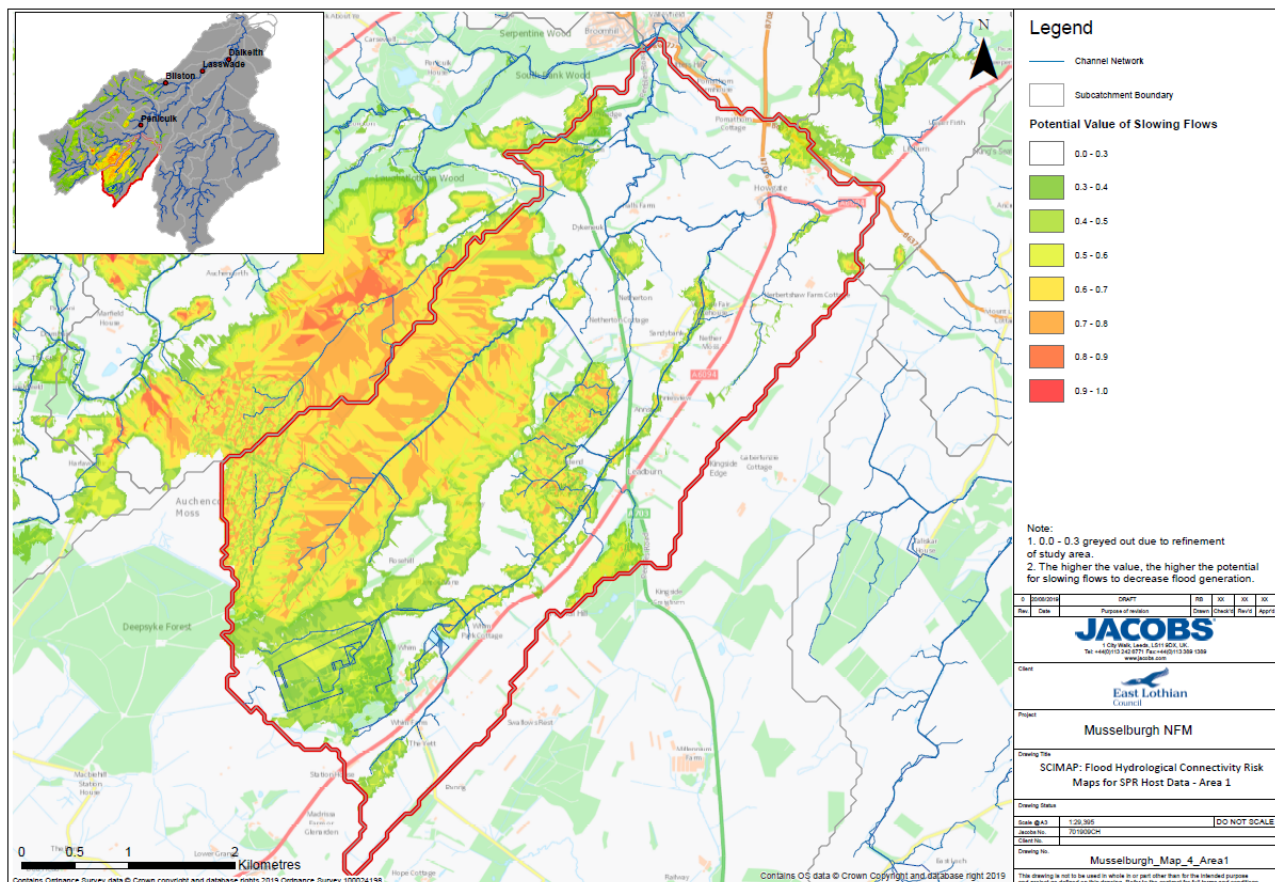


Figure 5-6: Hydrological Connectivity Risk Map for SPR in Area 1.

SCIMAP-Flood Comparison between Corine and SPR

The combination of the two assessments (Corine and SPR, in Figure 5-5 and Figure 5-6, respectively), show areas of high hydrological connectivity that could contribute to flood peak throughout almost the entire Lead Burn (Appendix A.4) catchment. The locations of high-risk land cover and high-risk soils have minimal overlap which suggest further investigations could look at both locations for different interventions. This means the catchment could potentially be suitable for a variety of NFM measures that could increase infiltration (in high landcover low SPR locations), slow the propagation of flow (suitable to both high risk areas) and attenuate the flow (suitable to both high risk areas).

Areas with higher potential highlighted in the Corine land cover (Figure 5-5) assessment would be particularly suitable to land cover change, such as planting woodlands/expanding those that already exist or by improved land management practices that mechanically deliver the improvements sought through tree planting. Improved land management could include adopting techniques such as planting cover crops, relieving soil compaction and providing cross slope interception of flows. Methods of increasing surface roughness are said to have a positive feedback loop, this feedback loop can be generated using interception planting, cover crops or riparian planting. The introduction of vegetation increases infiltration and slows runoff. By doing so it allows nutrient recapture which replenishes the soils thus making the land more fertile, thus meaning vegetation becomes self-generating quickly.

5.2.2 Opportunities in Area 1

The common occurrence of treelined fields and roads as detailed above may provide opportunity for buffer strips, cross slope swales and similar linear flow pathway interception structures. The major carriageway which runs centrally through a large swathe of high-risk area could be used to provide a corridor of interventions. That is a distinct opportunity worthy of investigation particularly if this could be timed to coincide with any carriageway works delivering efficient savings. Similarly, this could also provide enhancements by intercepting and treating runoff before it enters the watercourse providing water quality improvements.

5.2.3 Multiple-Benefit Opportunities in Area 1

An assessment of the MImAS data showed no morphological capacity restrictions in Area 1, as such an assessment of the SEPA Water Classification Data was completed. The SEPA Water Classification Data¹⁹ highlights that the current Water Framework Directive (WFD) status of the Lead Burn (Appendix A.4), the main watercourse within Area 1, was classified as 'Poor' in 2017, and has been since 2013. Lead Burn classifies as poor for the following parameters;

- Pre-HMWB (Heavily Modified Water Body) Status

¹⁹ Water Classification Data: <https://www.sepa.org.uk/data-visualisation/water-classification-hub/>

- Overall Ecology
 - o Biological elements
 - o Fish

The Black Burn (Appendix A.4), a tributary of Lead Burn, highlighted in Figure 5-6 with high potential for slowing the flow is not outlined on the water classification mapping, as such status of this watercourse is assumed to be similar within that of the Lead Burn. The absence of records within MImAS does not confirm that there are no morphological capacity issues for the catchment, simply that records are not held. There may be opportunities on the ground to improve channel morphology and WFD status, however, these should be assessed in any subsequent phases on a site by site basis.

The various measures mentioned above in Section 5.2.1 could be implemented in order to reduce runoff and provide storage without further degrading the 'Poor' WFD status that has been assigned to 'Fish' for the Lead Burn. There is potential for these interventions to be beneficial to water quality by encouraging sediment dropout and reducing diffuse pollution entering the watercourse. In addition to those mentioned in Section 5.2.1, measures such as instream wooden dam structures allow for the passage of fish while restricting discharge and slowing the flow of water through the system. Additionally, these structures can improve floodplain reconnection, restoring the natural function of floodplains, re-meandering of channels could also help to improve riparian and aquatic habitats while increasing water retention within the system benefiting low flows hydrology.

5.3 Area 2

Area 2 comprises of three subcatchments (Figure 5-7), that run along the length of the upper reaches of the River North Esk, running parallel to the Pentland Hills. The main land use across Area 2 is improved grassland and urban areas, with small areas of moorland and unimproved grassland. Improved grassland generally runs adjacent to the River North Esk, with areas of unimproved grassland and moorland in the upper reaches and hillslopes. The town of Penicuik, one of the points of impact, lies in the most easterly end of the three catchments, with the A766/A702 running parallel to the River North Esk throughout the three catchments.

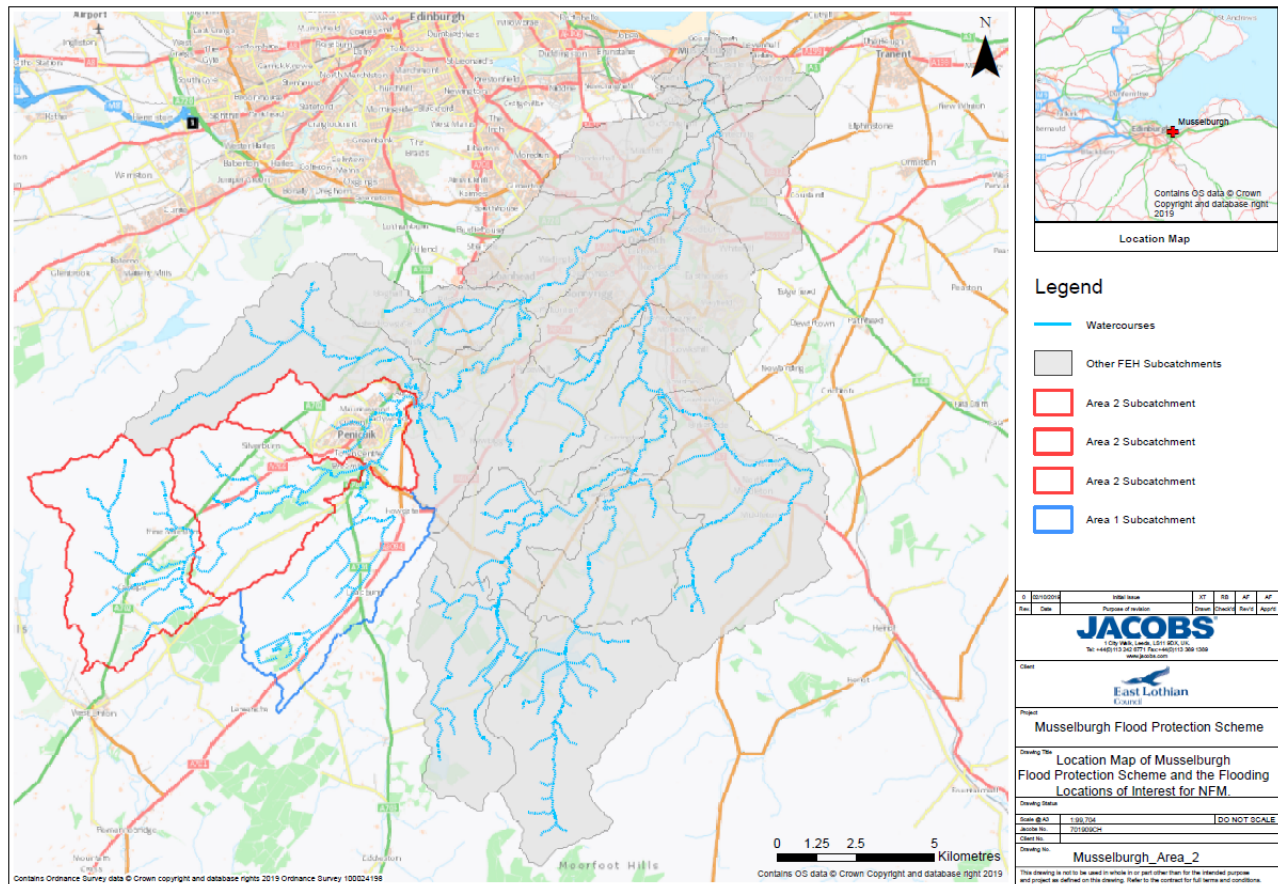


Figure 5-7 Location Map for Area 2 (Red Catchments).

5.3.1 SCIMAP-Flood High Risk Areas

The results of SCIMAP: Flood risk mapping shows relatively high hydrological connectivity in the Lead burn catchment including its tributaries (Figure 5-8 and Figure 5-9). The results of SCIMAP-Flood are spatially variable risk ratings within the catchment boundary, risk ratings range from 0 at the lowest risk to 1 at the highest risk relative to the catchment.

SCIMAP-Flood Using Corine Land Cover Mapping

Large parts of the Area 2 subcatchments have high hydrological connectivity when using the Corine land cover dataset (Figure 5-8). Risk weightings are generally between 0.3 and 0.7 (30-70% risk of contributing to peak flows), immediately adjacent some watercourses there are areas with higher risk weightings greater than 0.7 (greater than 70% risk of contributing to peak flows). These high-risk areas appear to represent steep catchments that connect into gullied watercourses. The dominant factor controlling risk here appears to be topography, as opposed to the land cover. 'Tails' of high risk, >0.8 (greater than 80% risk of contributing to

peak flows) are evident in the vicinity of the confluences of the various watercourses, particularly Cornton Burn and its tributaries (Appendix A.4), characteristic of gullies formed as a result of a steep slope and high runoff. These tributaries drain the Pentland Hills, hence the steep slope characteristics. As such, runoff in these areas is likely to be fast flowing and mostly driven by physical/topographic forcing. Flow path intervention methods such as runoff attenuation features like swales and timber bunds are likely to be the most suitable methods to intercept, attenuate and discharge in a controlled manner along less steep slopes to the River North Esk. Other 'end of system' opportunities could be considered such as online/offline ponds could be considered downstream of the steep areas of the catchment.

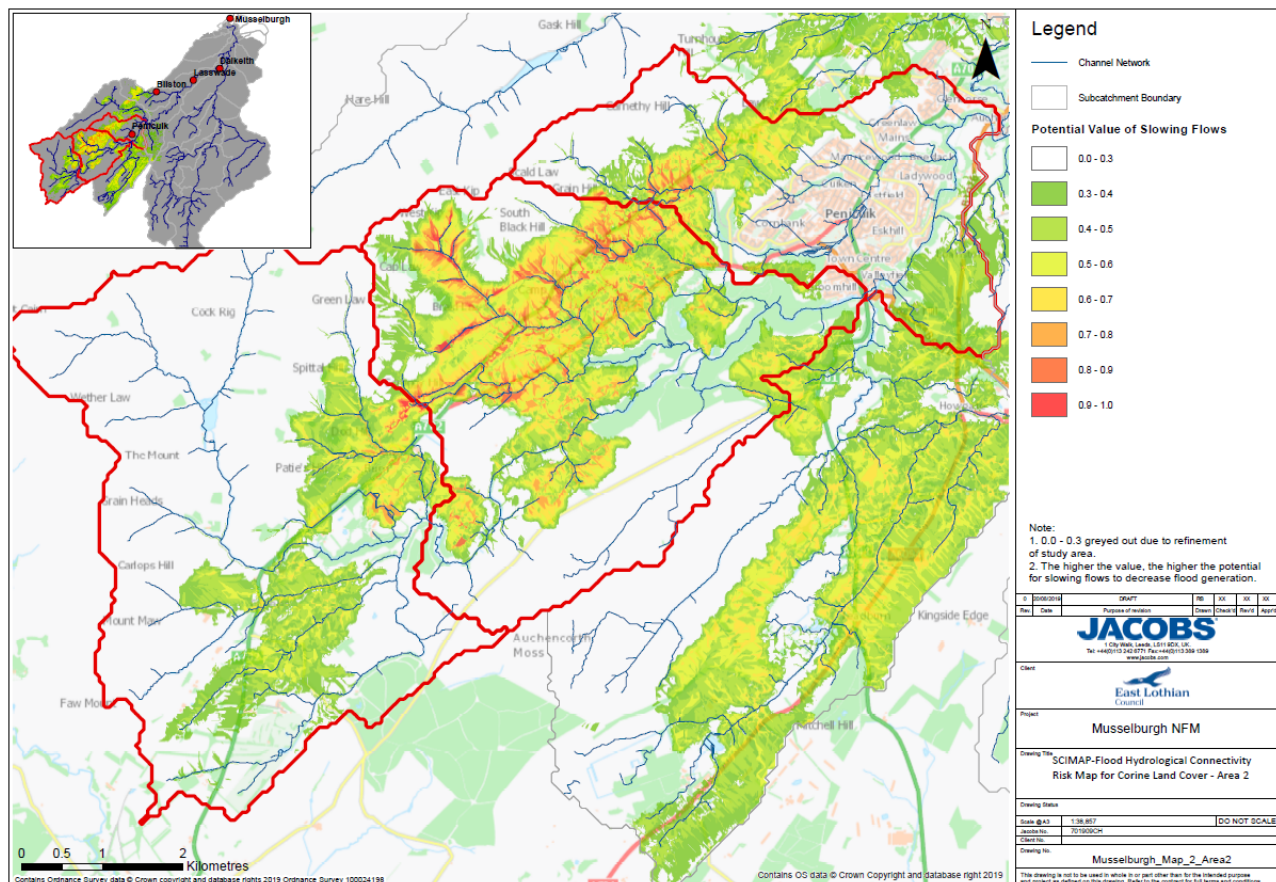


Figure 5-8: Hydrological Connectivity Risk Map for Corine Land Cover in Area 2.

SCIMAP-Flood Using SPR Mapping

The primary high-risk area identified using SPR sits immediately adjacent the high-risk area identified in Area 1 (Figure 5-9), lying within the southern region of the central subcatchment of Area 2. Predominately the high risk is in the vicinity of a tributary of the River North Esk, Hare Burn (Appendix A.4). Again, like Area 1, this area with a high runoff risk is associated with the high runoff weighting assigned to organic basin peat deposits,

by SEPA in the runoff risk map (Appendix A 1.3). An assessment of the input data shows that the topography of the area (predominately flat) has a less significant influence on runoff generation compared to the SPR of the soil. As such it is thought that the main driver of high runoff generation in this area is the soil SPR, with the SPR value in the vicinity of Hare Burn being classified as High (0.7), as shown in appendix A 1.3. A result of this is that interventions in these locations should target ground changes to hydrological response using techniques such as increasing surface roughness, runoff attenuation features or other storage approaches as there is limited scope to increase infiltration. Another noticeable factor within this location is that the high risk SPR is immediately adjacent to the watercourse, in most locations the high SPR values do not extend right up to the watercourse. There is quite often a buffer around the watercourse of lower SPR, this is commonly associated with alluvial gravels and silts that are permeable. This is not the case in the peat areas demonstrated by the high SPR risks. The locations identified as suitable for interventions are located in Area 2 with values generally sitting between 0.3 and 1.0 (30% to 100% likelihood of generating runoff that contributes to peak flows), as shown in Figure 5-9.

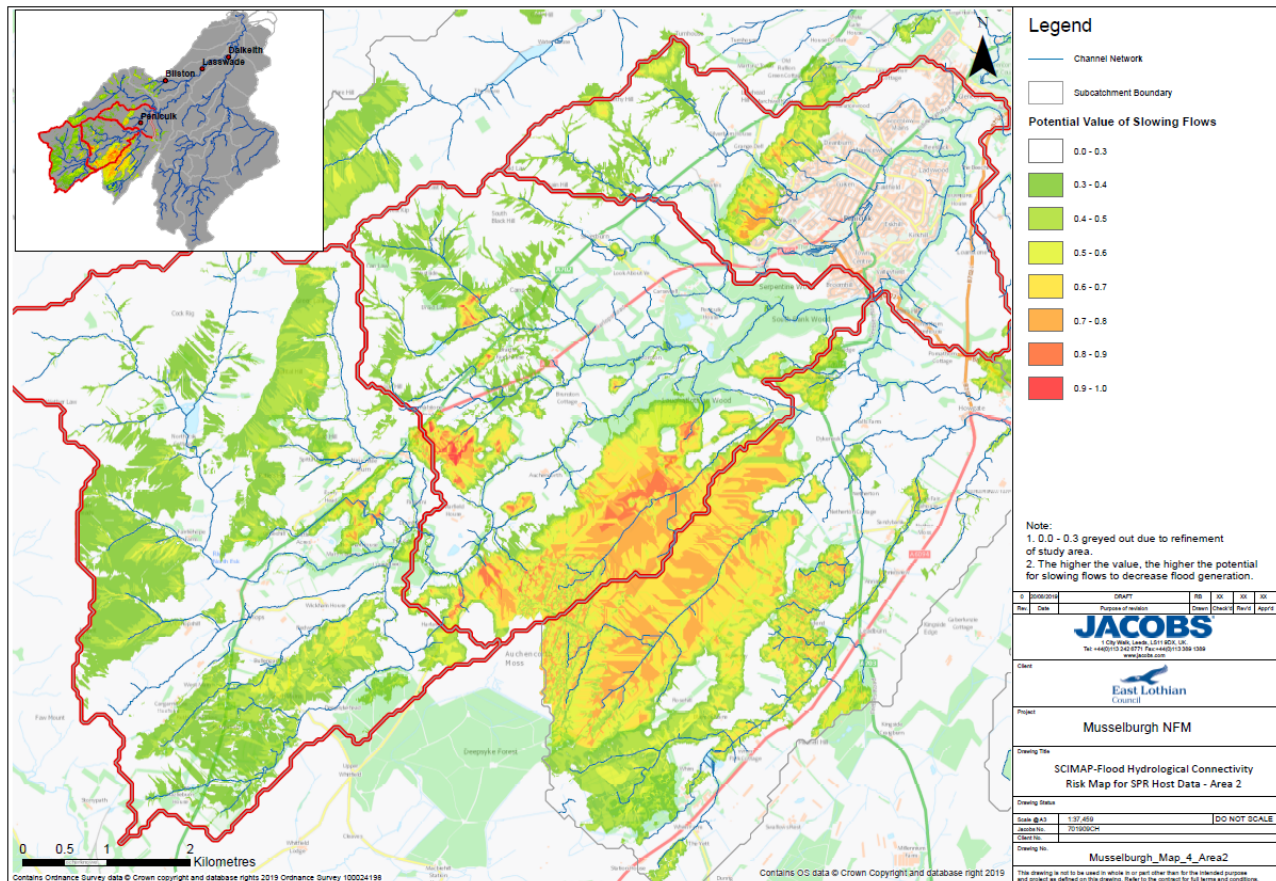


Figure 5-9: Hydrological Connectivity Risk Map for SPR in Area 2.

SCIMAP-Flood Comparison between Corine and SPR

The combination of the two assessments (Corine and SPR, in Figure 5-8 and Figure 5-9, respectively), show areas of high hydrological connectivity that could contribute to flood peak throughout Area 2. The locations of high-risk land cover and high-risk soils have minimal overlap which suggest further investigations could look at both locations for different interventions. This means the catchment could potentially be suitable for a variety of NFM measures that could increase infiltration (in high landcover low SPR locations), slow the propagation of flow (suitable to both high risk areas) and attenuate the flow (suitable to both high risk areas).

Areas with higher potential highlighted in the Corine (Figure 5-8) assessment would be particularly suitable to land cover change, such as planting woodlands/expanding those that already exist or by improved land management practices that mechanically and manually deliver the improvements sought through tree planting. Improved land management could include adopting techniques such as planting cover crops, relieving soil compaction and providing cross slope interception of flows. Methods of increasing surface roughness are said

to have a positive feedback loop, this feedback loop can be generated using interception planting, cover crops or riparian planting.

5.3.2 Opportunities in Area 2

Much of the area identified as being at elevated risk as detailed above is uphill of another major carriageway located in a number of discrete catchments. This is another opportunity to use the infrastructure adjacent to the carriageway to intercept, slow and store surface water before it drains into the main channel. The ground modifications associated with a major carriageway would make above ground storage potentially feasible.

The areas of higher risk appear to be steep areas of moorland, there are opportunities to use techniques to maximise peat bog storage such as those used at Kinder Scout. The benefits of these interventions are largely to the peat moors themselves which flood risk management benefits varying due to saturation of peat and rapid onset of saturation driven overland flow. Benefits are more pronounced when performed on degraded/drained peat moorland; high level sampling performed has not suggested this is the case however this is a possibility worthy of detailed review.

5.3.3 Multiple Benefit Opportunities in Area 2

An assessment of the MImAS data for Area 2 (Figure 5-10) showed that there have been a number of morphological changes to the area, predominately green embankment reinforcement (bank reprofiling), of which is noted throughout all three subcatchments. In addition, there are also several locations in the downstream subcatchment where there are grey bank reinforcements (set-back embankments/ Hard bank reinforcements), embankments with no bank reinforcements and a section of the river with embankments with bank reinforcement (floodwall). All these locations highlight areas where there have been morphological changes to the river, the removal or modification of which could provide areas of multiple-benefit, particularly locations subject to hard engineering where NFM interventions could generate an improvement in the WFD status of the river. As such, these areas could be subject to NFM measures such as re-meandering which would encourage out of bank flows delaying the arrival at the downstream receptor, thus providing flood management and improving the waterbody status of the river. Removal of embankments needs to be carefully considered as in some locations these banks throttle the flow being passed downstream and prevent water that spills onto the floodplain connecting back into the channel and therefore inadvertently provide offline storage.

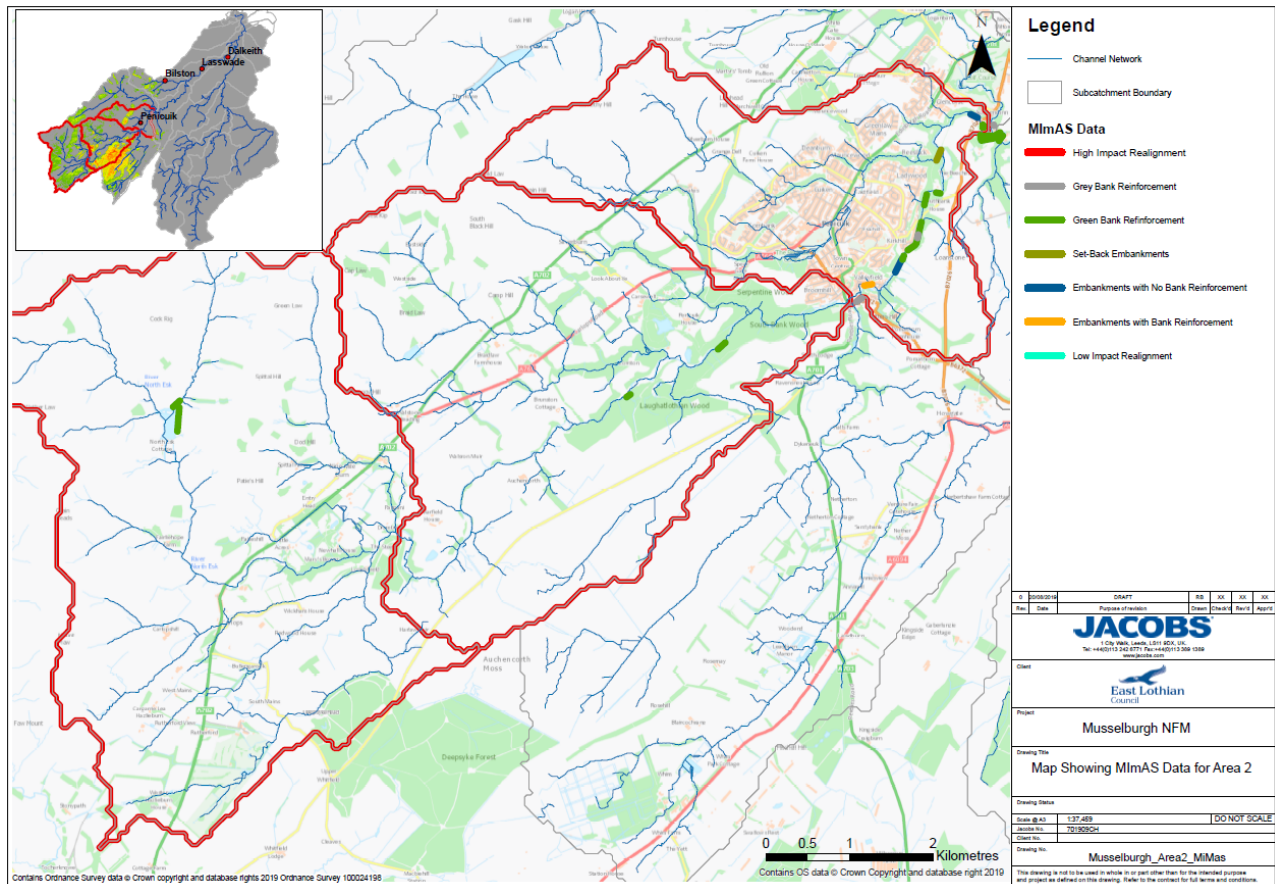


Figure 5-10: MImAS Data Identified in Area 2.

In addition to the MImAS data, an assessment of the SEPA Water Classification Data²⁰ was also completed. The SEPA data highlights that the current WFD status of the River North Esk, the main watercourse that flows through Area 2, is currently classified as 'Poor' in 2017, and has been since 2013. The River North Esk is split into two sections throughout Area 2, with the upper-most reach, which runs from the most westerly subcatchment and into the middle subcatchment (referred to as 'Source to Penicuik House') holding 'Poor' status for the following parameters;

- Pre-HMWB Status
- Overall Ecology
 - o Biological elements
 - o Fish

²⁰ Water Classification Data: <https://www.sepa.org.uk/data-visualisation/water-classification-hub/>

Various runoff reduction measures could be implemented in order to slow and attenuate the flow without further degrading the 'Poor' WFD status that has been assigned to 'Fish' for the River North Esk. Measures such as instream dam structures made from wood allow for the passage of fish under the structures.

The second section of the River North Esk, known as Penicuik House to Glencorse Burn confluence (Appendix A.4), runs through the middle subcatchment and into the third subcatchment, and is classified as poor for the same parameters as the section of the River North Esk that runs from the 'Source to Penicuik House'. As such, similar runoff reduction measures could be looked at for this area of the North Esk.

6. Conclusion and Recommendations

It is evident that throughout the River North Esk catchment there are several areas that could benefit from the implementation of attenuation and runoff reduction measures in order to decrease flood generation, particularly in the upper reaches of the catchment. By reviewing and comparing the outputs from the SCIMAP-Flood tool using Corine land cover and SPR data, it is possible to see that there is potential for the changes brought about by land cover to have influenced high-risk runoff generation in different areas of the catchment, from what would have been the 'natural' hydrological connectivity of the catchment.

The areas identified, Area 1 and 2, allow for a focus for future studies to look at the potential for NFM within areas that are most likely to contribute to the flood peak at the downstream receptors. Whilst various measures are discussed, the limitations of catchment data mean these aren't recommendations. They do however help narrow the scope of further investigations spatially and technically, identifying locations where certain types of techniques are less likely to be suitable.

As mentioned previously, there is great potential with NFM to achieve multi-benefits such as biodiversity and environmental net gain. If NFM measures are to be implemented in these areas following further analysis for suitability, it is possible that such measures could provide a multi-benefit outcome. For example, the Lead Burn (Appendix A.4) has a 'Poor' WFD status and NFM measures that remove confinement, facilitate fish passage and reduce diffuse pollutants could aid with the improvement of the WFD status as an incidental benefit of reducing flood risk.

In summary, the key points from this study are:

- Further NFM studies could be considered for Musselburgh, however, to do so it is recommended that a study is undertaken which considers all the receptors along the River North Esk in a holistic catchment management plan. The size of the intervention areas highlighted in Area 1 and 2 are small in relation to the catchment contributing to Musselburgh and would therefore likely result in minimal benefits and volume change. Changes in flood peak at Musselburgh alone would require larger subcatchments that could be looked at to change the way the areas respond to rainfall. Therefore, it is recommended that for Musselburgh FRMS alone further NFM assessments are not undertaken, it is anticipated that interventions would have insufficient changes to flood risk to deliver demonstrable benefits.
- Above ground storage may be considered throughout the floodplains of the North Esk, however, without understanding the existing flood extent for specific flood events it is not known whether there is scope to sustainably increase that storage potential. This study has identified that the North Esk is

primed for a multi-receptor NFM assessment and there are catchment conditions that generate an elevated likelihood of rapid connectivity that could contribute to the flood peak at Musselburgh.

- The study narrows the focus of detailed and costly hydrological modelling from the entire River Esk catchment to specific locations, such as Area 1 and Area 2, filtering out those that would likely not influence flood conditions at Musselburgh and other receptors within the catchment. The GEAR rainfall data used for the study showed that higher intensity rainfall was experienced predominately over the North Esk catchment area throughout the 21 chosen rainfall events. This assessment has not determined whether there is a causal link between the spatial distribution of rainfall and flood risk at Musselburgh. However, for the 21 incidents used in this assessment there does appear to be a correlation with rainfall distribution and peak flows. As such, a more extensive rainfall data set should be assessed to gain a comprehensive understanding of rainfall tracking over the whole of the Esk catchment.
- Finally, areas identified should undergo further analysis for the suitability of NFM, including site visits and investigations. Recommendations would include completing a site visit to get an improved understanding of land use, to enable a more detailed refinement of the runoff weightings within the catchment areas identified as potential areas to look at the implementation of NFM. In addition to this, research into special designations assigned to the various land parcels would also allow further refinement of where to further assess if NFM measures could be implemented.

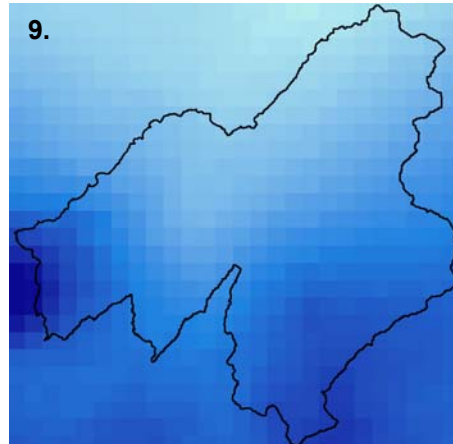
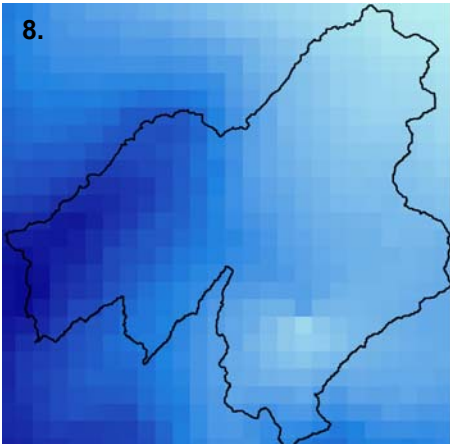
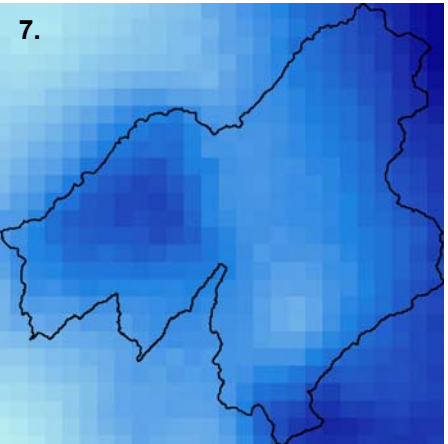
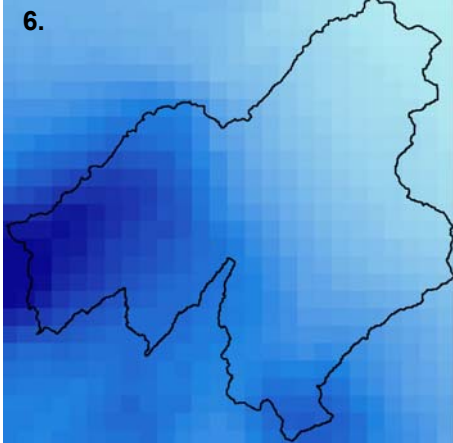
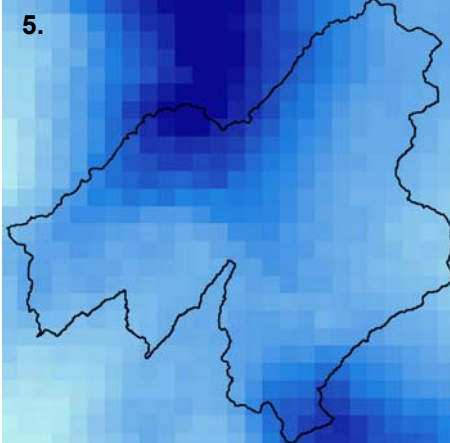
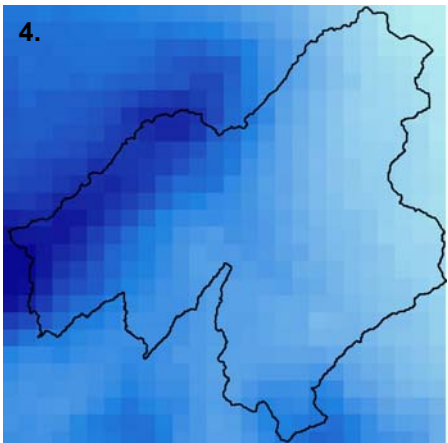
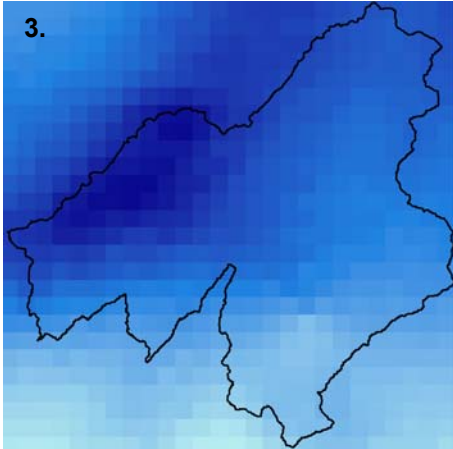
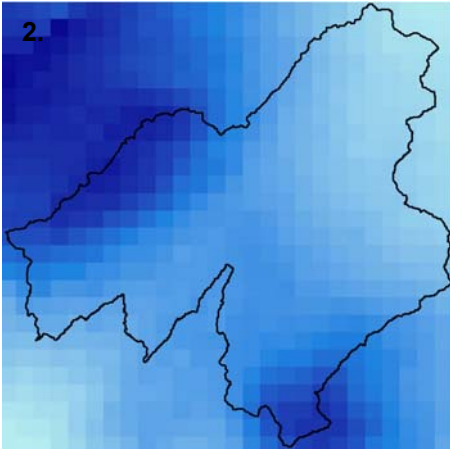
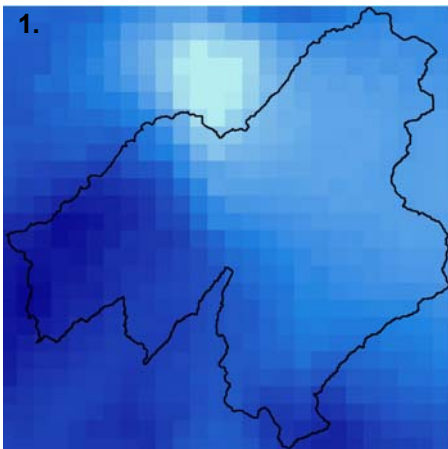
Appendix A. Additional Information

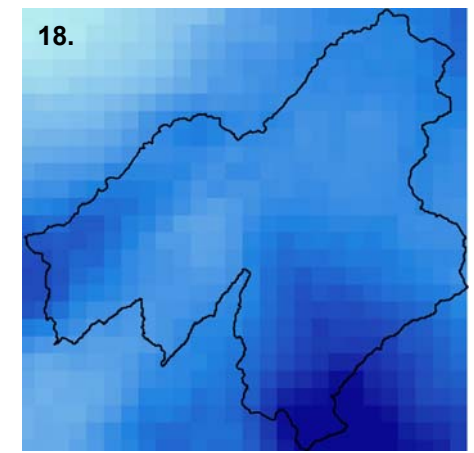
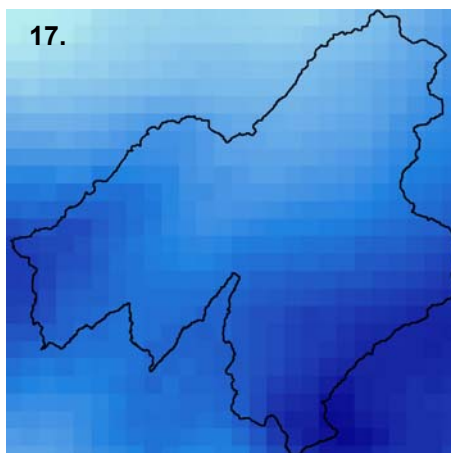
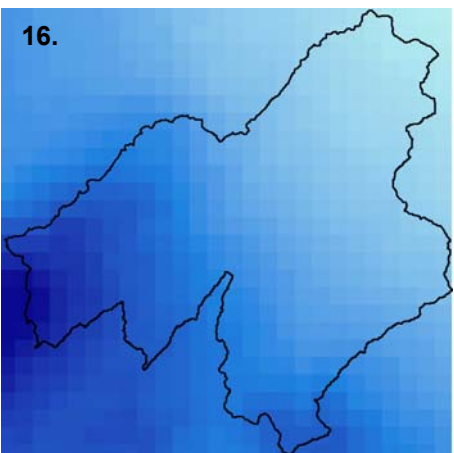
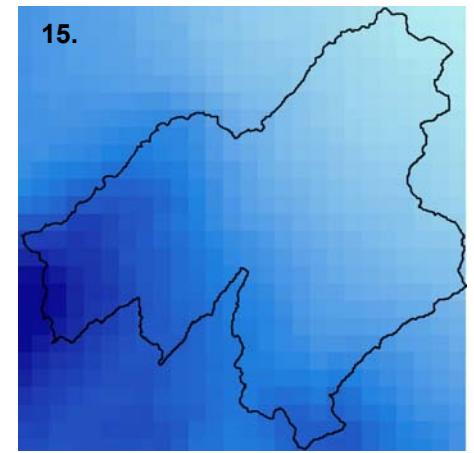
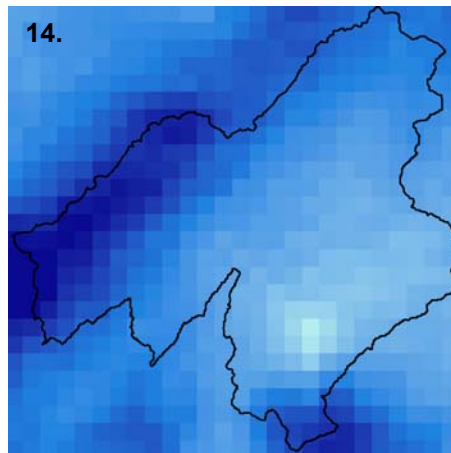
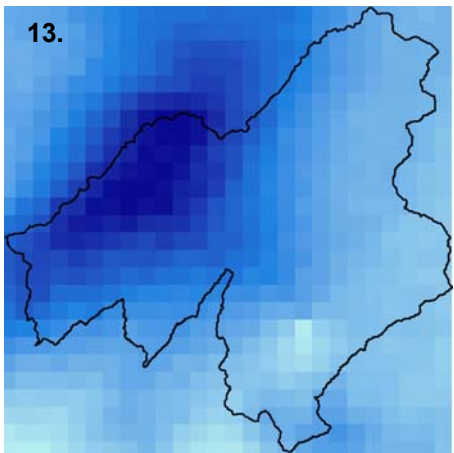
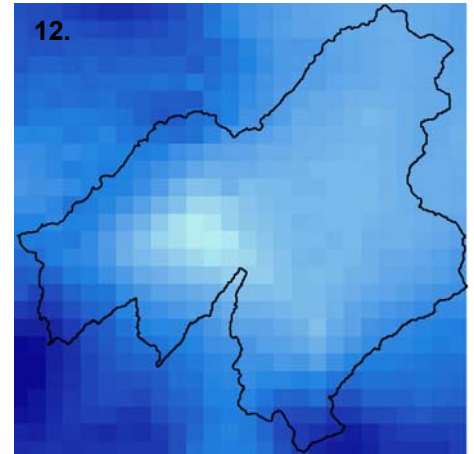
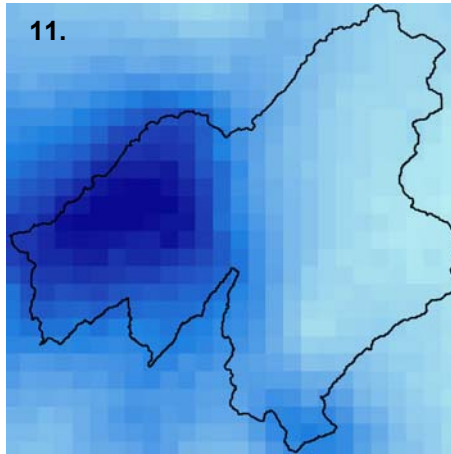
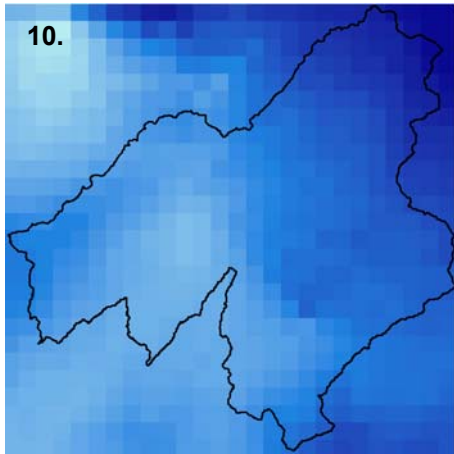
A.1 Input Data

A.1.1 GEAR Rainfall Event Selection

Table 1: GEAR Rainfall Events Selected based on Flow Data Observed at the Dalkeith and Cowbridge River Gauges.

Event	Time	Flow	Storm Date	Year
1	16/11/2006 01:30	53.138	15/11/2006	2006
2	19/08/2007 09:00	52.862	18/08/2007	2007
3	21/11/2007 21:00	69.094	21/11/2007	2007
4	09/01/2008 00:45	61.640	08/01/2008	2008
5	07/08/2008 05:30	90.191	06/08/2008	2008
6	26/10/2008 00:30	58.289	25/10/2008	2008
7	04/09/2009 12:30	66.058	03/09/2009	2009
8	19/11/2009 22:30	50.404	19/11/2009	2009
9	16/01/2010 15:00	62.676	15/01/2010	2010
10	30/03/2010 20:30	69.283	30/03/2010	2010
11	13/01/2011 14:30	57.887	13/01/2011	2011
12	07/02/2011 15:30	73.605	06/02/2011	2011
13	11/08/2011 16:15	106.798	10/08/2011	2011
14	17/10/2011 20:15	79.539	17/10/2011	2011
15	05/01/2012 02:00	50.160	04/01/2012	2012
16	07/07/2012 11:45	142.697	06/07/2012	2012
17	25/09/2012 11:15	96.873	24/09/2012	2012
18	30/12/2013 18:00	64.642	30/12/2013	2013
19	22/12/2014 07:45	80.015	21/12/2014	2014
20	05/12/2015 07:30	86.089	05/12/2015	2015
21	26/12/2015 21:45	93.452	26/12/2015	2015





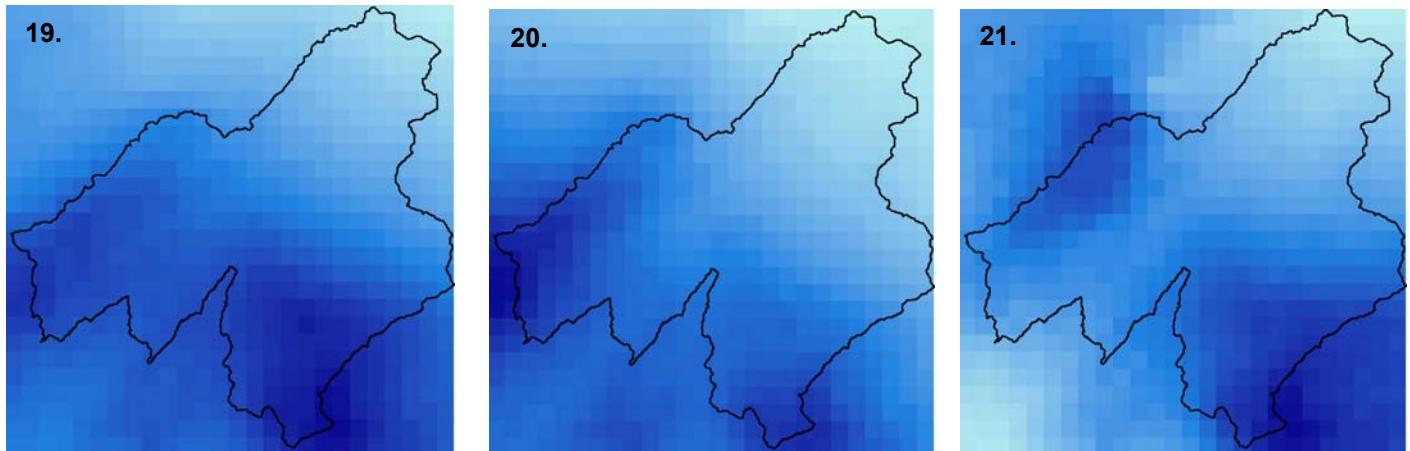


Figure 1. The 21 Selected GEAR Rainfall Events (Light Blue = Low Rainfall, Dark Blue = High Rainfall).

A.1.2 Corine Land Cover Data for the River Esk Catchment

Table 2: Water Generation Risk Weightings, based on a Simplification of the CEH Land Cover Weightings, taken from the SCIMAP-Flood Tool Methodology.

Id	Land Cover	Weight	Notes
1	Woodland	0.05	Woodland has been given a lower risk weight due to the high infiltration rates and lower saturation deficits within the soil
2	Arable	0.8	Arable has been assigned a high-risk weight due to the widespread use of soil drainage that rapidly transfers water to the river channels.
3	Improved Grassland	0.3	Improved grassland has been given a higher weighting than un-improved grasslands due to the likely compaction of the soils by livestock, which results in lower infiltration rates.
4	Unimproved Grassland	0.15	Unimproved grassland has been given a risk weight above woodland.
5	Urban	1.0 [*]	Urban has been assigned a high-risk weight due to the impermeable surfaces and effective drainage that rapidly transfers water to the river channels. Although not tackled directly with NFM, SuDS and elements of NFM could be applied.
6	Moorland	0.1	Moorland has been given a lower weighting than unimproved grasslands to reflect the more natural soil structure and low potential compaction.
7	Water and inland rock	0.0	Although lakes, rivers and inland rock will convert all of the rainfall water to runoff, it is not possible to modify this behaviour with NFM measures and hence water has been given a low value

^{*} This is the default value, for the purpose of this study, this value was changed to 0.



A.1.3 SPR HOST Data for the River Esk Catchment

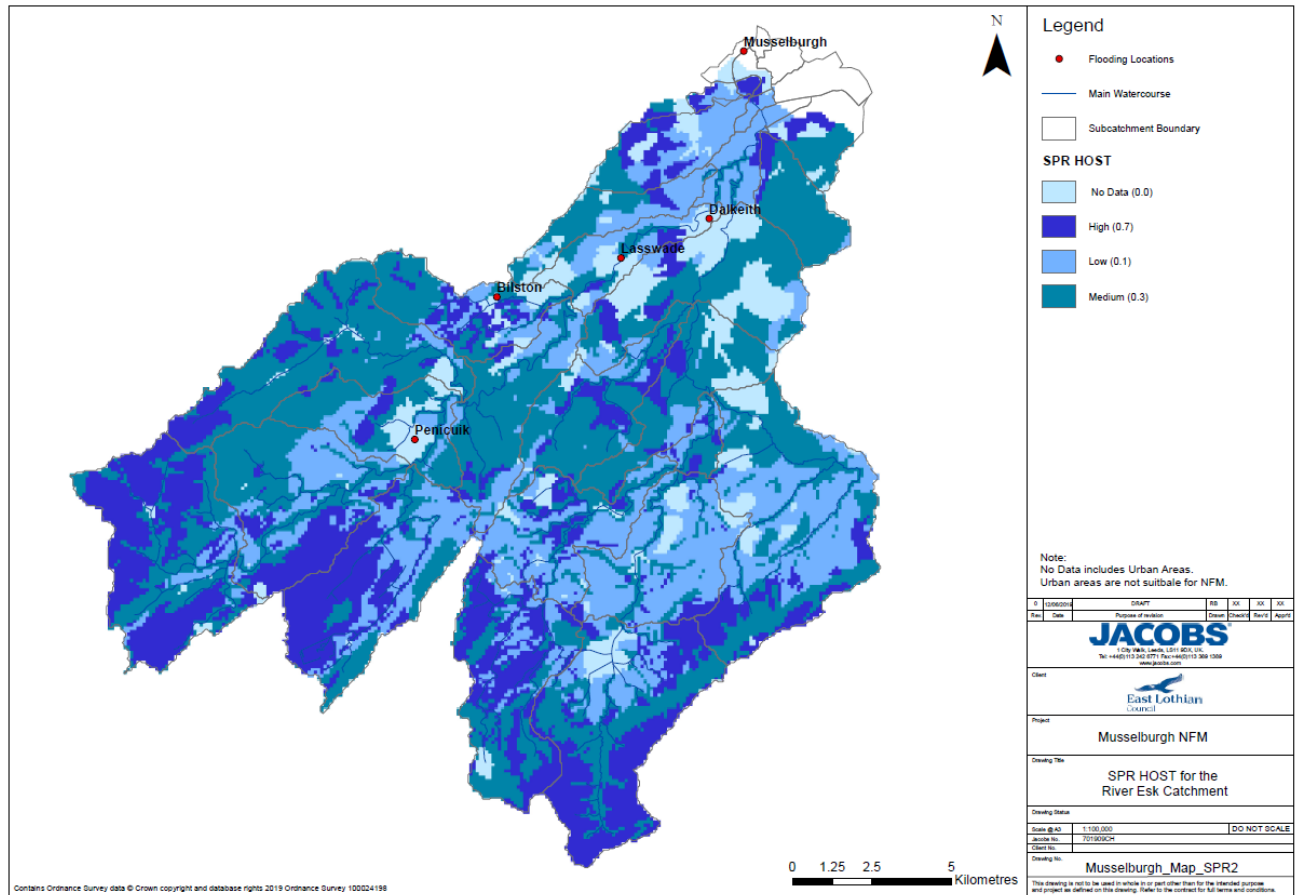


Figure 3: SPR HOST Map for the River Esk Catchment.

A.1.4 Travel Time Distributions for a) Musselburgh, b) Dalkeith, C) Lasswade, D) Bilston and E) Penicuik.

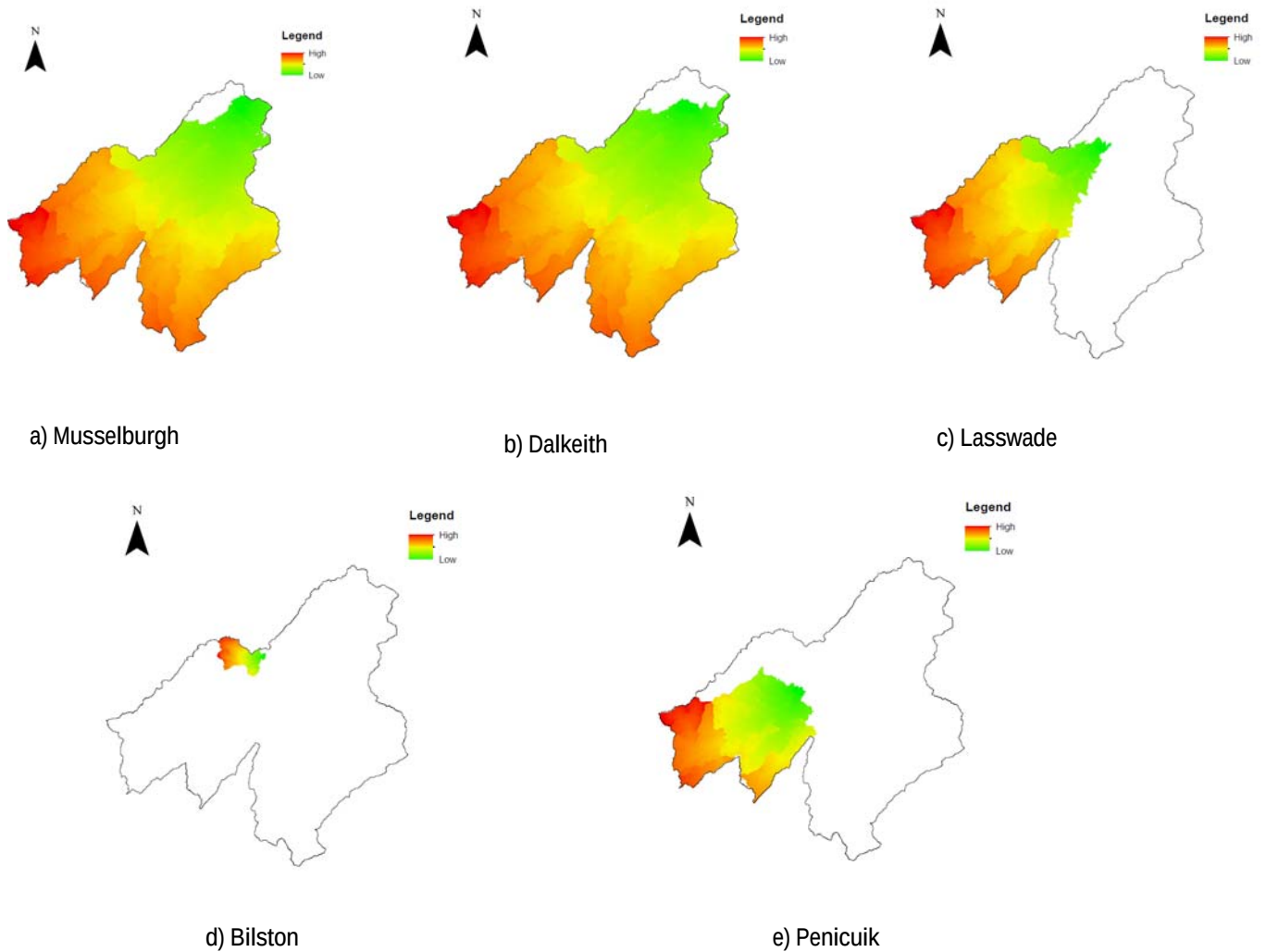


Figure 4: Travel Time Maps for the Selected Points of Impact within the River Esk Catchment (Red= Long Travel Time, Green = Short Travel times).

A.1.5 Hydrological Connectivity for the River Esk

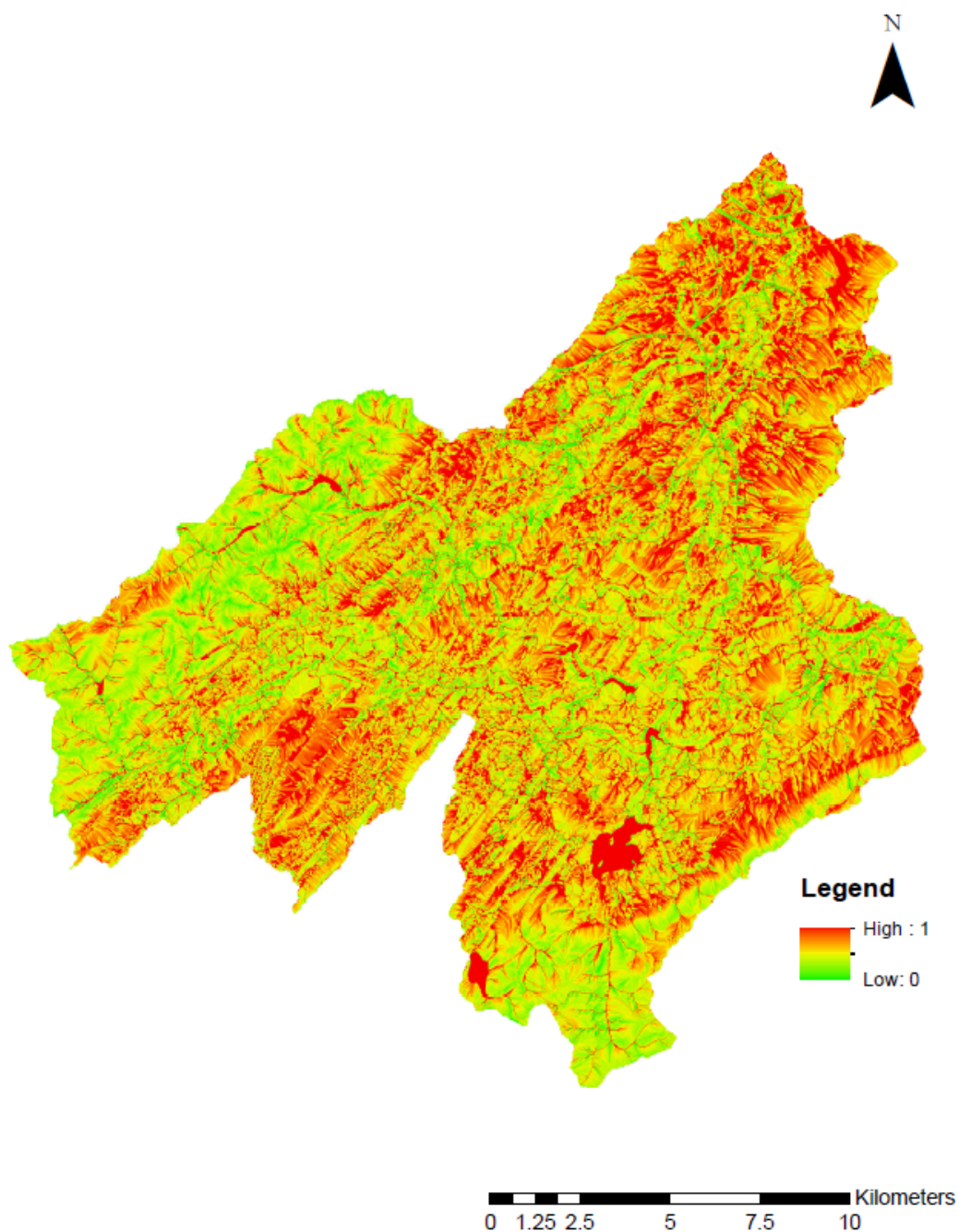
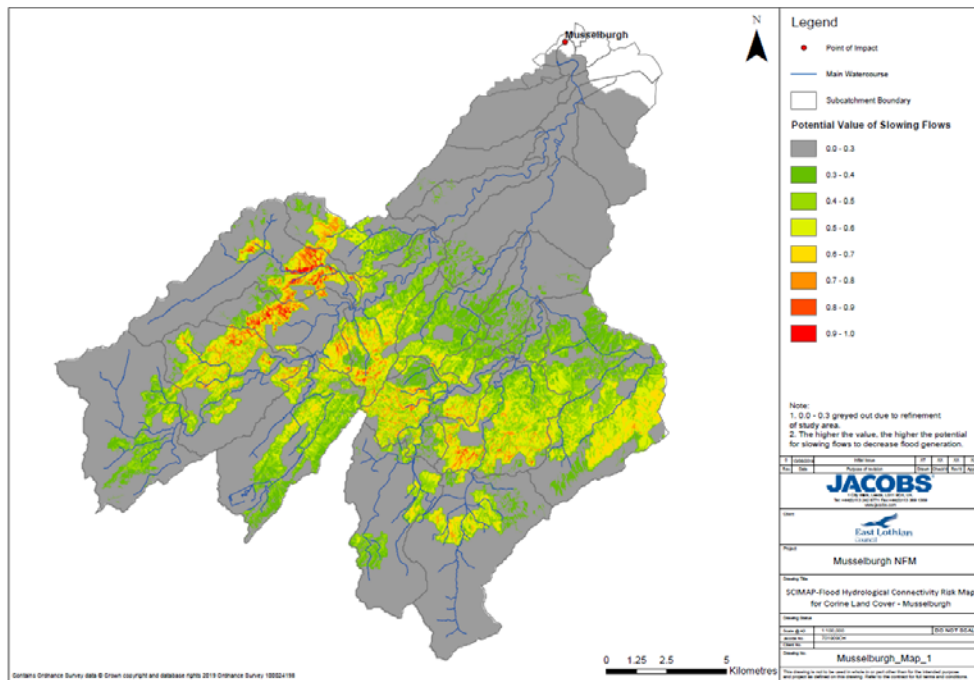


Figure 5: Hydrological Connectivity Risk Map for the River Esk Catchment.

A.2 Map Output

A.2.1 Musselburgh Outputs

a)



b)

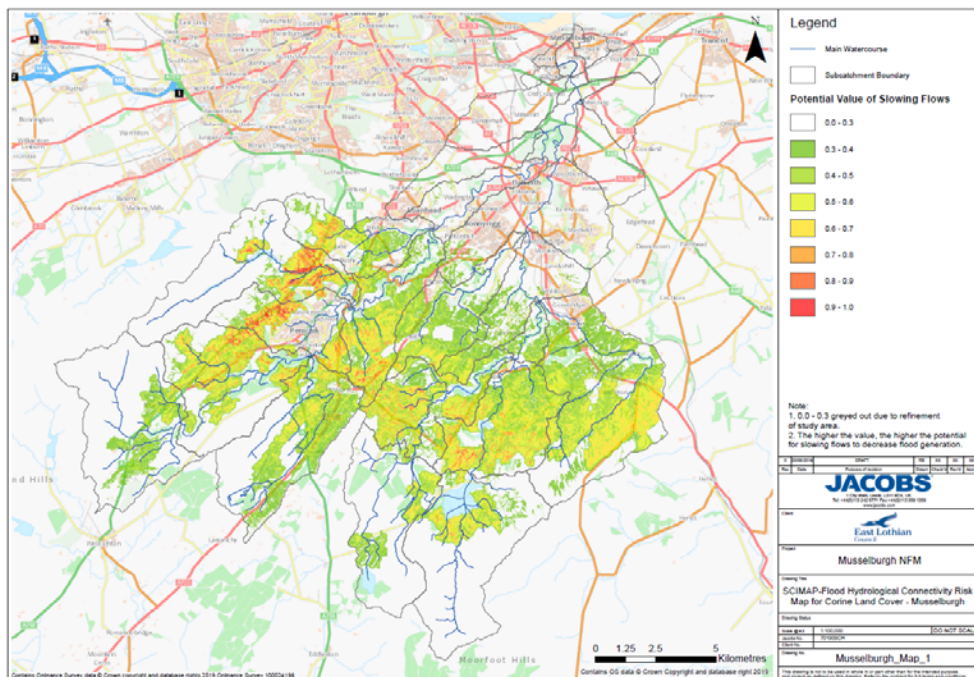
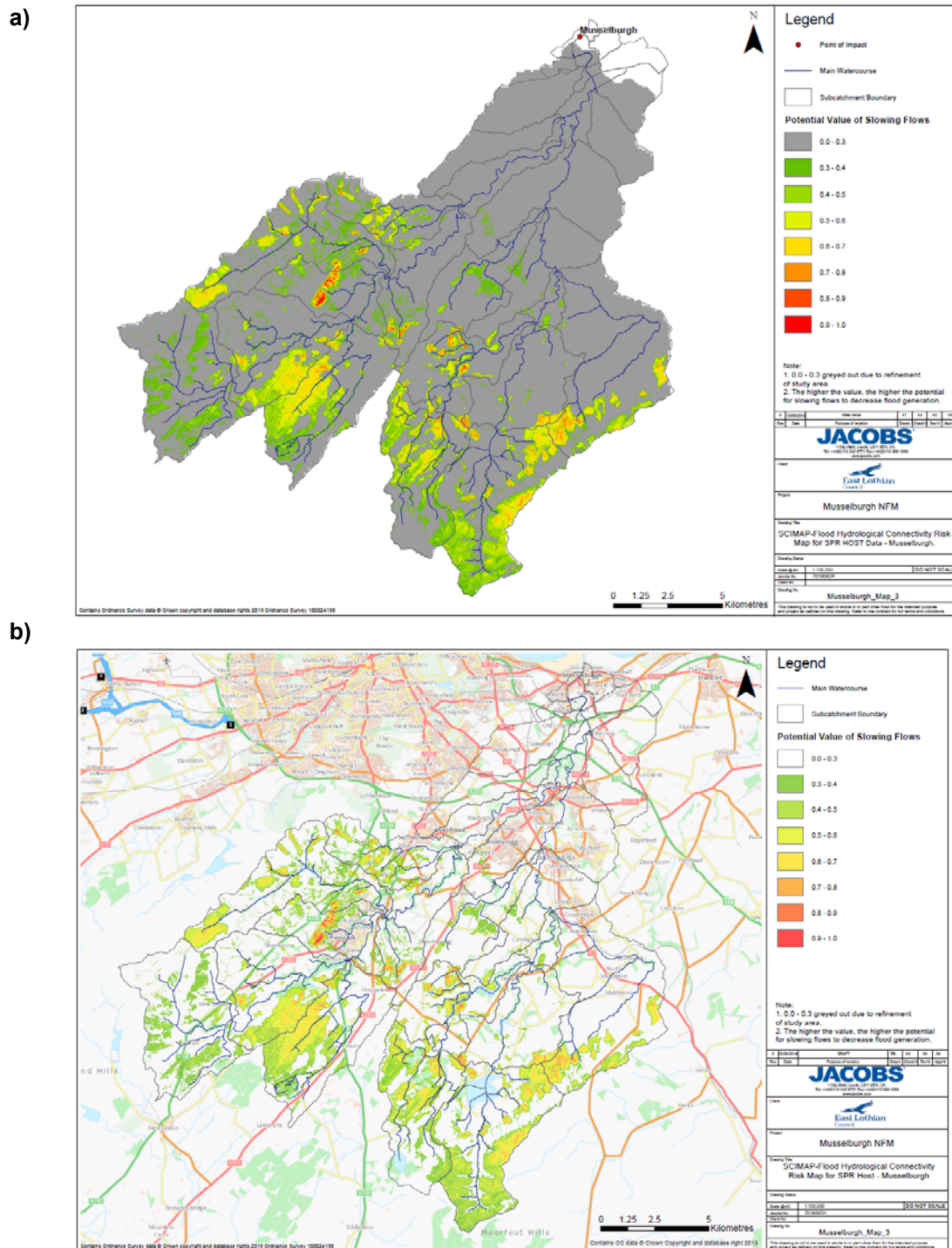
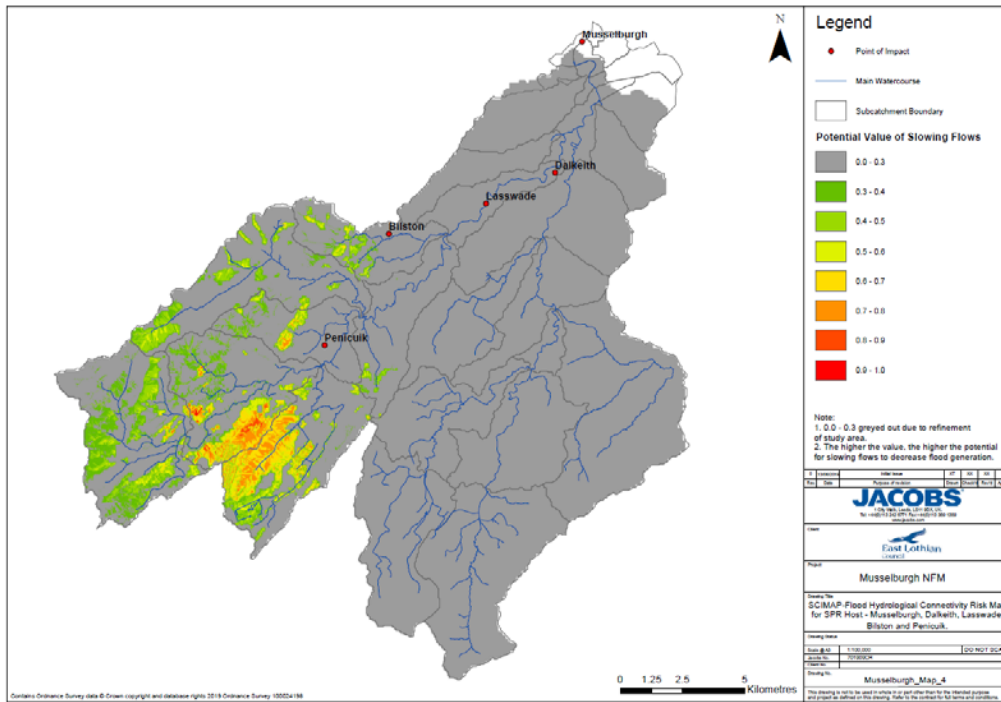


Figure 6: Maps showing areas of highest runoff and connectivity based on Corine land cover data for Musselburgh.



a)



b)

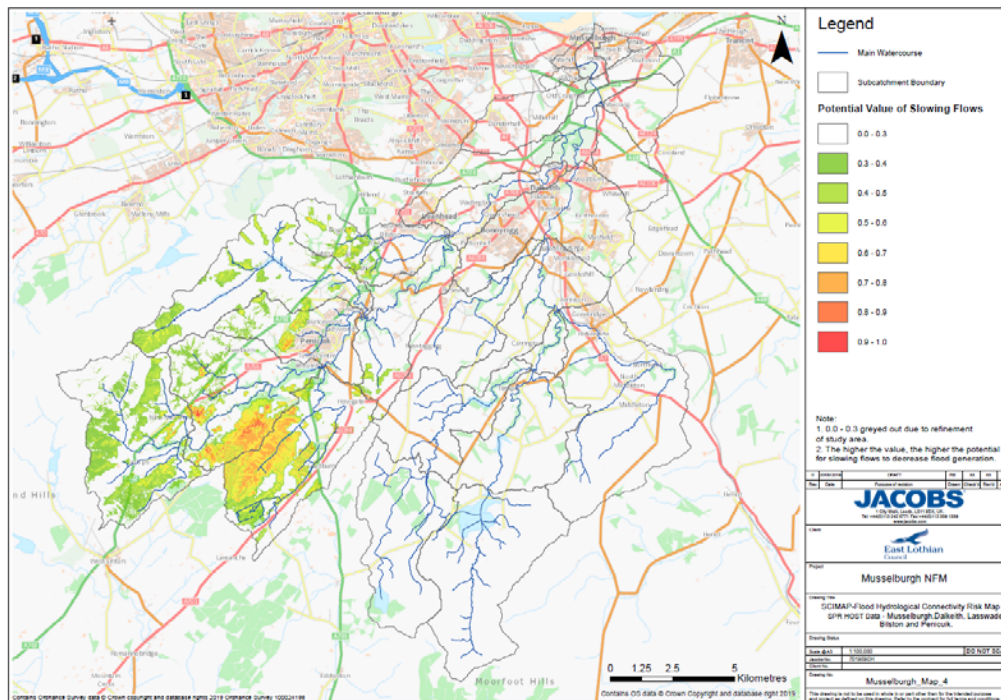


Figure 9: Maps showing areas of highest runoff and connectivity based on SPR for Musselburgh, Dalkeith, Lasswade, Bilsdon and Penicuik.

Based on the 15 sample points below, sample points 2, 6, 9, 10, 12 and 14 show signs of gripping. That's 6 out of the 15 sample points chosen.



Figure 11: Sample Point 1



Figure 12: Sample Point 2



Figure 13: Sample Point 3



Figure 14: Sample Point 4



Figure 15: Sample Point 5



Figure 16: Sample Point 6



Figure 17: Sample Point 7



Figure 18: Sample Point 8



Figure 19: Sample Point 9



Figure 20: Sample Point 10



Figure 21: Sample Point 11



Figure 22: Sample Point 12



Figure 23: Sample Point 13



Figure 24: Sample Point 14



Figure 25: Sample Point 15

A.4 Watercourses within the River Esk Catchment

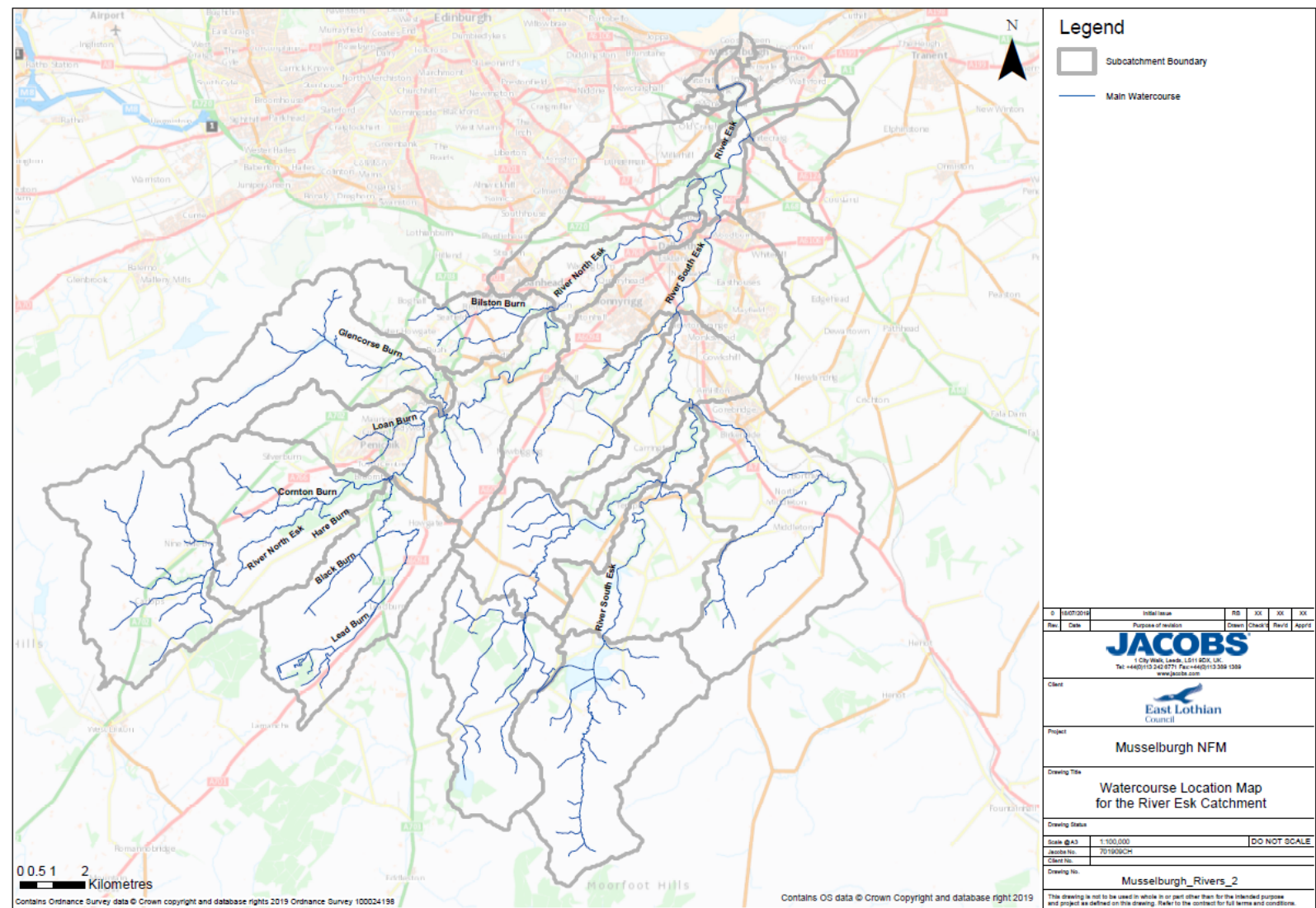


Figure 26: Watercourses within the River Esk Catchment.