Member of the SNC-Lavalin Group

Flanders Moss peatland restoration

Hydrological impact assessment

Forestry and Land Scotland

24 July 2023

Detailed report

Notice

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This document has 47 pages including the cover.

Document history

Document title: Hydrological impact assessment

Document reference: Detailed report

Revision	Purpose description	Originated	Checked	Reviewed	Authorised	Date
1.0	First Draft	SC, FC	GO	-	-	20/06/2023
2.0	Second Draft	SC	GO	EJG	EJG	03/07/2023
3.0	Final	SC	GO	EJG	EJG	24/07/2023

Client signoff

Client	Forestry and Land Scotland
Project	Flanders Moss peatland restoration
Job number	5221236
Client signature/date	

Contents

Tables

Figures

Executive Summary

Forestry and Land Scotland (FLS) have commissioned Atkins to undertake a hydrological assessment for their proposed peatland restoration works in the Flanders Moss, Easterhill and Garternich Moss forestry blocks (NS 55989 96596). Historically the bogs formed part of an extensive complex of raised bogs and were drained through the cutting of artificial drains in the surface of the peat to try and improve them for agricultural and forestry land uses. The Flanders Moss, Easterhill and Garternich Moss former forestry blocks are classified as lowland raised bogs and have now mostly been cleared of the forested plantation crop and this will be complete by the summer of 2023.

A raised bog is a rain-fed system which can be compared to a ‘dome’ of water, with a shallow Acrotelm layer overlying a permanently saturated Catotelm layer. As the bog has very little capacity for water storage, the response to rainfall events is relatively rapid, ‘flashy’ flows. Following drain cutting, a greater proportion of flow is directed into ditches, typically resulting in greater peak flows entering neighbouring river catchments more rapidly. Drain cutting is also associated with greater erosion, reductions in the water quality in flows leaving the catchment and greater carbon dioxide emissions.

The aim this report is to provide an understanding of the potential hydrological impacts associated with the proposed restoration activities. The hydrological assessment considers the likely impacts to:

- Runoff generation and overland flow paths during very wet/flood periods;
- Low flows hydrology during drier, prolonged periods without rainfall; and
- Water quality.

The likely impact of the restoration works at Flanders Moss is reduced peak flows, with a greater proportion of flow directed overland and slowed down. Particularly for the eastern edge of Gartrenich Moss and the north and east of Flanders Moss, many of the drains to be blocked are orientated downslope and will see more significant reductions in peak flow following blocking; this is likely to reduce peak flows where ditches discharge onto adjacent farmland. However, there is unlikely to be a significant difference in the total volume of storm flow, as there is not expected to be a significant change in the overall storage capacity of the forestry blocks at the site. As the blocking is likely to reduce flow rates it will reduce the velocity of the flow and therefore the potential for erosion of bare peat, which was observed in some ditches, therefore, improving water quality.

The ground smoothing operations are expected to block many of the existing flow paths in the former plantation areas of all three blocks. As a result, a larger volume of water will be retained on and near the surface following precipitation, which will locally encourage the growth and recovery of Sphagnum moss and recovery of the microtopography.

The hydrological effects of drain blocking are hard to predict and will vary across the site. The greatest increases in the water table elevation towards the peatland surface and associated habitat restoration will occur near where drains are blocked, however effects may be less noticeable further away from where artificial drains are dammed. Overall, the main impacts of restoration works are likely to be ecological rather than hydrological and localised to where artificial drains are not being retained. Where water drains into artificial drainage ditches oriented perpendicular to the slope, damming will have a reduced effect on flows and for many of the edges of the blocks restoration will be limited as these drains lie within the buffer zone and will not be altered.

Gartrenich Moss was identified as being in the best condition and will see the least change following restoration; areas of Flanders Moss were identified as being in the worst condition and are likely to see significant improvements following restoration works. It is unlikely any substantial changes in ground elevation at the site will occur, as the truncated shape of the forestry blocks will not change. The retained artificial drains just outside the FLS boundary and within the 30m buffer zone around the edges of the three blocks and particularly on both sides of the road through Easterhill and Flanders Moss will limit large-scale rewetting. Rewetting is likely to be locally concentrated where peat dams are constructed and may be more extensive in flatter areas where ditches are spaced far apart.

1. Introduction

1.1. Purpose of this report

Forestry and Land Scotland (FLS) have commissioned Atkins to undertake a hydrological assessment for their proposed peatland restoration works in the Flanders Moss, Easterhill and Garternich Moss forestry blocks (NS 55989 96596). This hydrological assessment will support a planning application to Stirling Council for the proposed works. The restoration works will consist of drain blocking and smoothing of the peat surface, where ridges and furrows were established to facilitate forestry growth.

Historically the bogs formed part of an extensive complex of raised bogs and were drained through the cutting of artificial drains in the surface of the peat to try and improve them for agricultural and forestry land uses. The Flanders Moss, Easterhill and Garternich Moss former forestry blocks are classified as lowland raised bogs and have now mostly been cleared of the forested plantation crop and this will be complete by the summer of 2023.

1.2. Scope

The scope of this report is to provide an understanding of the potential hydrological impacts associated with the proposed restoration activities. The hydrological assessment will consider the likely impacts to:

- Runoff generation and overland flow paths during very wet/flood periods;
- Low flows hydrology during drier, prolonged periods without rainfall; and
- Water quality.

1.3. Report structure

The report covers:

- **Section 1 –** Outlines the purpose and scope of this assessment.
- **Section 2 –** Provides a summary of the site characteristics and the proposed restoration works.
- **Section 3 –** Includes a summary of available literature and reports which provide an evidence base on which the assessment/judgements made in this report are made.
- **Section 4 –** Provides the results of a topographical flow path analysis that investigates the current overland flow paths, on and across the site and immediate surroundings.
- **Section 5 –** Summarises the findings of Sections 2 and 3 and provides a conclusion as to the likely hydrological impacts of the proposed works.
- **Section 6 –** Provides the complete list of references, including academic papers, reports, conference proceedings, news articles and websites that have been collated and cited in the report.
- **Appendices –** Contain detailed information, specific to each of the three forestry blocks, including the identified flow paths and suggested priority restoration actions.

1.4. Data sources

The data used in this report have been collated from a number of sources including academic papers, online articles, data portals and websites pertinent to peatland restoration. **Table 1-1** lists the primary digital data that have been used in this hydrological assessment but is not a complete list of all reports and academic literature cited in the literature review, these are catalogued at the end of the report in **Section 6**.

Table 1-1 - Data sources used in this assessment

Data description	Source	Summary
Drainage maps and FLS boundary	FLS	Georeferenced pdf data showing the FLS site boundary and drainage maps
Base map layers	Open Street Maps	Base map layer used in figures showing terrain

Local rain gauge data	SEPA	Historic rainfall data from Auchentroig rain gauge
Watercourse maps	Ordnance Survey API	Map layer showing the locations of additional drainage ditches and external watercourses
Digital elevation model (DEM)	Malcolm Hughes Land Surveyors	High-resolution 2D topographic maps of the site and nearby surroundings
Literature	*Listed in Section 6*	Existing information detailing natural and degraded peatland hydrology and restorations, used to write the literature review: Scientific papers, reports, conference proceedings, books, webpages and online videos

2. Site description and proposed restoration works

This section provides an overview of the physical and hydrological characteristics of the site and the proposed restoration works.

2.1. Site description

Flanders Moss lies in the Carse of Forth in West Stirlingshire, close to the villages of Buchlyvie to the south, Gartmore to the west and Port of Menteith and Aberfoyle to the north. The site is split into the three forestry blocks of Easterhill, Gartrenich and Flanders Moss, separated by the River Forth, as shown in Figure 2-1.

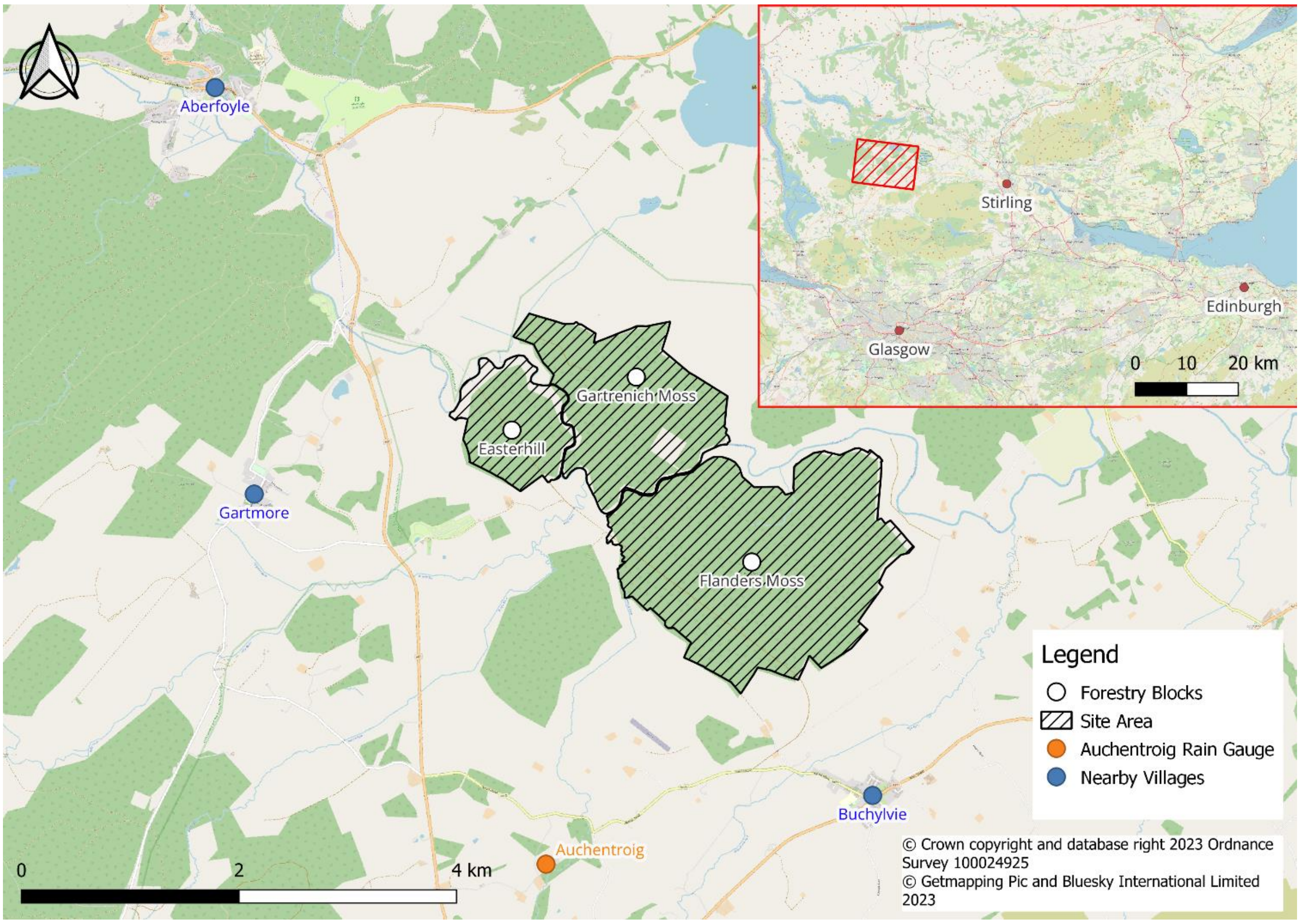

Figure 2-1 - Location of Flanders Moss within Scotland and with respect to nearby villages

2.2. Geology and superficial deposits

The site is underlain by interbedded sandstone and siltstone formed between 419.2 and 393.3 million years ago during the Devonian period (British Geological Survey, 2023). Superficial deposits on the site are primarily peat, a sedimentary deposit formed between 2.588 million years ago and present during the quaternary period.

2.3. Topography

A LiDAR survey is available for the study area and is further detailed in Section 4 and Figure 4-1. The ground levels within the area surveyed reach a maximum of 37.8 m AOD (Metres above ordinance datum); within the FLS forestry blocks the maximum elevation is 23.9 m AOD for Flanders Moss. It is evident that all three forestry blocks display the dome-like shape expected of a raised bog.

2.4. Site hydrology

The River Forth runs through the site, separating the Flanders Moss and Gartrenich forestry blocks and there are tributaries of the Keltie Water, Wardie Burn and Auchentroig Burn. In addition to the natural watercourses there is an extensive drainage network across the site which was cut to provide drier conditions for forestry growth. The following subsections provide a more detailed description of the drainage networks within and around the three forestry blocks.

The closest SEPA rain gauge with available data is located at Auchentroig, approximately 3 km southwest of Flanders Moss. Since 2014, the average annual rainfall measured by Auchentroig rain gauge was 1449 mm (SEPA, 2023); the most precipitation occurs during December, January and February with the driest months being April, May and June. The average monthly rainfall over this period was 120 mm.

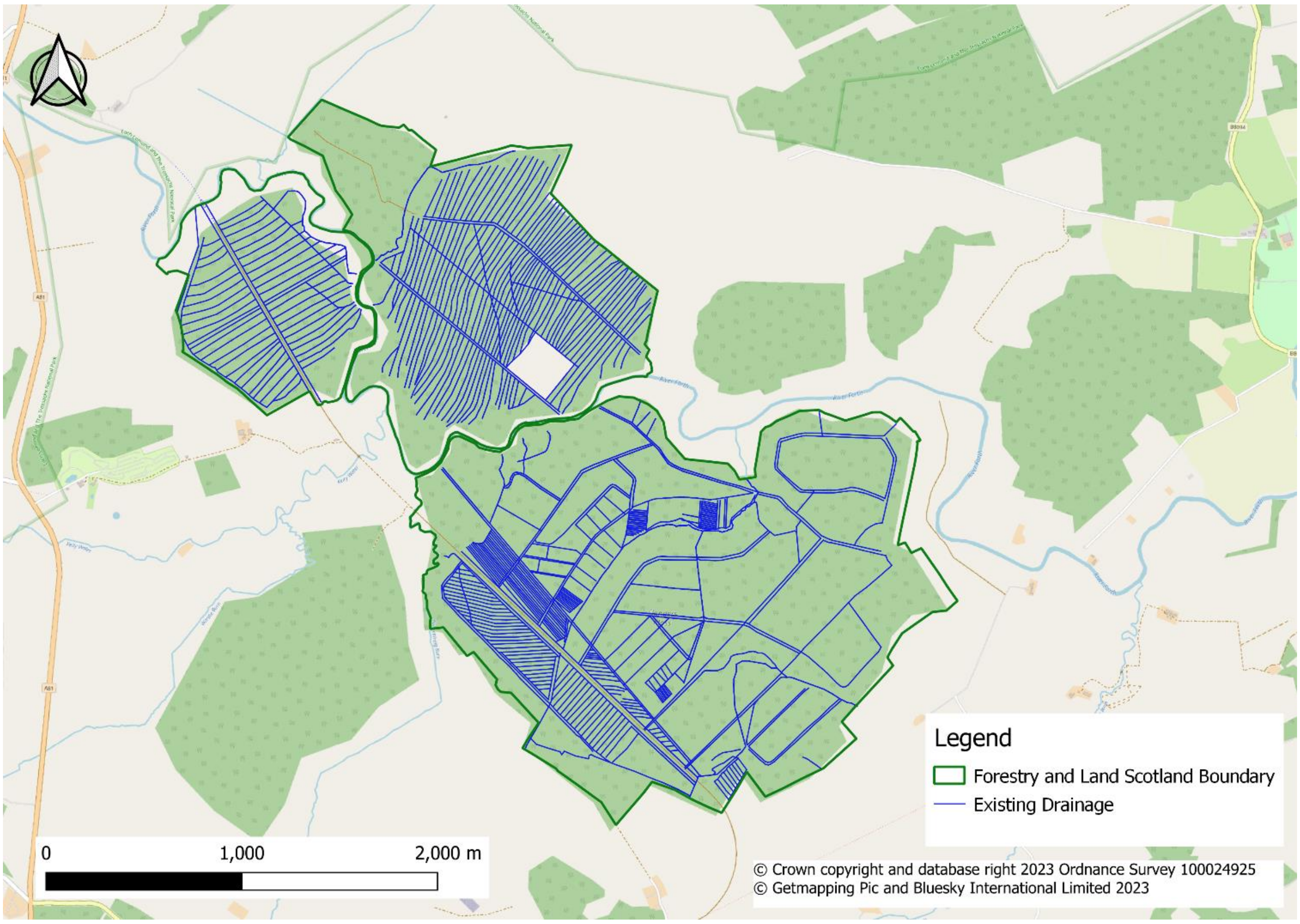

Figure 2-2 - Locations of existing drainage network

2.5. Restoration works

The works planned to restore the peat bogs involves the blocking and/or infilling of various drains within each of the forestry blocks and the smoothing of the surface to remove some of the ridges and furrows. Some drains will be maintained, and these are identified in Figure 2-3. The aim of the restoration works are to encourage the rewetting of previously drained peat which will bring additional benefits, including recovery of sphagnum moss and increased carbon sequestration (storage) by restoring degraded areas of peat to ‘active’ peatland where organic matter is accumulated.

It should also be noted that to prepare the sites for the rewetting stage of restoration, the regenerating trees that are currently present in the Flanders Moss main area will be mulched/felled. In the Gartrenich area, there is still commercial timber to be harvested, which will be completed prior to any restoration work, and on the northern fringes of the Easterhill block there is ancient woodland which will be retained, with no restoration works taking place here.

2.5.1. Drain Blocking and infilling

The blocking of the drains will be performed using a peat dam, constructed by pulling adjacent peat into the drain, closing the drainage path. This will be done at the end of all larger drains. The smaller drains (<1m wide) will be infilled by dragging the banks/adjacent peat and sphagnum into the ditch. This will result in a more minor depression in the bog/peat surface, compared to the original ditch, which is expected to infill naturally with sphagnum relatively quickly.

Several larger drains will be retained, as shown below in Figure 2-3; these include several ‘natural’ watercourses and drains bordering the road crossing the Gartrenich and Flanders Moss forestry blocks. As shown below, Easterhill and Gartrenich Moss contain extensive drainage networks, while that of Flanders Moss is less regular and contains larger areas with no drains.

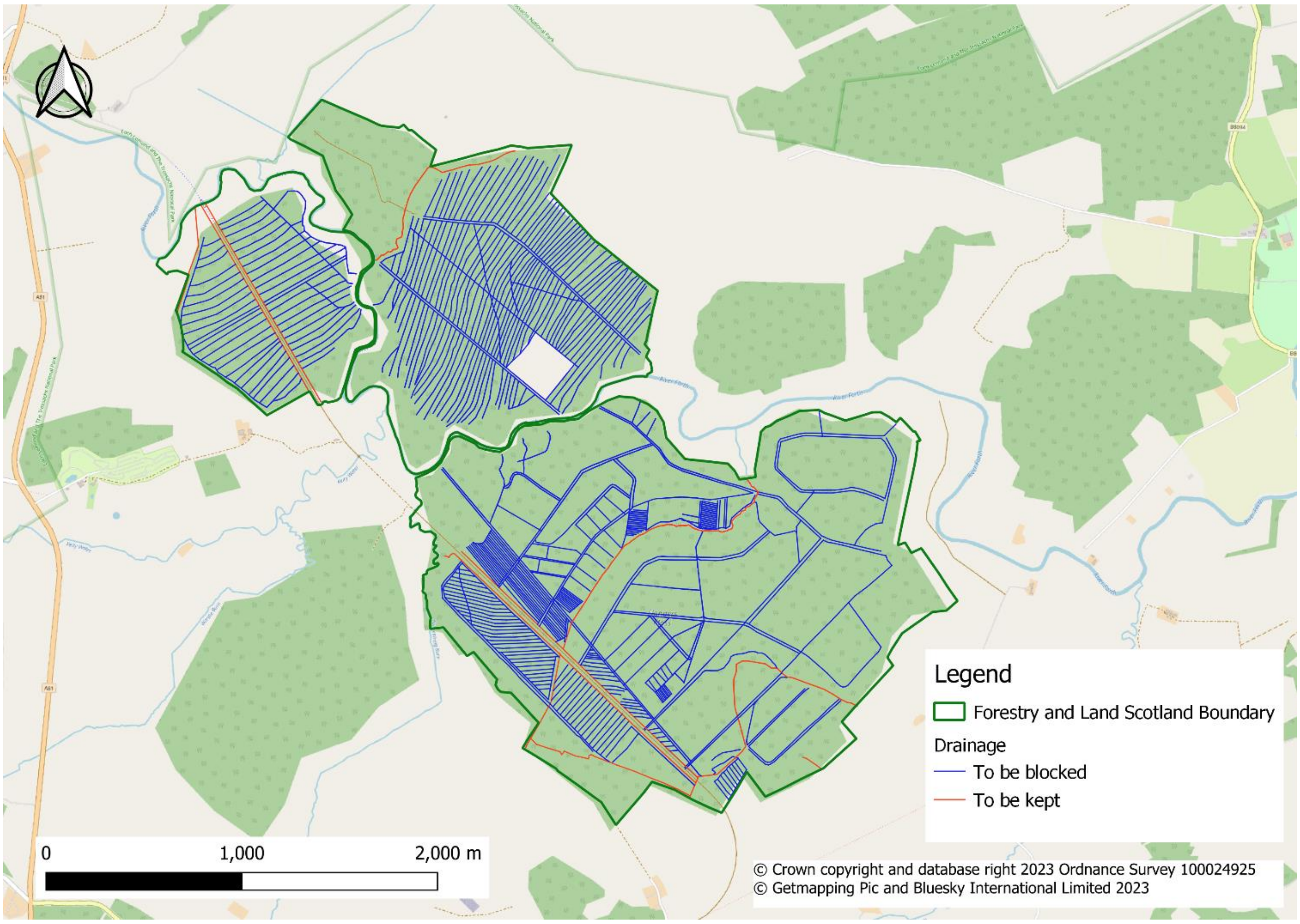

Figure 2-3 - Map of drains to be blocked and drains/watercourses to be retained

2.5.2. Surface smoothing

The forest ridges and furrows previously created from past cultivation will be smoothed out where possible. The exception to this will be a 10m exclusion buffer applied to all retained watercourses/drains and a 30m buffer applied to the boundary of the FLS land holding where no operations will take place. The smoothing of the surface will entail flipping the ridge/tree stumps into the adjacent furrow, thus removing the ridge.

2.6. Site visit

A site walkover was undertaken on the 29th and 30th March by Calum Peden and Fiona Chapman. The aim of this visit was to get an appreciation of the three forestry blocks, to better understand the current conditions of the peat bog, how well drained they were, how/if the bog wetness varied across the forestry blocks. The routes walked are shown in Figure **2-4** and these covered the north and south of Flanders Moss, Easterhill and Gartrenich Moss.

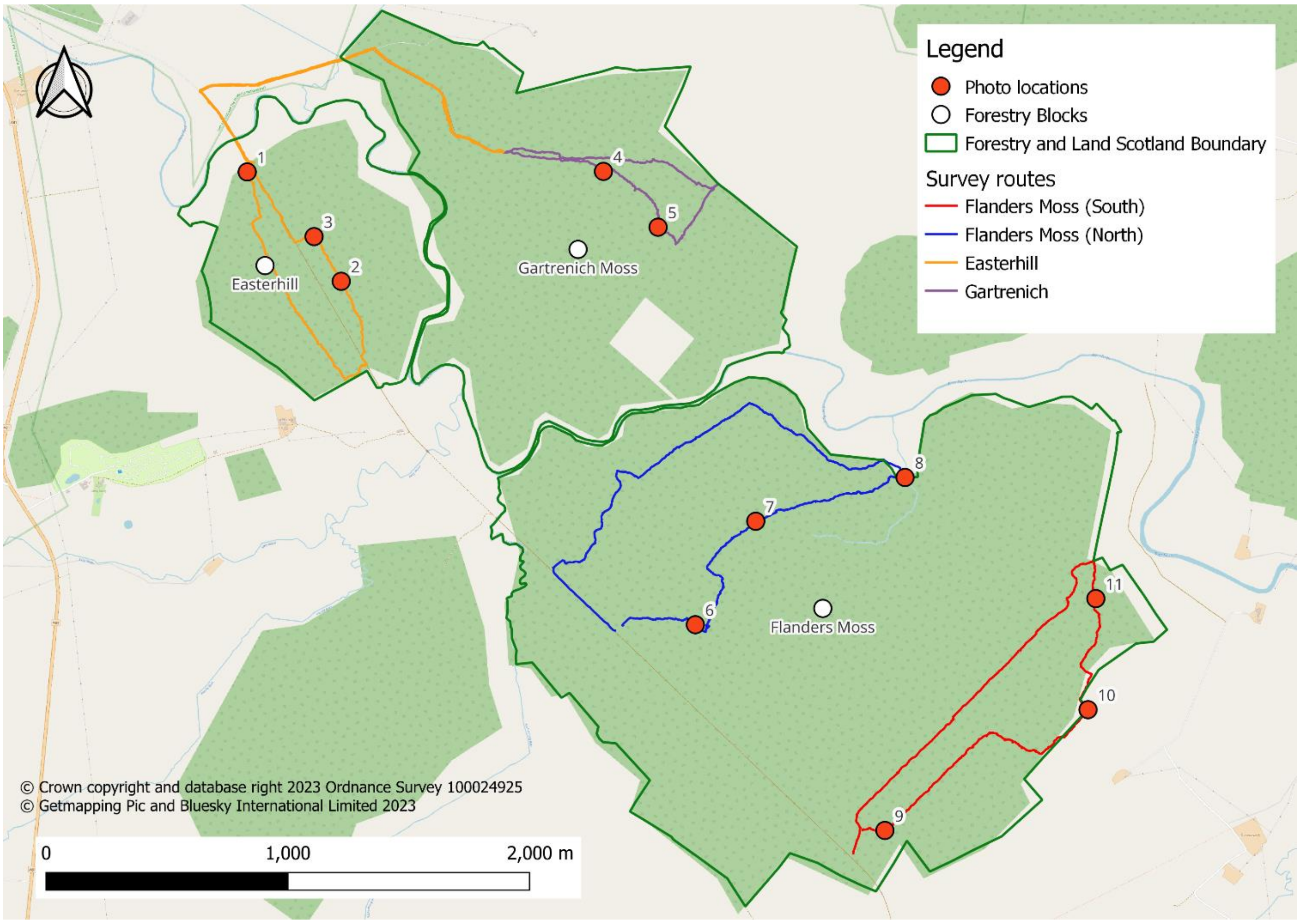

Figure 2-4 **- Survey routes and locations of photographs taken**

The weather during the two days on site was variable. On the first day (29th March) there was a number of small showers but no significant rainfall, only totalling 0.2mm and on the second day the weather remained dry with no rainfall recorded. The weather in the week leading up to the visit was unsettled with a total of 36.8mm of rain falling within the 7 days prior to the visit, though, only 2.2mm fell in the 3 days prior to the visit. There was 162mm of rainfall recorded at Auchentroig for the month of March, this is above the long-term average for March which is 118mm.

A summary of the observations at each of the forest blocks is provided in the following sub-sections, along with relevant photographs taken during the visit. Locations where the photographs used throughout the report are numbered in Figure **2-4**.

2.6.1. Easterhill

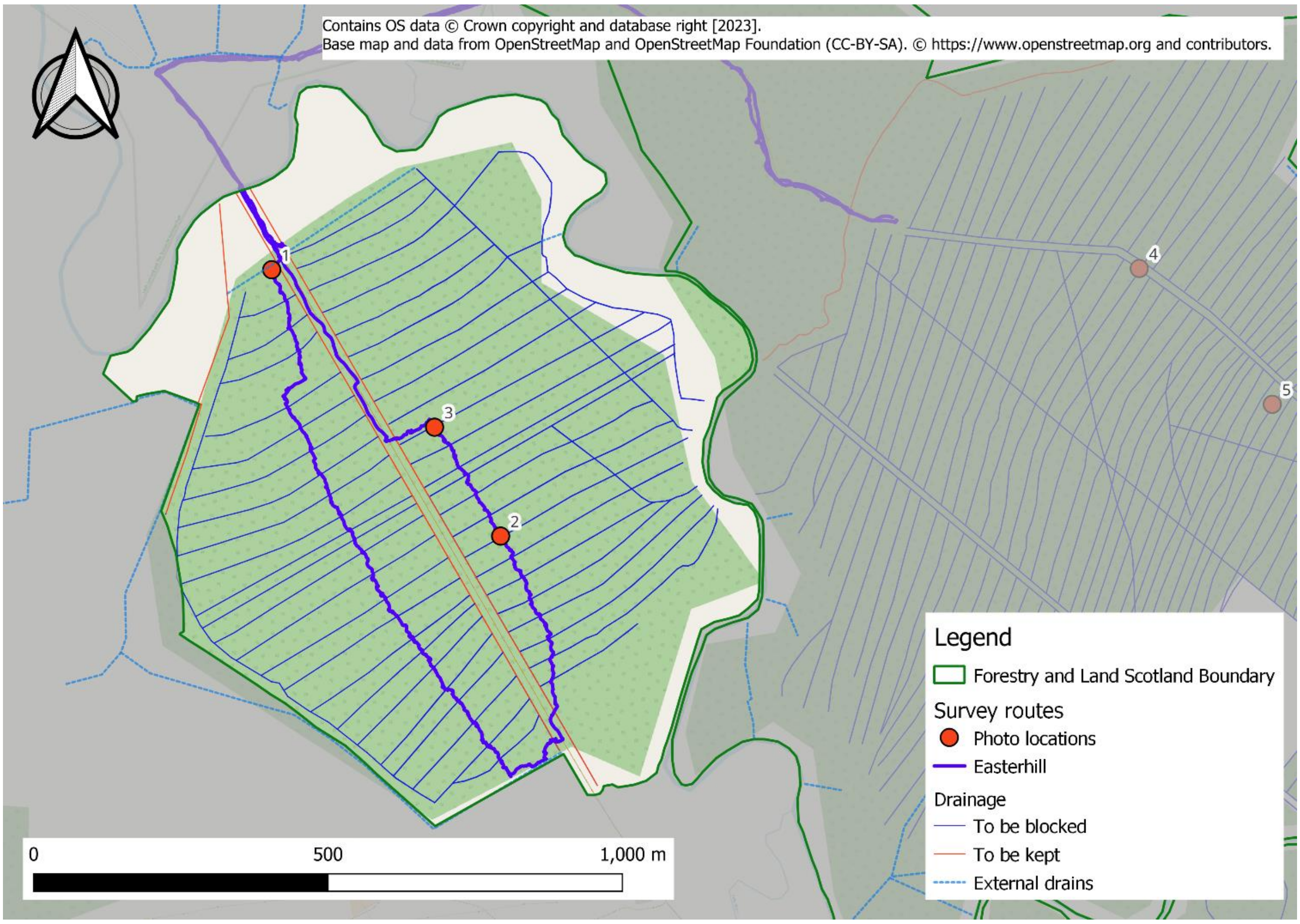

Figure 2-5 - Easterhill Forestry Block

The Easterhill block, situated to the northwest, has predominant landcover of small, young, trees and grassland. In general, the site was found to be wet with many areas of standing water evident and the ground to the west of the road running through the centre of the Easterhill site, which is located between the two parallel orange lines in Figure 2-5 above, was largely saturated, which can be evidenced from Figure 2-6. The area to the east of this track was found to be slightly dryer, but still saturated overall.

The drainage ditches across this block are dominated by sphagnum growth and deposited organic matter (Figure 2-7). There is very little throughflow of water, although some water is making it to the larger drains near the track. The majority of the drains are already largely naturally infilled.

Much of this block had some degree of tree regeneration, as can be seen in Figure 2-8, although there were some areas where it was likely too wet for regeneration to occur, particularly in the middle of the western half of the site.

Figure 2-6 - Easterhill - saturated ground (Photograph 1)

Figure 2-7 - Easterhill – Naturally infilling drainage ditches and sphagnum growth (Photograph 2)

Figure 2-8 - Easterhill – Regeneration (Photograph 3)

A detailed description of the topography, current state, drainage network, flowpath analysis and assessed need for restoration for Easterhill is detailed in Appendix A at the end of this report.

2.6.2. Gartrenich Moss

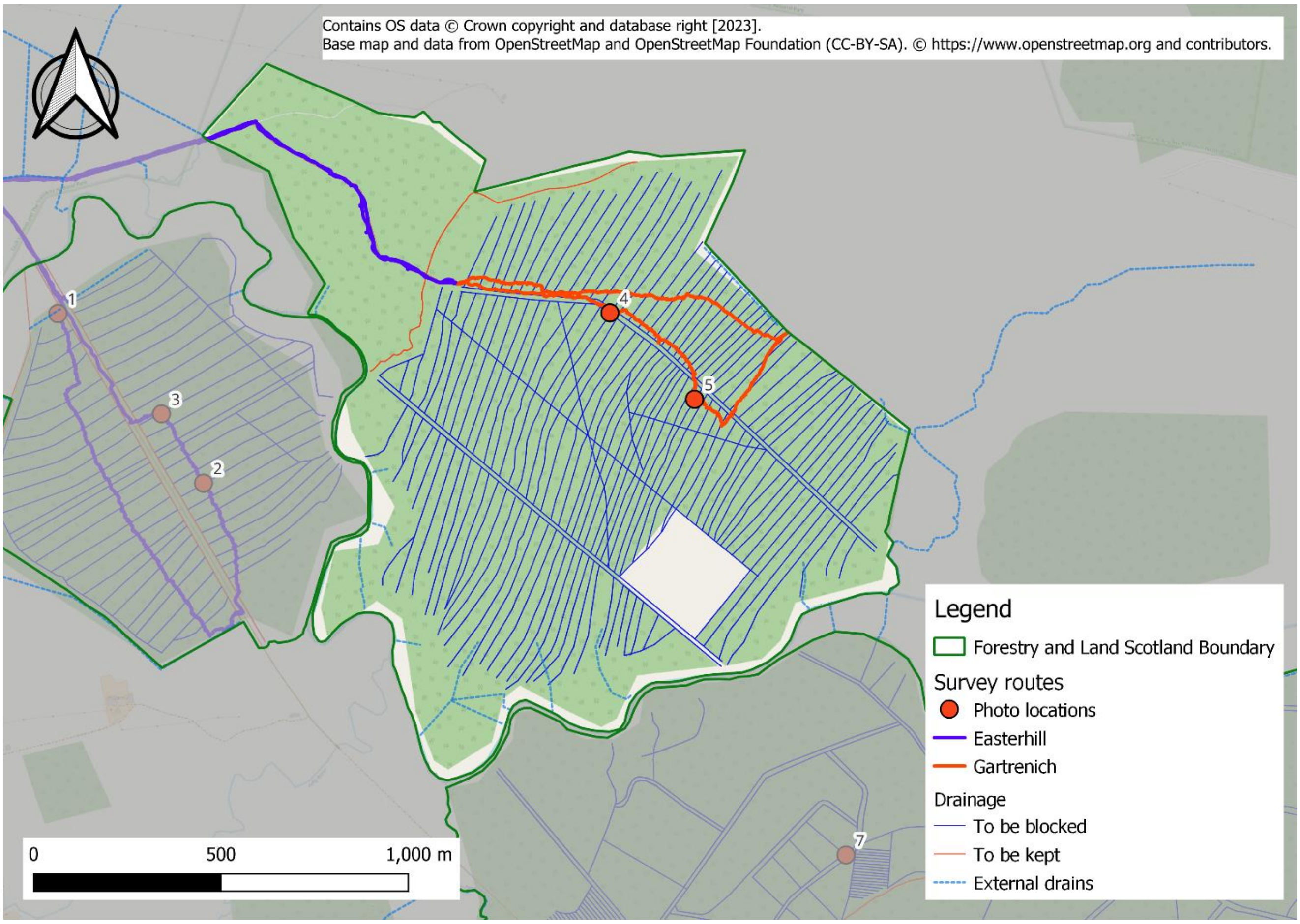

Figure 2-9 - Gartrenich Moss Forestry Block

The Gartrenich Moss was the wettest of the areas visited. It was perceived, that of the three forested blocks/raised bog areas, Gartrenich Moss was in the best condition (i.e. closest to a more natural/restored state). There are few visible drainage ditches and where these occurred there was little to no visible throughflow of water. The map of existing drainage ditches provided by FLS is shown in Figure 2-9; only one watercourse is planned to be retained.

Due to the very wet ground conditions (Figure 2-10), traversing the site was extremely difficult and it was not possible to walk through the wooded areas. However, observations from the edge of the south side woodland near the centre of the site confirmed these areas to also be saturated (Figure 2-11). FLS staff indicated that these trees have not been felled at present due to the ground being too wet for machinery access. Additionally, the trees appeared to have been heavily affected by the saturated ground as they were not growing healthily.

This bog was very obviously raised above the adjacent surrounding areas. There was little to no tree regrowth in the felled areas across this block, likely due to the wetness of the site.

Figure 2-10 - Gartrenich - Ground conditions (Photograph 4)

Figure 2-11 - Gartrenich - Saturated woodland (Photograph 5)

A detailed description of the topography, current state, drainage network, flowpath analysis and assessed need for restoration for Gartrenich Moss is detailed in Appendix B at the end of this report.

2.6.3. Flanders Moss

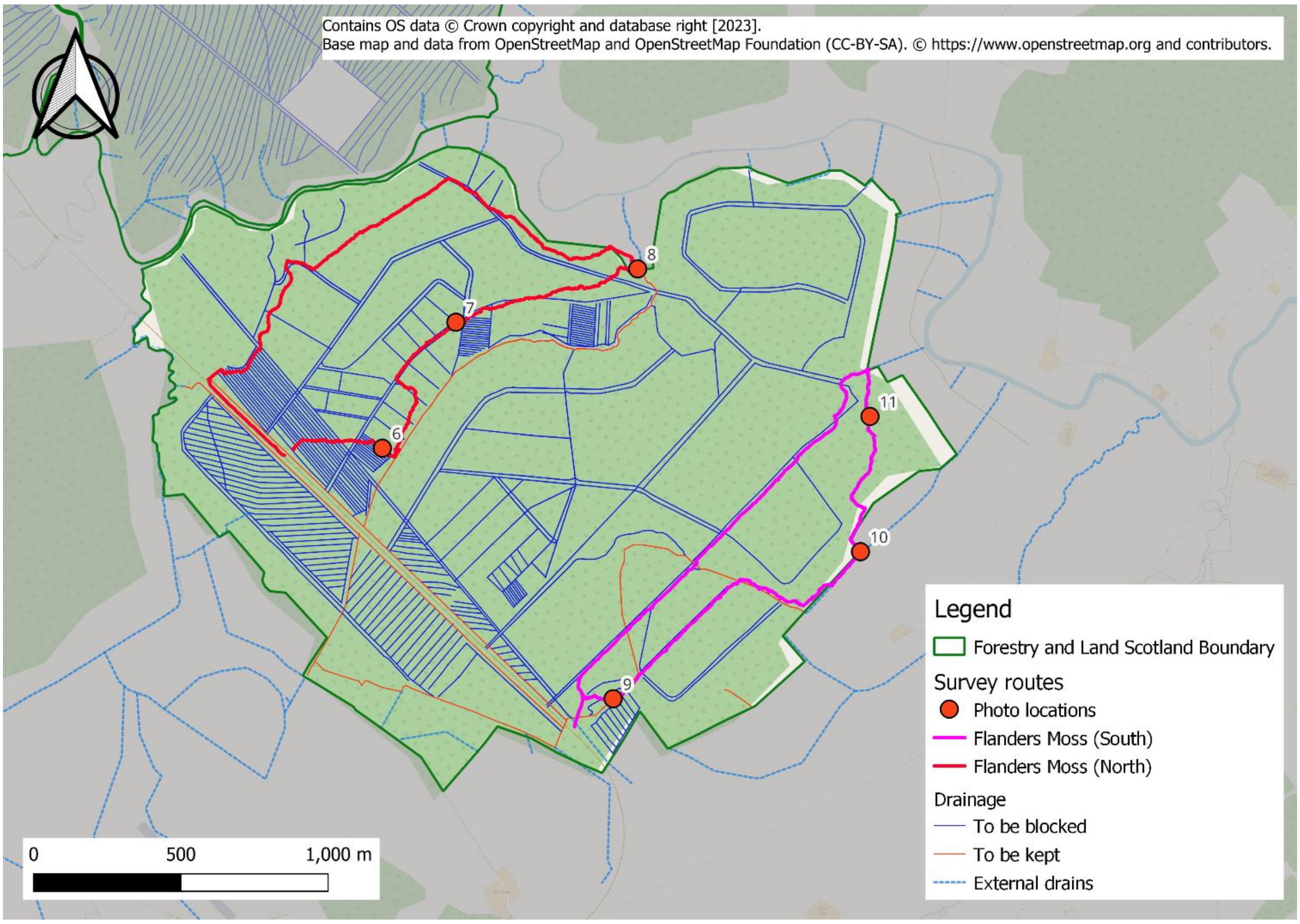

Figure 2-12 - Flanders Moss Forestry Block

As shown above in Figure 2-12, the Flanders Moss forestry block was the largest of the three blocks, so two separate survey routes were walked, labelled ‘Flanders Moss (North)’ and ‘Flanders Moss (South)’, shown in red and pink respectively.

2.6.3.1. Flanders Moss (North)

The northern section of Flanders Moss was found to be considerably dryer than Gartrenich Moss and Easterhill. The drainage ditches across the site were much more pronounced and there was a notable throughflow of peaty water (Figure 2-13). There has been considerable tree regrowth in many areas of this block, although this was more evident towards the south of the area walked (Figure 2-14).

From the site observations, it may be difficult to prevent drainage of the area without blocking more drains than are currently indicated in Figure 2-12 due to a main river channel running northeast through the site into the River Forth. The main watercourse shown in Figure **2-15** is well established and has been identified by FLS to be retained. This watercourse appears on historic maps predating the forestry operations, although it is possible that this watercourse was constructed to drain the bog. Given how deeply incised the watercourse is, and how dry the adjacent land is, there is likely to be a substantial area of land on either side where the water levels are directly drawn down into it.

Additionally, there are some very large drains around the edge of the site adjacent to the track to be retained that will likely limit the effectiveness of any rewetting around the periphery of the bog however these are likely to be necessary to maintain the road access into the site. It may be necessary to look at whether work needs to be done near to the edge of the bog to ensure the bog can become fully rewetted and how this can avoid off site impacts for example to the access road, while still rewetting the bog.

Figure 2-13 - Flanders Moss (North) – Drainage (Photograph 6)

Figure 2-14 - Flanders Moss (North) – Regeneration (Photograph 7)

Figure 2-15 **- Flanders Moss (North) - Watercourse (Photograph 8)**

2.6.3.2. Flanders Moss (South)

The site to the south of Flanders Moss was largely very dry and grassy (Figure 2-16) with some locally very wet areas. The locally wet area may possibly be attributed to the distance to the larger drains on the site. Many of the drains appeared be naturally infilling with vegetation and old organic matter. Little to no throughflow was perceived in the naturally infilling drains, whereas the more open drains have substantial flow. There are many areas of exposed, degraded peat noted to the south of Flanders Moss (Figure 2-17). Many of these relate to the large drain to the southeast of the block (Figure 2-18), which looks to be entirely man made and is having a substantial draining effect on the land adjacent to it. This large drain is not shown on the drainage maps provided by FLS but is within 30m of the FLS boundary, therefore it is assumed that it is to be retained. Peat pipes with flowing water were noted intersecting this drain and hence the effect in terms of drying likely extends well away from the drain.

Areas further north and west were wetter but would not be described as very wet. A possible suggestion for this area is to look at whether the main drain in this area should be infilled as this appears to be the main draining feature effecting the subsurface water levels. Due to its size, not blocking this drain is highly likely to limit the effectiveness of any local rewetting.

Figure 2-16 - Flanders Moss South - General ground cover (Photograph 9)

Figure 2-17 - Flanders Moss South - Exposed peat (Photograph 10)

Figure 2-18 - Flanders Moss South - Large drain (Photograph 11)

A detailed description of the topography, current state, drainage network, flowpath analysis and assessed need for restoration for Flanders Moss is detailed in Appendix C at the end of this report.

2.7. Summary

The three forest blocks/raised bogs are very different in terms of the ground condition and levels of saturation. Flanders Moss (South) is the driest area which can be attributed to the large drainage ditch draining the area. As this ditch is within 30m of the FLS boundary it is assumed the drain will remain and therefore its impact will remain and will limit the effectiveness of any re-wetting in the Flanders Moss South Site. Gartrenich is the wettest area with no real pronounced ditches or flow and can be described as being in the best condition for a raised bog. Easterhill and Flanders Moss (North) are both reasonably saturated but with pronounced drainage ditches and areas of tree re-growth.

3. Literature review/evidence base

This section provides an overview of the unique hydrological mechanics of a lowland raised peat bog, both in a natural (undisturbed) state and following degradation due to drain cutting, as has occurred extensively at Flanders Moss, Gratrenich Moss and Easterhill. The hydrological and environmental impacts of drain blocking/damming, to restore a more natural hydrological regime are also explored, with discussion of the difficulties/limitations of predicting the behaviour of a specific restored peat bog due to multiple site-specific factors.

3.1. Lowland raised bogs

Lowland raised bogs are a distinct type of peat bog characterised by the formation of an area of peat within which the water table sits above the surrounding water table. Under natural undisturbed conditions lowland raised bogs form a distinctive dome shape. Peat bogs are by definition rain fed rather than groundwater fed (IUCN UK, 2014).

Drainage, peat mining and reprofiling of ground within and around peat bogs results in significant and ongoing damage to peat bogs due to the organic matter within the peat bog requiring stable saturated conditions to avoid degradation (IUCN UK, 2014).

3.1.1. The hydrological mechanics of Lowland Raised Bogs

The subsurface of lowland raised peat bogs can be categorised into two separate layers (IUCN UK, 2014):

- The ‘Acrotelm’ which is a thin surface layer (approximately 10 – 20cm) which has a low resistance to horizontal and vertical movement of water (high permeability). This layer can be readily drained with drainage effects from a drainage feature potentially being present several hundred meters from the drain.
- The ‘Catotelm’ which is the saturated layer below the Acrotelm which has low horizontal and vertical permeability (up to 1 million times less permeable than the Acrotelm). As a result, there is very little drainage of water from this layer even when deep drainage features are present.

Formation of a raised bog

Peatlands are a type of wetland landscape in which net litter formation exceeds decomposition and organic matter builds up as peat (Holden, et al., 2016) due to waterlogged conditions preventing it fully decomposing. Saturated peat is 90-98% water by mass, and it may be 90-95% water by mass even above the water table (Holden, 2009). A raised bog is a type of peatland which forms due to anoxic conditions (greatly deficient in oxygen/ oxygenless) and subsequent peat formation in a shallow lake, which is eventually invaded by sedges to form a fen. Further peat deposition removes contact between plant roots and nutrient-rich groundwater, resulting in invasion by raised bog species (primarily *Sphagnum* moss), and the eventual formation of a dome-shaped raised bog grown beyond the influence of groundwater.

A natural raised bog surface displays small-scale surface patterning, or a ‘microtopography’ of hummocks and mounds, typically created by the varying growth forms of different *Sphagnum* species (IUCN UK, 2014). A raised bog, in natural condition, is surrounded by a halo of fen vegetation referred to as a ‘lagg’, but this is typically heavily degraded or completely absent due to historical land use changes.

Natural hydrological behaviour

As peat retains large volumes of water even during dry conditions, peat bogs have little capacity for storage of rainfall. A lowland raised bog can be described as ‘rain-fed’ or ‘ombrotrophic’ as it is irrigated exclusively by and solely receives nutrients via precipitation. A mature raised bog in good condition would typically have waterlogged, acidic and nutrient-poor surface conditions (Natural England, 2020); waterlogged conditions are required for the survival of peat-forming plant species. The maximum summer water table depth below the ground surface is commonly accepted as the critical depth for the growth of raised bog plant communities (Price, et al., 2003). Evapotranspiration in peatland is suggested to always be very close to potential evapotranspiration (Gerris, 2012). When the water table drops sufficiently far below the bog/ground surface in the Acrotelm, the water table within the bog stops contributing to atmospheric water losses (Price, et al., 2003).

Two main mechanisms generate rapid flow from peat catchments: saturation-excess overland flow where the saturated peat cannot accept any further input of water from the surface, and rapid Acrotelm flow over the saturated Catotelm (Evans, et al., 1999) (Evans, et al., 1995); the response to rainfall is dominated by these two mechanisms. As a result, lowland peat bogs can function as a source of 'quickflow', resulting in river levels rapidly rising and falling in response to rainfall (Holden, 2009). Conversely, during drier periods many peatland streams may carry virtually no flow at all (J. Holden, 2003). During summer dry periods, evapotranspiration can exceed precipitation and daytime water table lowering will result.

The hydrological regime of healthy peatbogs is therefore generally dominated by water movement close to the surface, with high hydraulic conductivities in the Acrotelm and low hydraulic conductivities in the Catotelm. For the high water tables required for an active raised bog to be maintained, very gentle topographic gradients and thus gentle hydraulic gradients are required; where gradients are too steep, the Acrotelm cannot be maintained and lateral losses are dominated by more intense overland flow events (Mackin, et al., 2015).

While the hydraulic conductivity of saturated peat is highly variable, it generally decreases exponentially with depth, with smaller pores in the more heavily decomposed Catotelm peat being smaller than those in the Acrotelm (Price, et al., 2003). While little soil water storage occurs, some storage of surface water will occur due to the hummock and mound microtopography found in healthy raised bogs (Allot, et al., 2019).

Additional transport occurs in depth in blanket peat via larger holes called 'peat pipes' (Holden, 2009) and macropores. Peat pipes are underground erosion channels through the peat through which water can flow, and can be many centimetres in diameter (Labadz, et al., 2010). Research has indicated that around 50% of the dissolved organic carbon (DOC) in bog streams enters through soil pipes, and as much of 50% of stormflow in a peatland system may be transported by pipes and macropores (Evans, et al., 1995).

Hydrological impacts of drain cutting

Drain cutting or 'gripping' is the practise of digging drainage ditches in peatland areas, which was carried out at Flanders Moss during the 1920s to promote grouse shooting at the site (Shah & Nisbet, 2019). Historically, drain cutting has often been believed to have a very limited impact on bog drainage and merely provide 'more rapid removal of surface water' instead of deep water-table draw down. However, artificial drainage impacts can extend well beyond drain margins and in some cases may affect the entirety of the bog (Richard Lindsay, Richard Birnie, Jack Clough, 2014), lowering the mean water table. The Acrotelm is sensitive to drainage and may be readily emptied over distances of up to several hundred metres, damaging peat-forming conditions and allowing encroachment by non-peat forming plant species.

The formation of gully drainage networks increases drainage density, hillslope-channel connectivity and catchment drainage efficiency, therefore generally resulting in flashier storm hydrographs and higher storm-flow peaks which have been linked to increased downstream flood risk (Evans, et al., 1995). Cross-slope ditches alter water-table depths and dynamics, and typically produce deeper and more variable water tables immediately downslope of each ditch as a result of the upslope contributing area effectively being shortened (J. Holden, 2003). Artificial drainage networks can contribute to flooding by increasing runoff velocities by up to two orders of magnitude.

Drainage ditches can both hinder rapid runoff generation by providing additional temporary storage and aid it by increasing connectivity to river networks (Labadz, et al., 2010). The configuration and location of drainage ditches may result in either flattened or increased peak discharge, as ditch construction will change which parts of the catchment deliver flows to a river at different times. Gripping in catchment headwaters for smaller catchments of around 20 km^2 is therefore more likely to increase flood risk, while gripping closer to catchment outlets may in fact reduce flood peaks (Labadz, et al., 2010).

Resulting subsidence from drain cutting

Subsidence also occurs following gripping, particularly near drains; as a result of the bog surface compressing and 'chasing the water table down', large-scale subsidence may occur across a bog with little visual indication. The reduction in void space in compressed peat results in larger groundwater fluctuations in dry weather, exacerbating drying out of the peat. Where a raised bog has been used for forestry, as is the case for Flanders Moss, further subsidence may have occurred due to the increasing mass of the former tree stand (Wieder & Vitt D, 2006). Some degree of natural 'rewetting' may occur near the surface after the bog compresses and adjusts to the altered groundwater profile (IUCN UK, 2021).

Impacts on emissions of drain cutting

Oxidation of dried peat releases carbon dioxide (CO_2), which is anticipated to be greatest in proximity to drains but may occur over large areas of the Acrotelm during longer dry periods, resulting in greatly accelerated decomposition in the aerobic environment. The loss of a functional Acrotelm reduces or stops peat formation and reduces the capacity of the peatland to sequester CO_2 and may convert the bog from a net carbon sink to a net carbon source. However, an increase in water table elevation following successful restoration actions may increase methane emissions (Holden, 2009).

Water quality impacts of drain cutting

UK studies generally indicate that peatland drainage network creation results in enhanced dissolved organic carbon (DOC) release. Additionally, drainage ditch cutting usually increases nutrient leaching, such as producing elevated ammonium concentrations, with implications for downstream eutrophication; however, there is a significant lack of data on the long-term effects of bog drainage on water quality. A 1992 study of Finnish peatlands found that where drainage ditches had been constructed, a net loss of Ca, Mg and K occurred, whilst the inputs and outputs of these elements were roughly balanced for undrained peatlands (Westman & Laiho, 2002). Research suggests that artificial drainage networks encourage the formation of pipes and macropores capable of transporting sediment, nutrients and water from within the Catotelm (Holden, et al., 2006) due to the artificial drop in the water table causing the peat to dry out.

Hydrological impacts of ditch blocking

Ditch blocking is a common peatland restoration method, and typically involves the creation of dams at regular intervals along the ditches. These dams may be constructed from peat, plastic, heather or wood or as more extensive bunds. Effective ditch blocking to the level of surrounding peatland allows surface water to spill out across surrounding peatland, producing new drainage pathways and converting ditch flow to overland flow (Allot, et al., 2019).

The increased surface roughness due to gully blocking and associated re-vegetation does not significantly alter storage or the volume of storm runoff but succeeds at reducing hillslope runoff rates and reducing flood risk immediately downstream (Shuttleworth, et al., 2019), with an increased proportion of relatively slower overland flow (Artz, et al., 2018). This encourages the recovery of vegetation such as *Sphagnum* moss, further increasing surface roughness and additional slowing of storm flows. Drain blocking generally succeeds at raising the local water table elevation by up to 10 cm, although it may not reach the levels expected for an undisturbed raised bog (Gerris, 2012) and considerable drops in the water table level may still occur during summer.

Impacts on runoff from ditch blocking

A 2019 study found that a combination of surface revegetation and drain blocking increased storm runoff lag times by 200%, produced attenuated hydrograph shapes and reduced peak flows by 51% relative to a control, however, did not find evidence that drain blocking had resulted in changes in catchment storage volumes (Shuttleworth, et al., 2019). Bog rewetting from drain blocking is generally expected to result in attenuation of flood peaks (Richard Lindsay, Richard Birnie, Jack Clough, 2014), particularly at smaller catchment scales. However, it has been suggested that this occurs primarily as a result of ephemeral pool formation where ditch blocking has been performed, with these pools draining between storm events (Allot, et al., 2019), rather than recovery of the water table over the short-term.

In a 2016 study, while a 500% reduction in ditch discharge was initially recorded following damming, discharge increased in subsequent levels to around double that of the first year after blocking (Holden, et al., 2016). Whether this was a result of shallower water tables due to recovery of the Acrotelm or the formation of leaks in the dams remained unclear, but an additional Finnish study indicated that even following restoration water tables were deeper along restored ditch lines (restoration, 2015). The longer-term and larger-scale effects of ditch blocking remain poorly understood. The orientation of drains must also be considered, as blocking downslope-orientated drains is more likely to reduce flood peaks than blocking drains orientated across slopes (Allot, et al., 2019).

Impacts on water quality and emissions from ditch blocking

Drain blocking generally reduces colour, DOC and particulate organic carbon (POC) concentrations in bog streamflow over both the short and long-term, but these trends have not been observed at all studied sites (Wilson, et al., 2010). DOC released from blocked drains has been found to consist of lighter, less humic and less decomposed carbon (Wilson, et al., 2010). A study of drain blocking at 32 UK sites found an average reduction of 28% in DOC where drains had been blocked (Labadz, et al., 2010). Conductivity and pH values in blocked drains have also been reported to decrease (Wilson, et al., 2010), with fine sediment yield also decreasing.

A negative effect of drain blocking is that methane flux is likely to increase from peatland where many drain-blocking pools are formed (Holden, 2009); where possible areas of open water on a restored bog should be minimised to reduce the formation of methane emission hotspots (Holden, 2009). Drain reprofiling was associated with increased methane emissions in a Yorkshire restoration project and subsequently discontinued at the site (Artz, et al., 2018). It should be noted that after forest clearance at Flanders Moss, phosphate, DOC, colour and suspended solid concentrations all increased, with colour levels remaining elevated years after felling (Shah & Nisbet, 2019), so the water quality impacts of surface regrading and drain blocking may be harder to quantify.

Consideration of drain blocking technique

The method of drain blocking employed has significant impacts on restoration efforts. Permanent deep inundation should be avoided as this results in insufficient sunlight penetration and limited or no growth of *Sphagnum* and other hummock-forming species (Tomassen, et al., 2010). The water level upstream of a dam should not be greater than a few tens of centimetres when fully inundated and should not fall to surface level in summer. Dam spacing should reflect surface slope and dams should be more closely spaced on steeper slopes (Tomassen, et al., 2010).

While peat dams are commonly utilised, peat dams may degrade over time, and in some cases have been destroyed by storm events (Tomassen, et al., 2010). Conventional peat dams should not be used on steeper slopes where the gradient exceeds 12° due to the risk of erosion around the top and sides of the dam; for constructing peat dams on slopes steeper than this, turf should be placed on top of the dams at a 45° angle to protect against erosion (NatureScot, 2019).

Peat dams have been identified as the most cost-effective method for ditch blocking, make use of locally available natural materials and blend in with the natural landscape (NatureScot, 2019).

As drainage produces the most pronounced subsidence near ditches, even for a dammed ditch water may continue to flow or accumulate in the ditches instead of spreading across the peatland, producing a mosaic of drier and wetter areas which does not resemble a natural raised bog (Wieder & Vitt D, 2006). Extending dams several metres to the sides of the ditches improves rewetting by spreading water flow more evenly across the peatland.

3.2. Summary

A raised bog in natural condition is an entirely rain-fed system, where the response to rainfall is dominated by water movements close to the surface in the Acrotelm layer, and relatively rapid 'quickflow' is expected during storm events due to the inability of the saturated peat to store additional water. In a healthy raised bog, the water table remains close to the surface even during dry summer periods, although surface streams may run dry.

Ditch cutting has multiple negative impacts on raised bog hydrology; water tables can be lowered over large areas, with associated subsidence, vegetation changes hindering peat formation, increased carbon dioxide emissions and greater concentrations of dissolved and particulate organic carbon and other nutrients entering rivers. While more severe downstream flooding with shorter lag times is likely to result, the runoff response to ditch cutting is complex and site dependent.

Ditch blocking can be employed to provide temporary storage of water during storm events, slow runoff by redirecting a proportion of it overland and locally raise water tables towards their 'natural' levels. Water quality improvements and reductions in dissolved nutrients are likely to be achieved by ditch blocking, although methane emissions may increase. The choice of drain blocking technique should be carefully considered to maximise peatland vegetation growth and restoration of the water table while minimising pools of deeper water.

4. Topographical flow path assessment

This section provides an assessment of the overland flow paths across the surface of the peat. This assessment is in effect the worst-case hydrological/flood scenario where the peat is completely saturated and generating 100% runoff; given the lack of storage capacity of both a degraded and natural raised bog, it is likely to be a somewhat accurate representation of the real response to precipitation. The aim of this analysis is to understand how water currently runs-off the peat, including how the ridges and furrows play a role in routing overland flows and if/how the drainage ditches intercept overland flow routes. Through this process we have delineated both the flow paths and the contributing upstream areas of all flow paths off the peat to the watercourses and/or adjacent farmland.

4.1. Data collation

To produce a complete topographic map, the site was mapped with LIDAR (light detection and ranging) via a drone survey carried out by Malcom Hughes Land Surveyors. The survey was taken at a 0.25 m resolution across the entire site; a very high resolution was required due to the need to display the microtopography of the raised bog surface, the locations of narrow drains less than 0.5 m in width and the pattern of ridges and furrows following ploughing for forestry. Interpolation was used to fill the gaps in the model; these mostly occurred along the surface of the River Forth and bodies of standing water, so would not have a significant impact on the flow path model.

Both a DSM (digital surface model) and DTM (digital terrain model) were produced; the DSM contained surface features such as existing trees and buildings outside the catchment, while the DTM contained the ground elevation only and was used for the flow path analysis. An overview of the DTM is shown below in Figure 4-1. Interpolation produced slightly distorted terrain in some locations where forest had not been cut down prior to the drone survey being flown, particularly on the slope between the southern side of Gartrenich Moss and the River Forth and the northernmost portion of Gartrenich Moss.

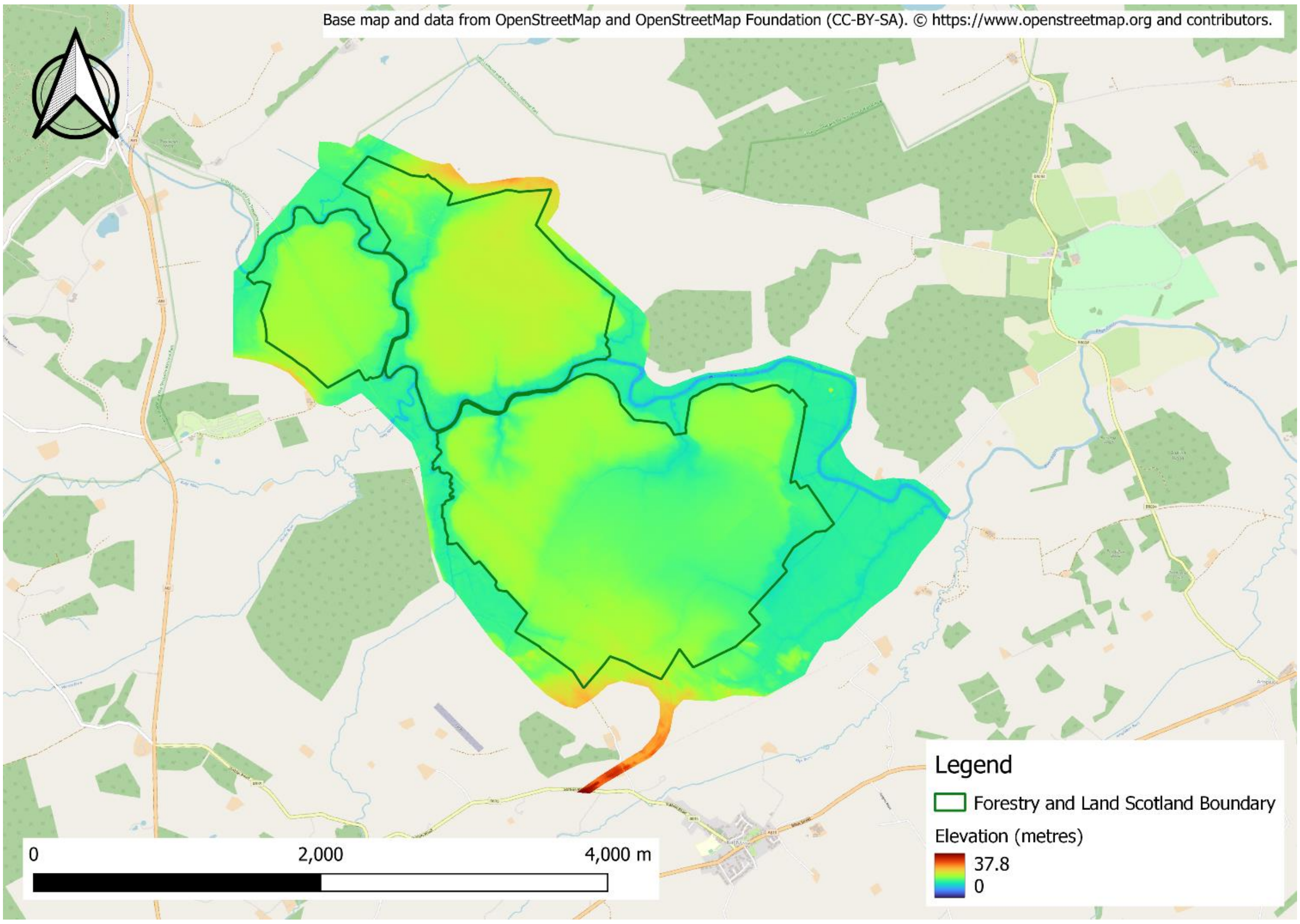

Figure 4-1 - Overview of the DTM produced covering the entire site and immediate surroundings

4.2. Baseline assessment

As it was useful to show drainage to nearby catchments outside the FLS boundary, the entire DTM area was processed to produce the flow channel network. The baseline DTM file was first processed, in ArcGIS, by applying the ‘fill’ hydrology tool function to identify and process sinks and depressions in the topography. A ‘flow direction’ function was then used to identify the direction water would drain to from each point, with a ‘flow accumulation’ function finally being applied to identify the resulting stream channels. The channel network was produced by displaying all cells where the accumulated flow was over 500 cells; this corresponds to an area of 31.25 m^2 or greater draining to these points.

The full channel network is shown below in Figure 4-2. It can immediately be seen that many of these flow paths follow the straight lines produced by both the historical ploughing of the site for forestry and the artificial drainage ditches. Larger drainage ditches located outside the three blocks run around the outside of the blocks and limit the potential for restoration closer to the edges as they will not be altered by restoration actions.

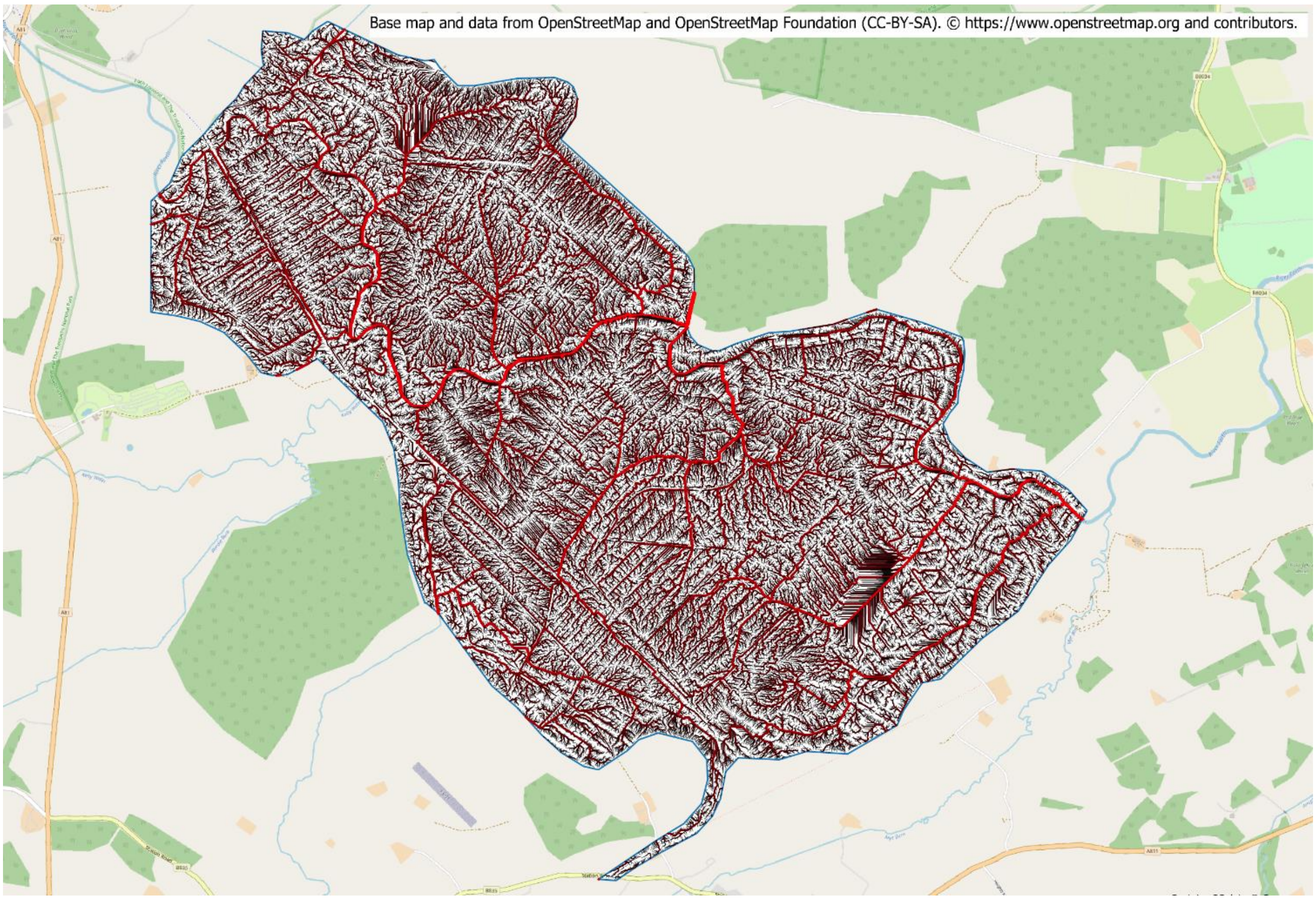

Figure 4-2 - Full channel network for the site and immediate surroundings

By comparing the map of the existing drainage network and the flow path map, it was clear that many of the smaller and intermediate-volume flow paths do not follow mapped drains and instead take overland routes or ‘shortcuts’ between them, often following the furrows left by ploughing.

However, the larger flow paths tended to follow the mapped drains, particularly those marked as ‘to be retained’ by Forestry Land Scotland. The most significant flow channels at the site included the ‘natural’ watercourses such as the watercourse to the north of the Flanders Moss Block, the drainage ditches immediately outside the FLS blocks and the drainage ditches bordering the road.

As shown below in Figure 4-3 and Figure 4-4, at smaller scales the furrows left from ploughing may exert an even greater effect on the drainage network than the drainage ditches, indicating the need for ground smoothing. The channels created by the ploughing will hinder the formation of the small pools which would form on the surface of a healthy raised bog and the resulting ‘hummock and mound’ microtopography from Sphagnum moss growth.

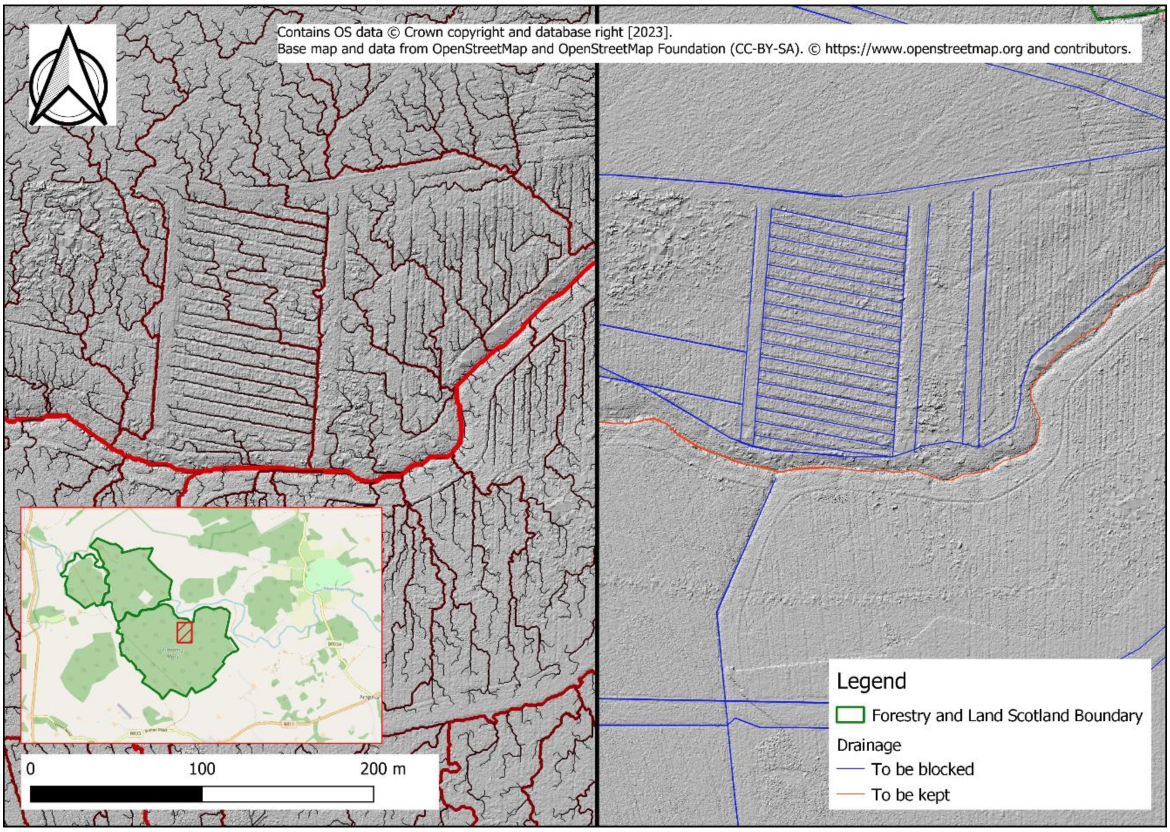

Figure 4-3 - Comparison between the channel network produced and the existing drainage network for an area with a dense ditch network. Note that not all ditches identified by the FLS map may actually function as ditches.

Figure 4-4 - Comparison of the channel network for central Easterhill to the artificial drainage network

As shown above in Figure 4-4 for an example area of Easterhill, in many areas of the site the smallest channels follow the furrows left from ploughing, which are perpendicular to the artificial drainage network. The flow path analysis identified that most of the existing drains on the map supplied by Forestry Land Scotland are flow paths, although in some cases water may 'cut' between drains overland, as demonstrated in the above two figures. A smaller number of the drains marked on the FLS map were not picked up by either the topographic map or the resulting flow path analysis, implying that some drains either do not exist or are so heavily blocked that restoration action is likely not required.

A possible limitation of the LIDAR analysis is that in some cases, drains may be blocked by accumulated vegetation, but sufficient permeability will still exist for throughflow of water to occur. Another likely limitation is the presence of underground peat pipes; assuming that all drainage of water is overland fails to account for potential subsurface drainage but no methods currently exist for accurately assessing the extent of peat pipes in peatland.

For the Easterhill block, the most significant drains were the pair of drainage ditches on either side of the road which will be retained; several large drains which discharge into the River Forth on the eastern slope have portions outside the 30 m boundary buffer zone and will be important to dam as part of restoration efforts. See appendix A for a full description.

For the Gartrenich block, there are three larger drains. As the northwestern one is marked as to be retained and the northernmost portion of Gartrenich does not contain any artificial drains, a smaller difference in the response to rainfall is expected. However, the flow path analysis shows that a large ditch in the south of the block serves as a conduit to a likely-natural watercourse unmarked on the FLS maps. Damming works on this ditch in particular would slow down flow along a significant drainage route. Another ditch to the southwest of Gartrenich carries substantial flow but is outside the FLS boundary so will limit potential restoration works. See appendix B for a full description.

For the Flanders Moss block, flow accumulation was dominated by the large, likely natural watercourse to the north shown in Figure C-4 in the appendices. As this watercourse was fed by several large artificial ditches, flow to this watercourse could be slowed down via ditch damming and ground smoothing in the smaller drains feeding it. The more widely spaced drains in the centre of Flanders Moss carried significant flow, making damming them important, especially given that significant conifer regeneration was occurring in some of these areas. See appendix C for a full description.

4.3. Restored peatland assessment

4.3.1. Impacts of surface smoothing

The effects of surface smoothing are difficult to accurately model given that the ground would not be perfectly levelled even after ridges and furrows were smoothed, and a restored bog would be expected to develop a more complex microtopography after the restoration of the water table to shallower depths.

However, it is clear from the topographic analysis identified that many of the furrows where ploughing has taken place effectively serve as small channels which increase the rate at which precipitation enters artificial drainage ditches and therefore enters nearby catchments. Ground smoothing would block many of these flow paths, resulting in more water pooling on the surface and more overland flow prior to water entering the drainage ditch network.

Flipping the tree stumps into adjacent furrows from ridges would assist in blocking many of the smallest flow paths, creating small and/or temporary pools. This would aid the recovery of Sphagnum moss in formerly forested areas, as well as hindering unwanted forestry regeneration by contributing to local rewetting.

4.3.2. Impacts of ditch blocking

As many of the major flow paths identified correspond to artificial ditches marked as 'to be blocked', ditch blocking is likely to form significant pools of standing water and enable local water table recovery in these areas. The size of pools formed will be heavily dependent on the lateral extent of the peat dams constructed, and where pools are larger a greater proportion of flow will be directed out of ditches and overland, particularly during storm events.

Ditch damming is expected to have the greatest impact on streamflows entering surrounding catchments where the drainage ditches to be dammed are orientated directly down the slope. This will have less impact for the western side of Easterhill and the eastern side of Gartrenich Moss, as in both areas an existing drain runs perpendicular to the slope along the edge of the block, inside the buffer area where restorations will not take place. The greatest impacts are likely to occur at the eastern edge of Flanders Moss, as several drains are orientated directly down a steep slope, as shown below in Figure 4-5, and connect to drains which run through farmland to the River Forth. Following blocking of these ditches up to the 30m buffer at the boundary, peak flow to the exterior drains would likely be reduced due to the increased temporary storage capacity provided by the dams on the relatively steep slopes and the greater proportion of the flow directed overland rather than directly to the ditches.

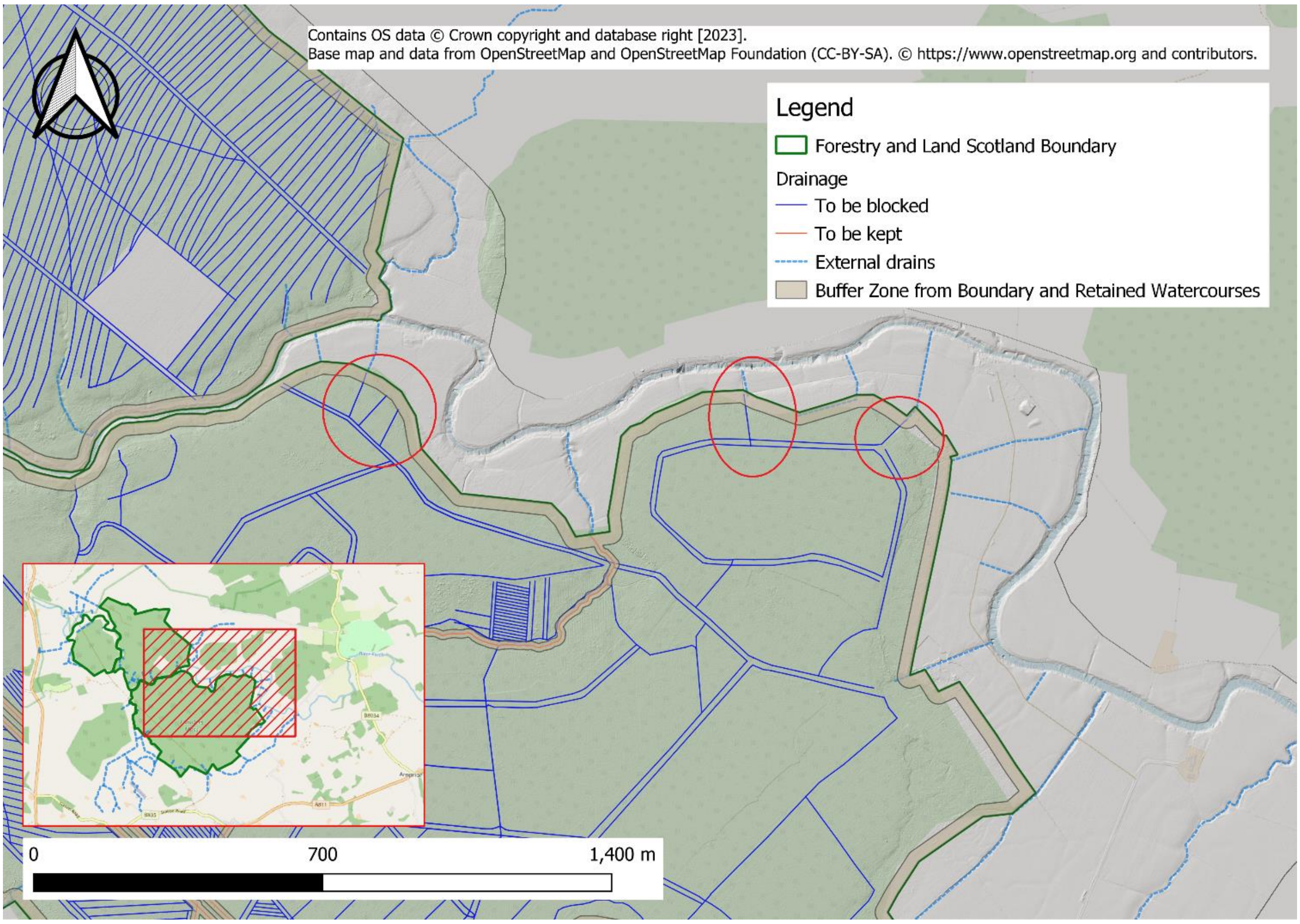

Figure 4-5 - Drains circled in red where reductions in peak flow would be likely following restoration works

4.3.3. Consideration of slope

The main difficulty associated with peatland drainage ditch dam construction is the dams being ineffective on steep slopes; for Flanders Moss, this will not be a significant issue, as only a negligible proportion of the drainage network to be blocked is at an angle greater than the recommended 12° angle threshold for normal peat dam construction, and the overwhelming majority of the site has a slope angle less than 6°, as shown in Figure 4-6. While the literature review identified that placing turf on peat dams is required for steep slopes, this can be ignored for Flanders Moss.

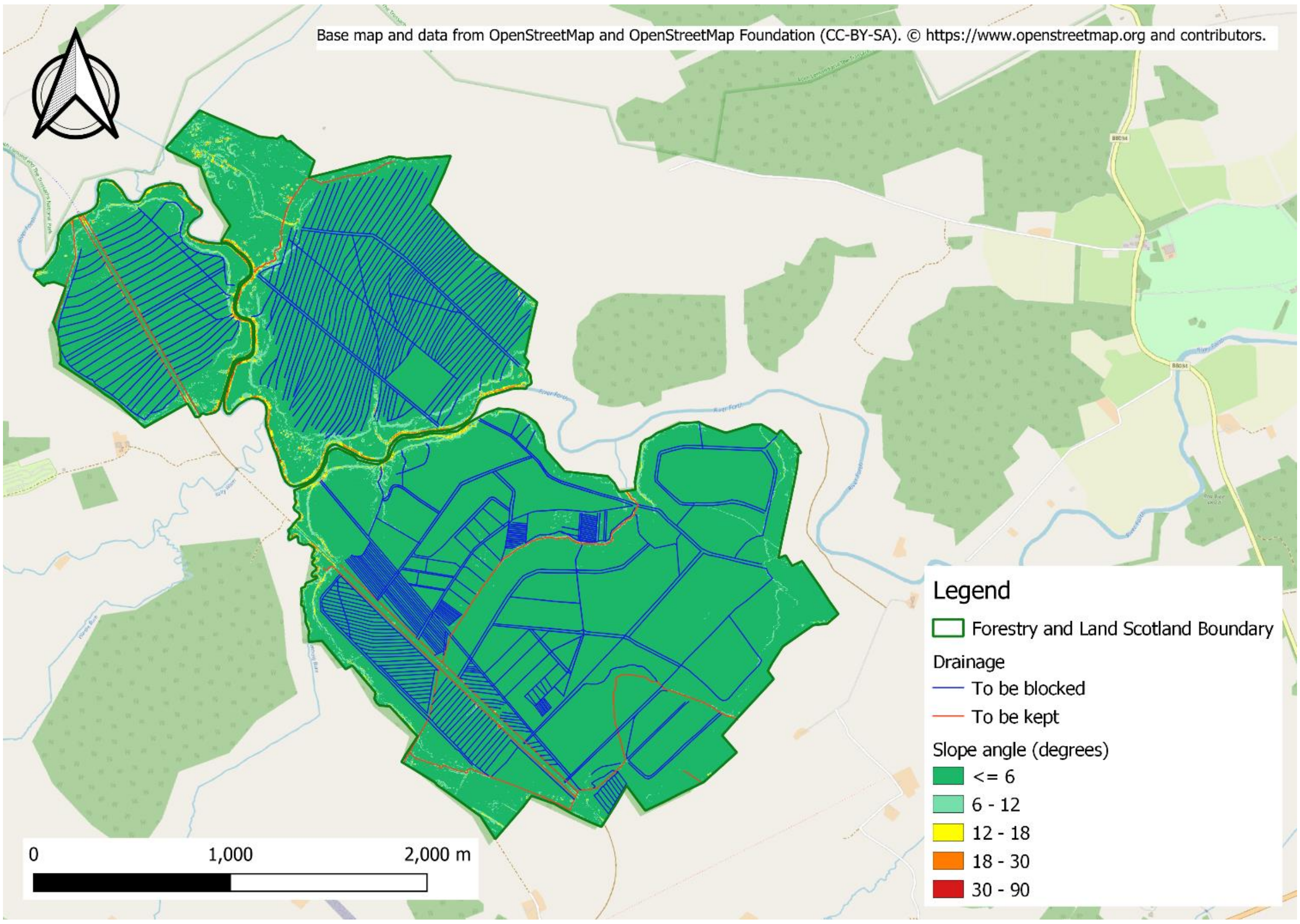

Figure 4-6 - Slope map for the three forestry blocks

4.3.4. Ecological impacts

Ecologically, the planned restorations would be expected to have a wide range of benefits. As evidenced by the site visit, all three forestry blocks currently contain areas of healthy sphagnum moss, allowing more rapid colonisation of previously afforested blocks once the water table recovers. The creation of new pools due to ditch blocking is likely to attract both moorland birds and amphibians to the restored sites (Beadle, et al., 2015).

Particularly for the Flanders Moss block, prioritising ditch blocking in those areas closest to existing pools and retained natural watercourses will promote colonisation of new pools by macroinvertebrates (Beadle, et al., 2015). Flanders Moss has previously been identified as among several currently degraded UK sites where recovery of vegetation with peat-forming capacity within 30 years following restoration of the water table could be achieved (Joint Nature Conservation Committee, 2020).

4.3.5. Long-term effects

While the original hydrological and ecological state of the forestry blocks will not be fully recreated, over time rewetting of the site as a result of the restoration works would be expected to lower the depth to the water tables and restore a much greater proportion of the site to being ‘active’ peatland where net accumulation of peat is occurring, and therefore more of the site will function as a carbon sink. An increase in biodiversity would be expected in restored areas (IUCN UK, 2014). While the restored bog would be expected to develop an ecosystem closer to that of an undisturbed bog, in previous studies an ecosystem developed that was intermediate between undisturbed reference sites and degraded peatland prior to restoration (Vitovcova, et al., 2021).

It should be recognised that due to the historical removal of the lagg fen from all three forestry blocks and the conversion of land at the edges of Flanders Moss to agricultural land uses with associated drain cutting will mean that the hydrological regime of the entire bog will already have adjusted to an altered, ‘truncated’ shape. No recovery of the lagg will occur as the artificial channels (see Figure 2-18) outside the FLS site will be retained. The planned restoration works will help restore a more natural raised bog hydrology and ecosystem within the boundaries without significantly modifying the altered overall shape or topography, with the restored bog coexisting with nearby land uses.

4.4. Summary

The high-resolution DTM model was used to generate a map showing the flow paths across the whole site for Flanders Moss. This provided a reasonably good approximation of the real response of the saturated raised bog to rainfall, although cannot account for any transport of water through subterranean peat pipes.

Overall, the flow path assessment supported the idea that historical drainage ditch cutting and ground smoothing to promote forestry has profoundly altered the natural hydrology of all three forestry blocks at Flanders Moss. In many areas, runoff initially follows channels along the furrows left by ploughing to perpendicular drainage ditches, before accumulating in certain artificial ditches and natural watercourses and discharging to the River Forth and drainage ditches in the surrounding farmland.

The Easterhill block was identified to be in the most altered state, with Gartrenich Moss being the most ‘natural’. However, as the site visit identified Flanders Moss to be in the driest condition and the flow path analysis indicated that many of the artificial drainage ditches in Flanders Moss served as major flow channels and ‘shortcuts’ for water following rainfall, it is likely that Flanders Moss is in the most severe need of restoration actions, particularly ditch damming. A more detailed description of the findings for each block is described in the appendices.

5. Summary and conclusions

A raised bog is a rain-fed system which can be compared to a ‘dome’ of water, with a shallow Acrotelm layer overlying a permanently saturated Catotelm layer. As the bog has very little capacity for water storage, the response to rainfall events is relatively rapid, ‘flashy’ flows. Following drain cutting, a greater proportion of flow is directed into ditches, typically resulting in greater peak flows entering neighbouring river catchments more rapidly. Drain cutting is also associated with greater erosion, reductions in the water quality in flows leaving the catchment and greater carbon dioxide emissions.

The likely impact of the restoration works at Flanders Moss is reduced peak flows, with a greater proportion of flow directed overland and slowed down. Particularly for the eastern edge of Gartrenich Moss and the north and east of Flanders Moss, many of the drains to be blocked are orientated downslope and will see more significant reductions in peak flow onto surrounding farmland following blocking; water quality improvements in the discharge to surrounding drains are also likely as the reduced flow velocities will have less ability to erode bare peat. However, there is unlikely to be a significant difference in the total volume of storm flow, as there is unlikely to be a significant change in the overall storage capacity of the forestry blocks at the site.

The ground smoothing operations are expected to block many of the existing flow paths in the former plantation areas of all three blocks. As a result, a larger volume of water will be retained on and near the surface following precipitation, which will locally encourage the growth and recovery of *Sphagnum* moss and recovery of the microtopography.

The hydrological effects of drain blocking are hard to predict and will vary across the site. The greatest increases in the water table elevation towards the peatland surface and associated habitat restoration will occur near where drains are blocked, however effects may be less noticeable further away from where artificial drains are dammed. Overall, the main impacts of restoration works are likely to be ecological rather than hydrological and localised to where artificial drains are not being retained. Where water drains into artificial drainage ditches oriented perpendicular to the slope, damming will have a reduced effect on flows and for many of the edges of the blocks restoration will be limited as these drains lie within the buffer zone and will not be altered.

Gartrenich Moss was identified as being in the best condition and will see the least change following restoration; areas of Flanders Moss were identified as being in the worst condition and are likely to see significant improvements following restoration works. It is unlikely any substantial changes in ground elevation at the site will occur, as the truncated shape of the forestry blocks will not change. The retained artificial drains just outside the FLS boundary and within the 30m buffer zone around the edges of the three blocks and particularly on both sides of the road through Easterhill and Flanders Moss will limit large-scale rewetting. Rewetting is likely to be locally concentrated where peat dams are constructed and may be more extensive in flatter areas where ditches are spaced far apart.

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Appendices

Appendix A. Easterhill

A.1. Overview

Easterhill is located to the northwest of the site and is the smallest of the three blocks with an area of 0.92 km^2 and a maximum elevation of 21.3 m AOD. Easterhill is crossed by a paved road running north to south, which roughly cuts the block in half. The northern edge of the site contains ancient woodland, which is being retained; in this area of the site, no restoration actions are taking place as the only existing drains are planned to be retained.

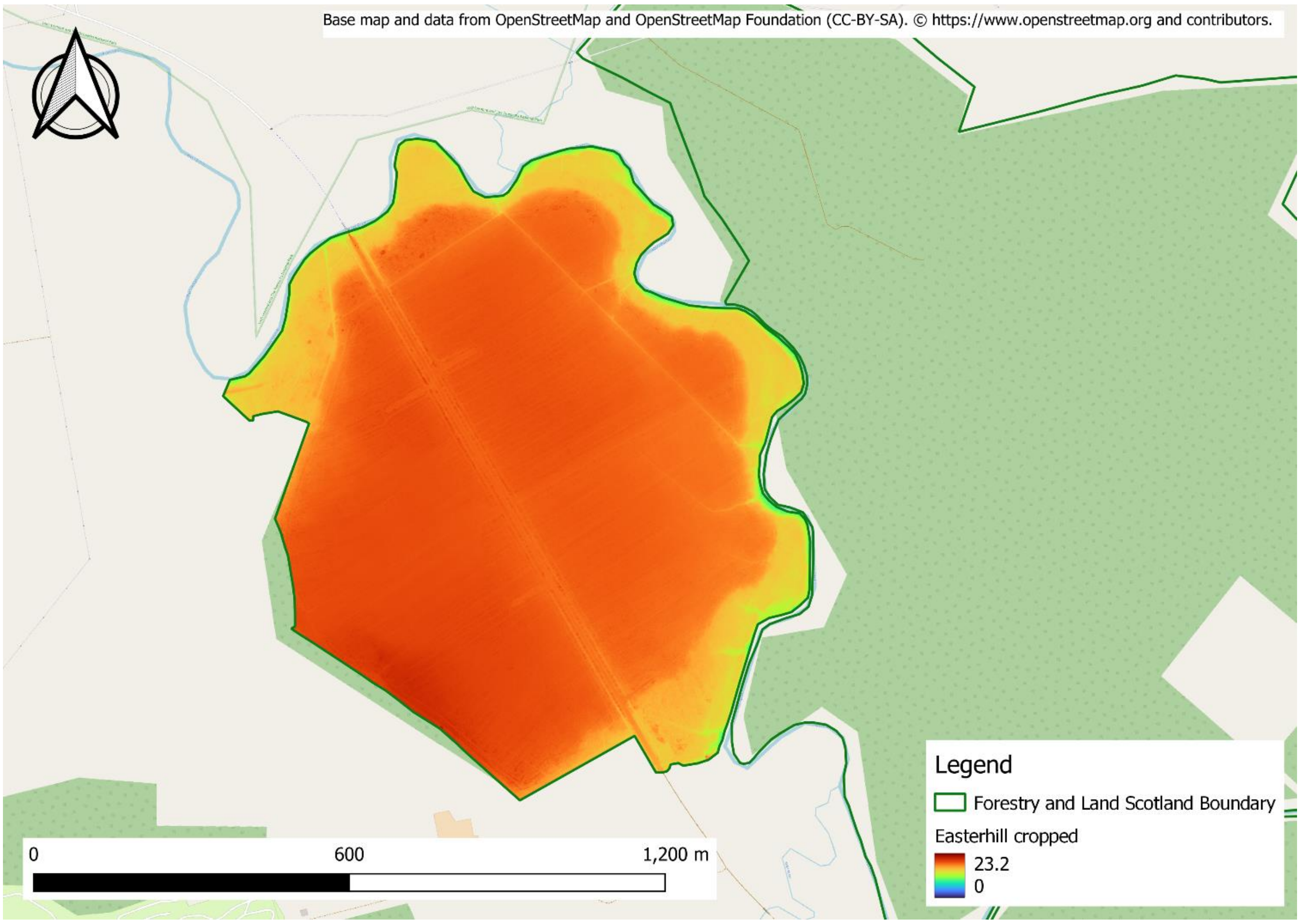

Figure A-1 - Topography of Easterhill

A.2. Current condition of the block

The site investigation identified that many of the smaller drains in Easterhill appeared to already be in a blocked or partially blocked state; the ground was very wet, particularly on the western side of the road. Substantial regeneration of young trees was noted to be occurring in Easterhill, indicating that these areas of the block were in an unnaturally dry state. The proposed stump flipping and ground smoothing actions at Easterhill to prevent tree regrowth is therefore important.

A.3. Existing drainage network

Figure A-2 - Existing drainage map of Easterhill

To the north and east, Easterhill drains directly to the River Forth. To the south and west, it drains to artificial drainage ditches immediately outside the FLS boundary and has had its natural shape significantly truncated by historical conversion of adjacent land to agriculture.

Easterhill contains the most extensive artificial network drainage of the three forestry blocks, with a network of closely and regularly spaced drains on either side of the road at a spacing of approximately 40 m between drains. The only locations where drains are not present are around the steeper slopes at the block edges.

A.4. Flow path analysis

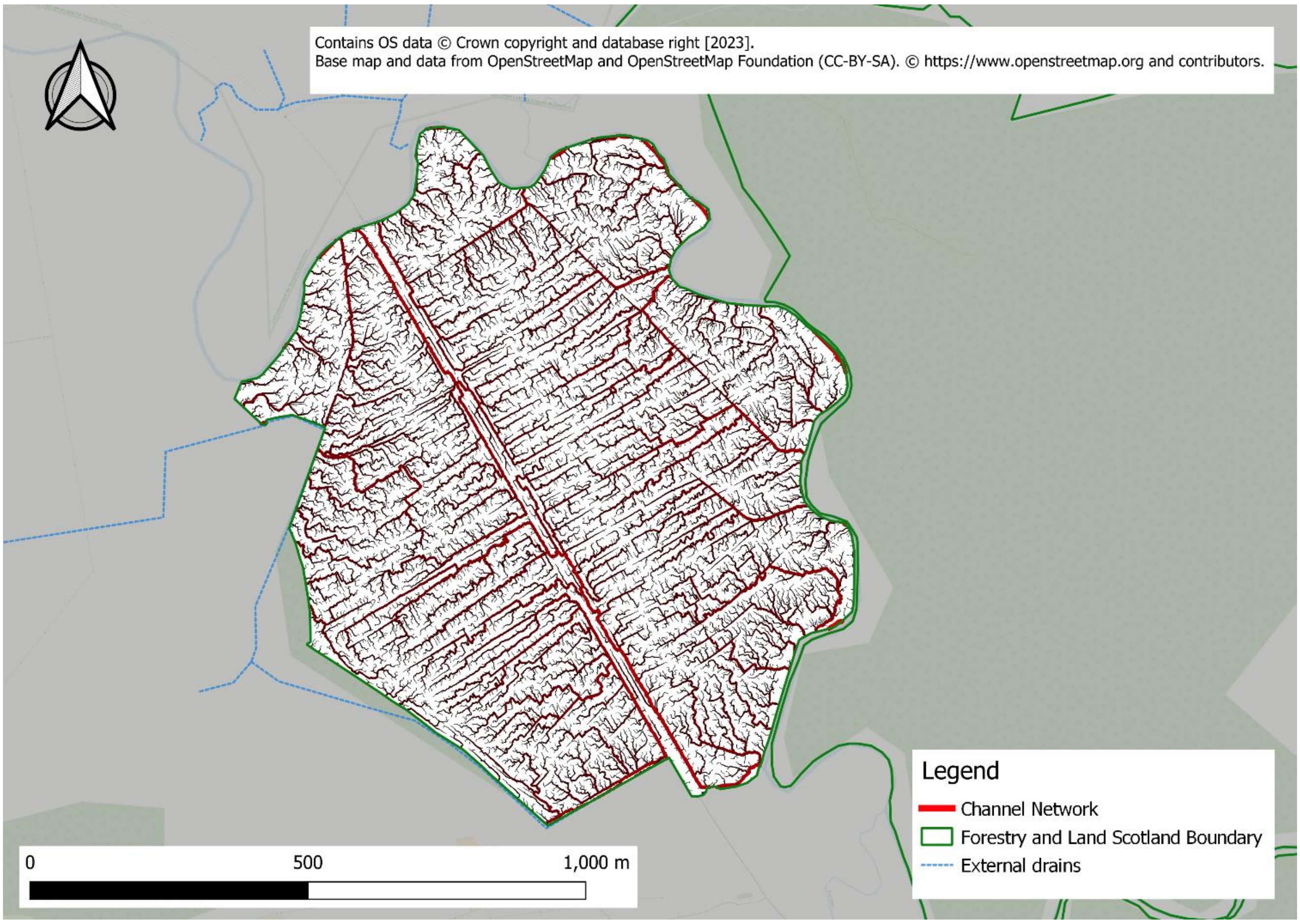

Figure A-3 - Flow channel network for Easterhill

As shown above, the drainage pattern in Easterhill is relatively consistent across the site and very heavily altered by the former land use for forestry. Small drainage channels along the furrows from ploughing run perpendicular to the larger drainage channels formed by the ditch network. Around the edges of the block, larger ditches oriented perpendicular to the slope direction collect water from the drainage ditches and transport it to the River Forth and artificial drains on the farmland outside the site.

A.5. Restoration potential

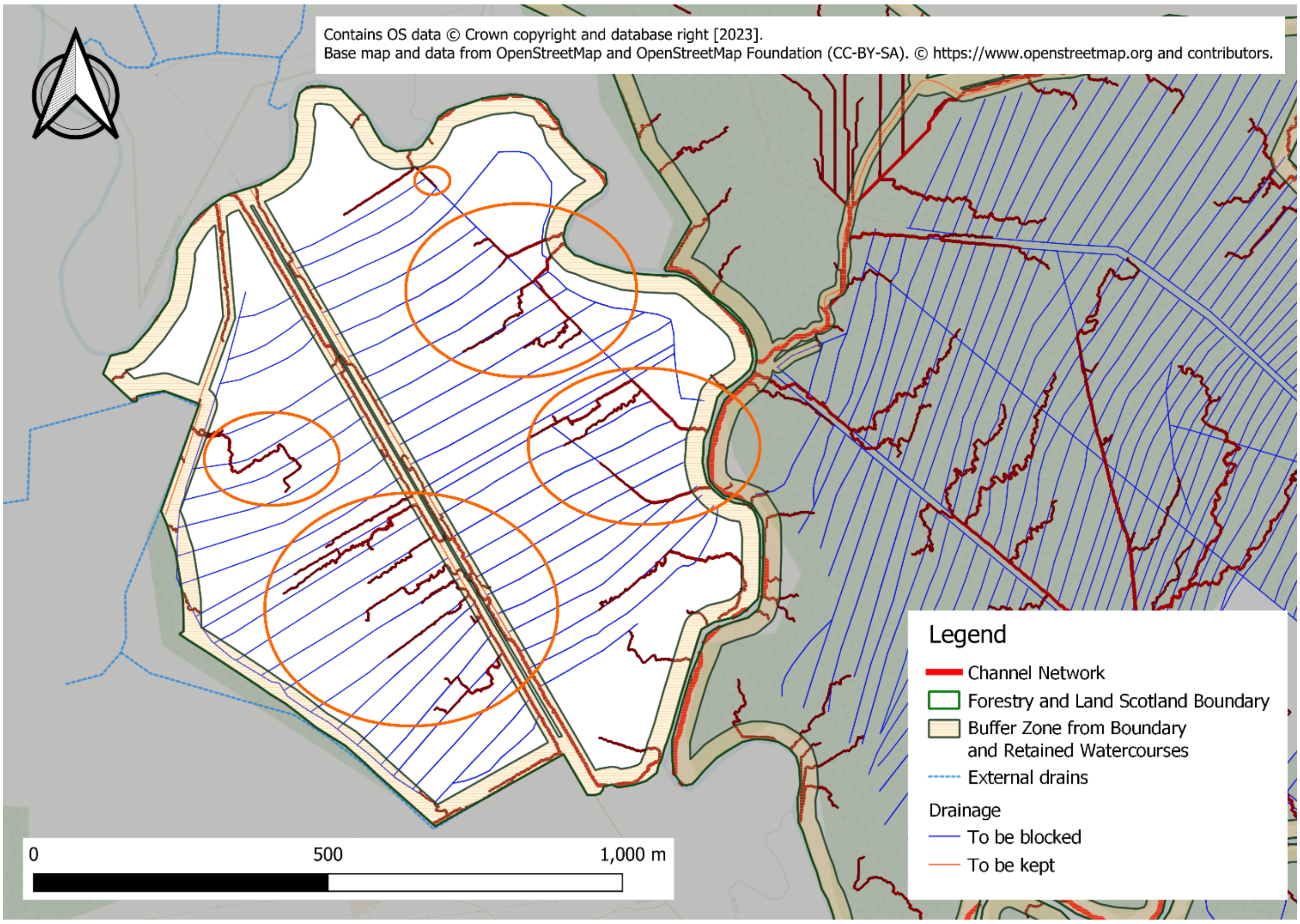

Figure A-4 - Comparison of the artificial drainage network at Easterhill to the major flow channels. Areas with significant overlap are circled in orange.

At Easterhill, ground smoothing actions are likely to have the greatest impact of the three forestry blocks, as this will block many of the extensive network of drainage channels along the furrows. Damming along the drainage ditches will also have an impact, particularly when the larger ditches to the northwest of the site are blocked.

However, as the drainage ditches along the road will not be modified, restoration will be limited. It would be expected that the peak flows transported by the two ditches bordering the road would reduce following restoration of the rest of the ditch network and water quality would increase; however, they are still likely to provide rapid drainage for a large portion of Easterhill. The central location of these retained ditches is also likely to severely limit water table recovery for a large portion of the block.

Damming of the drains circled in orange in the eastern portion of Figure A-4 will be particularly important to achieve successful rewetting, as they provide a major and shortened flow path for a significant portion of the artificial drainage network on the eastern side of the block.

Appendix B. Gartrenich Moss Block

B.1. Overview

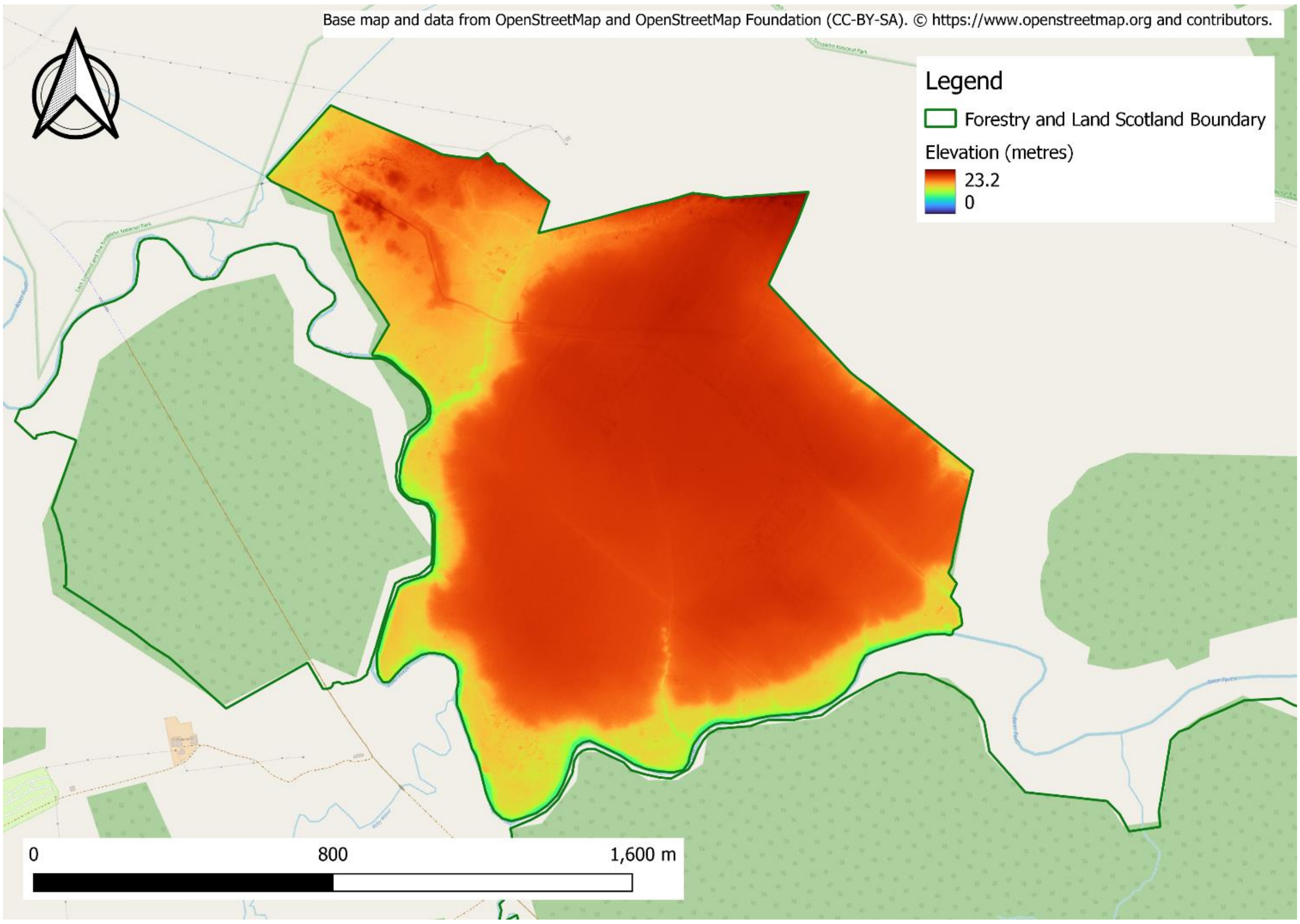

Figure B-1 - Topography of Gartrenich Moss

Gartrenich Moss is located to the north of the site and has an area of 1.97 km^2 and a maximum elevation of 23.2 m AOD. Unlike the other two forestry blocks, the conifer plantation on the block had not yet been fully harvested when the drone survey was carried out due to the steeper terrain on the southern slopes preventing easy access with machinery. Only part of the raised bog 'dome' is within the FLS boundary, with the raised bog continuing east. Depressions as a result of subsidence from ditch cutting are less prominent in the DTM compared to the other two blocks.

The DTM model produced from the LIDAR for Gartrenich contained areas of odd terrain to the north and southwest of the block. As these correspond to existing forestry areas, they are likely to be artifacts resulting from the LIDAR having to interpolate where trees had affected ground surface elevation data.

B.2. Current condition of the block

The site investigation identified Gartrenich as being in the wettest and 'most natural' state out of the three blocks, with much of the surface visibly saturated and with sphagnum moss present. Fewer drainage ditches were present and little visible flow of water was observed; the extensive drainage network shown in Figure B-2 for this block may not be an accurate representation of which drains are functional. Little regeneration was observed, indicating that the water table in the block was already relatively close to the surface.

B.3. Existing drainage network

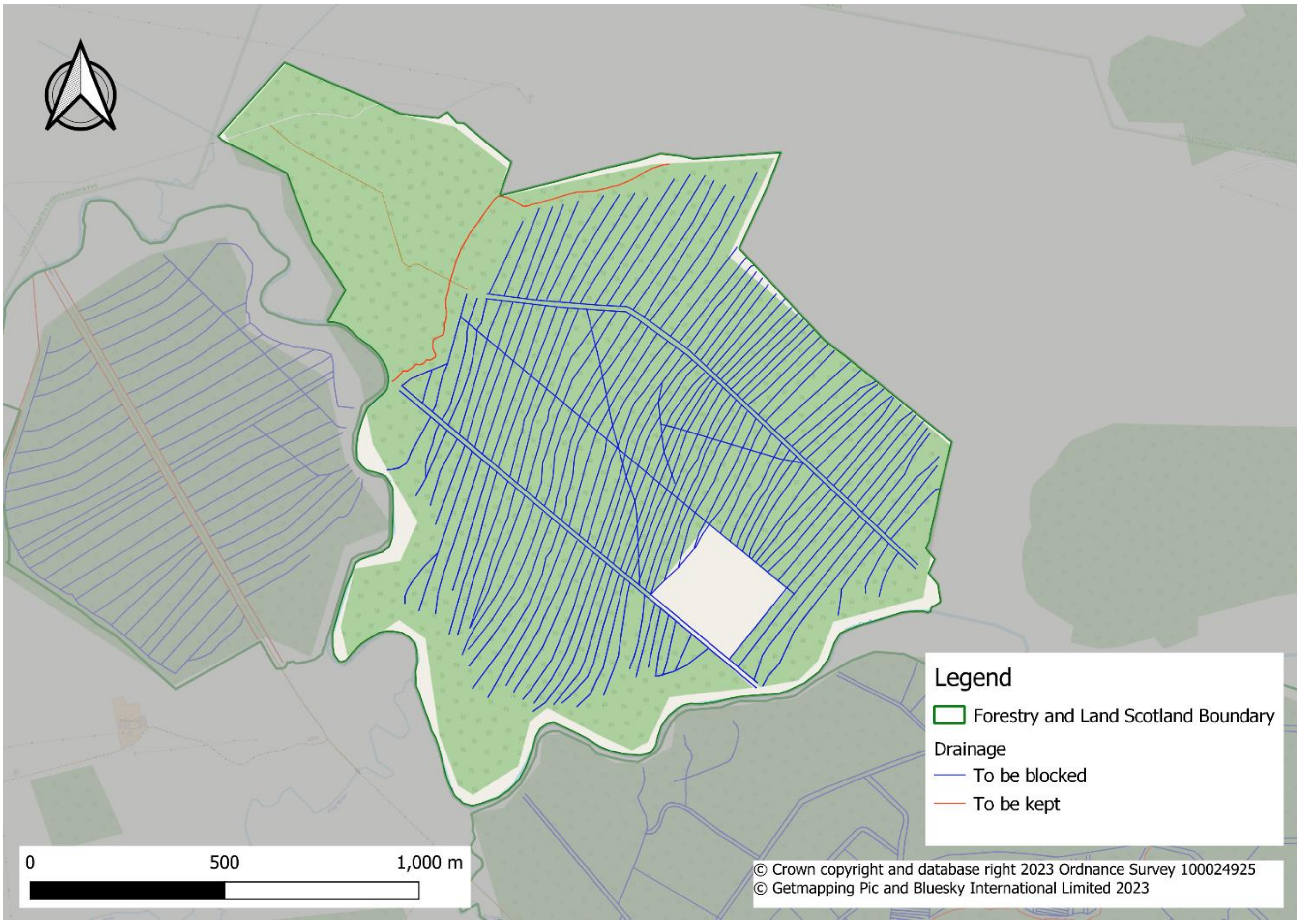

Figure B-2 – Existing drainage map of Gartrenich Moss

To the south and west, Gartrenich Moss drains directly to the River Forth. To the north it drains to an artificial drainage ditch just outside the FLS boundary which drains west to the River Forth. To the east, it borders other areas of raised bog which have not been recently afforested; this may contribute to the relatively ‘healthy’ state of Gartrenich identified by the site visit.

Most of the block is covered by an extensive drainage network of drains spaced at an approximate spacing of 35 m apart, although there are no drains in the northernmost section of the site and a square-shaped gap in the south, shown in Figure B-2. Drains do not extend to the steeper slopes at the south and southwest of the block.

It should be noted that an artificial drain lies along the eastern edge of the block; this was not marked on the map supplied by FLS and is not planned to be blocked. The presence of this drain will limit restoration potential along the eastern edges of the forestry block.

B.4. Flow path analysis

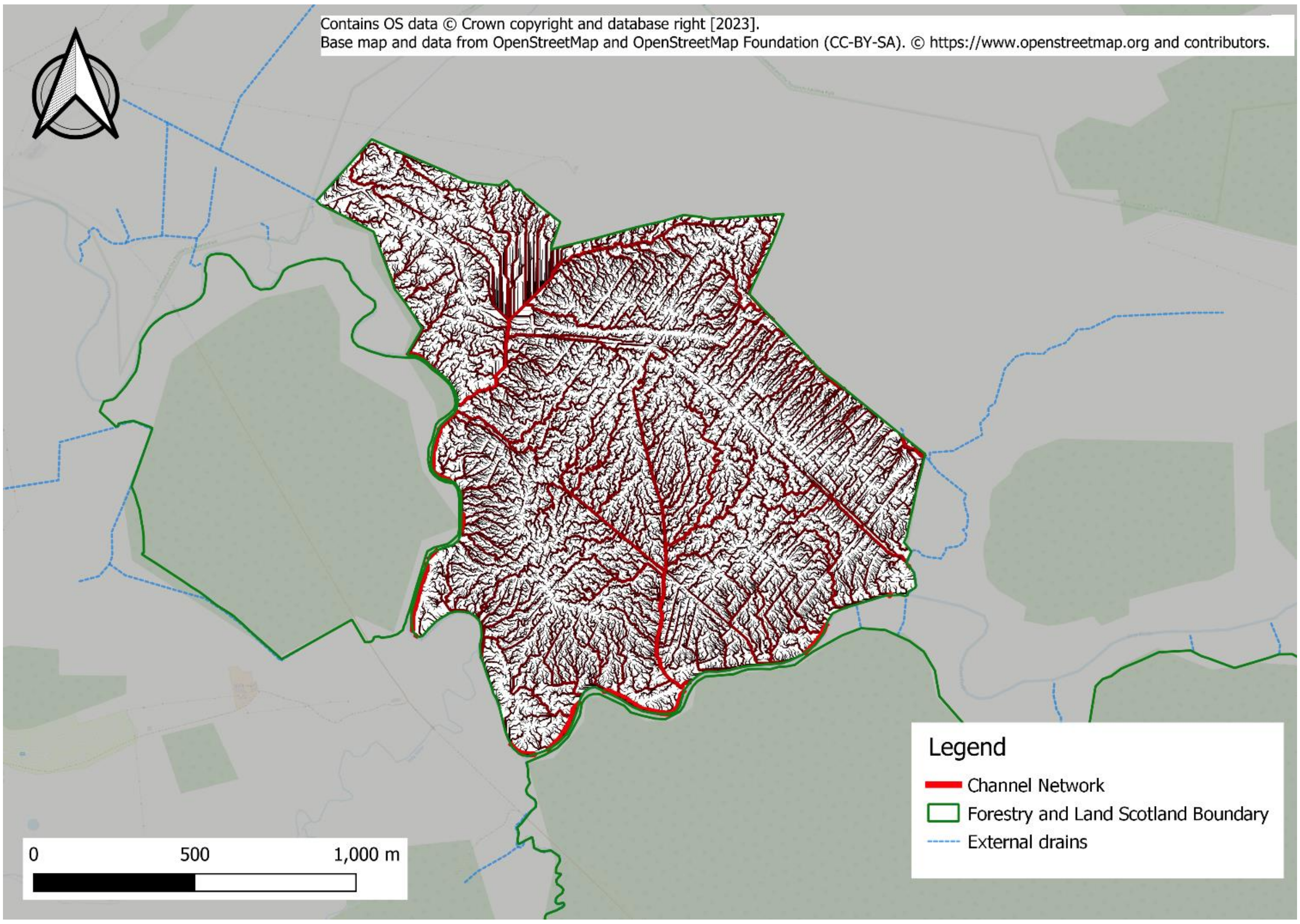

Figure B-3 - Flow channel network for Gartrenich Moss

As shown above in Figure B-3, the north, west, southwest and centre of Gartrenich Moss display a more natural channel network, although many of the smaller channels drain through the prominent artificial drain to the south. To the east, the channel network more closely resembles that of Easterhill, with small flow channels draining along furrows from ploughing into a perpendicular network of artificial drainage ditches. Where drains have not been cut along the steeper slopes bordering the river, the natural channel network is still mostly present.

B.5. Restoration potential

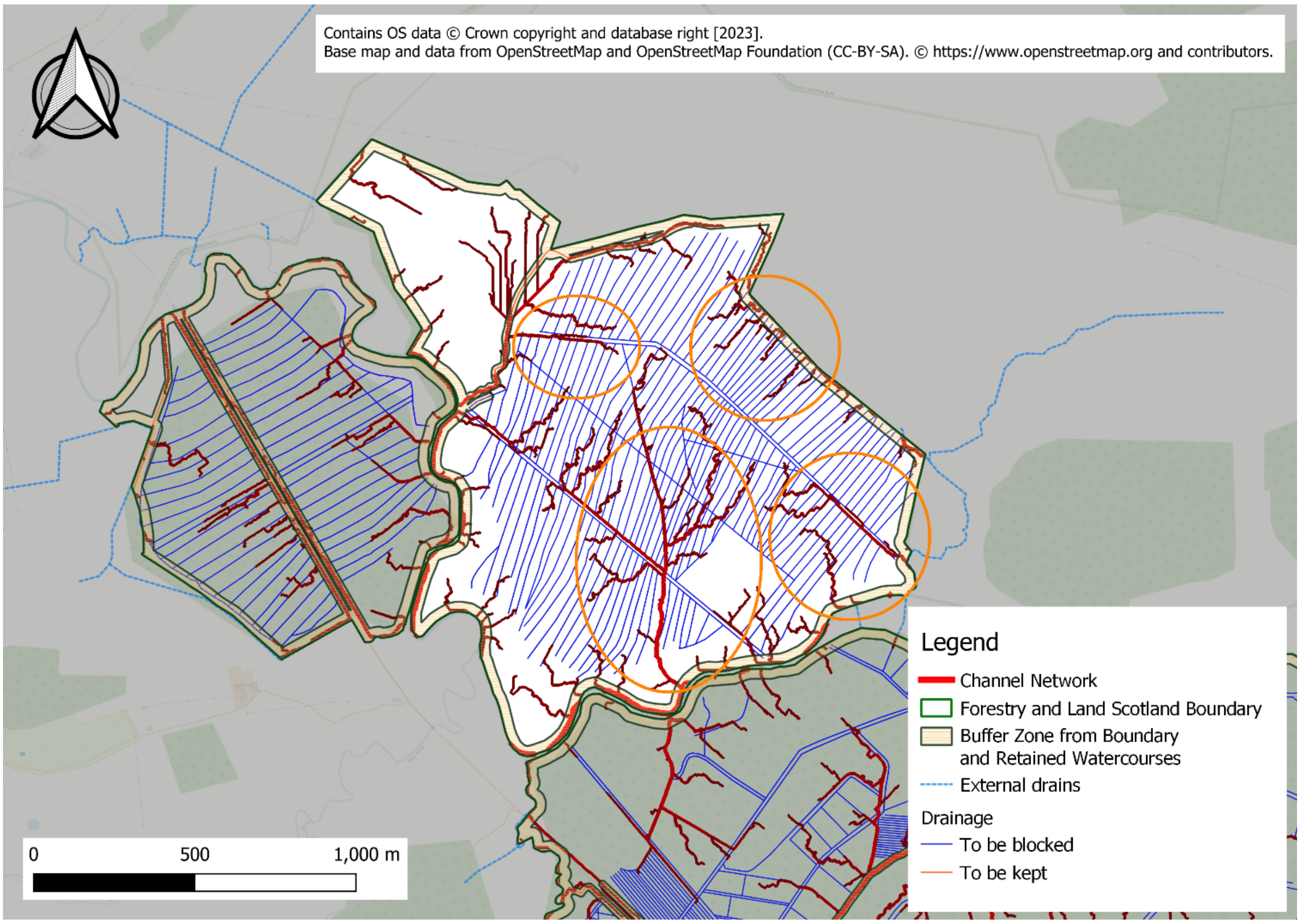

Figure B-4 - Comparison of the artificial drainage network at Gartrenich Moss to the major flow channels. Areas with significant overlap are circled in orange.

Gartrenich was notably identified by the site investigation as being in a more 'natural' state. Comparing the channel network and the artificial drainage ditches indicated that in many parts of the block, the artificial ditches appear to be infilled and the channels follow alternative paths, indicating a less pressing need for restoration actions than for Easterhill and Flanders Moss.

The drainage ditch to the south circled on the map above should be of high priority for drain blocking, as flow path analysis identified that it is a major drain for the block while being marked as 'to be blocked'. As this ditch runs downslope, damming it will also have a more significant effect for slowing discharge following storm events. The circled drain to the southeast should also be considered high priority, as it significantly shortens the flow paths and will result in faster runoff to the external ditch in the southwest.

Appendix C. Flanders Moss Block

C.1. Overview

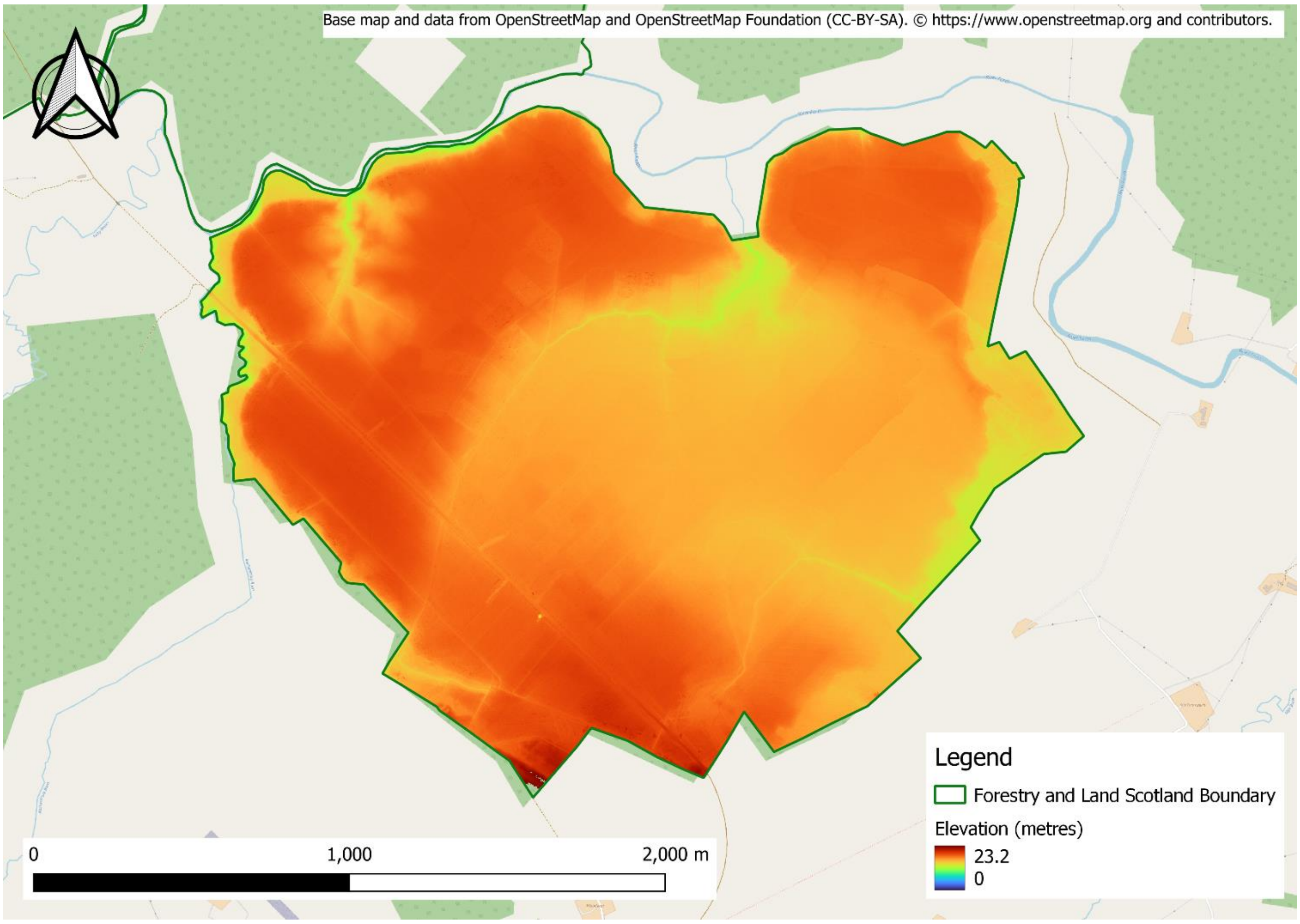

Figure C-1 - Topography of Flanders Moss

Flanders Moss is the largest of the three forestry blocks; it is located to the south of the site and has an area of 4.05 km^2 and a maximum elevation of 23.2 m AOD. A paved road runs across the southwestern edge of the site; full access across the road will be retained following restoration works. As shown by Figure 4-1, to the south the ground elevation increases beyond the edge of the block, with some areas outside the FLS boundary draining onto the block.

C.2. Current condition of the block

The original 'dome' shape of Flanders Moss has been heavily altered by the conversion of surrounding land to farmland and the cutting of drainage ditches within the bog. On the southern, western and eastern sides the raised bog has been truncated. Particularly in the northwest of the block, the truncation has resulted in steeper slopes and it is likely that the edges of the raised bog in this area no longer function as a raised bog ecosystem.

The site visit indicated that Flanders Moss was significantly drier than Gartrenich Moss and Easterhill.

Large areas of Flanders Moss were shown by the DSM and site visit to be undergoing significant regeneration of forest. This indicates that Flanders Moss is in a much drier state than under natural conditions, and drain blocking is needed in these areas. As shown below in Figure C-2, particularly in areas where there is a dense drainage network, heavy regeneration is occurring, demonstrating the need for both ground smoothing/stump flipping and drain damming.

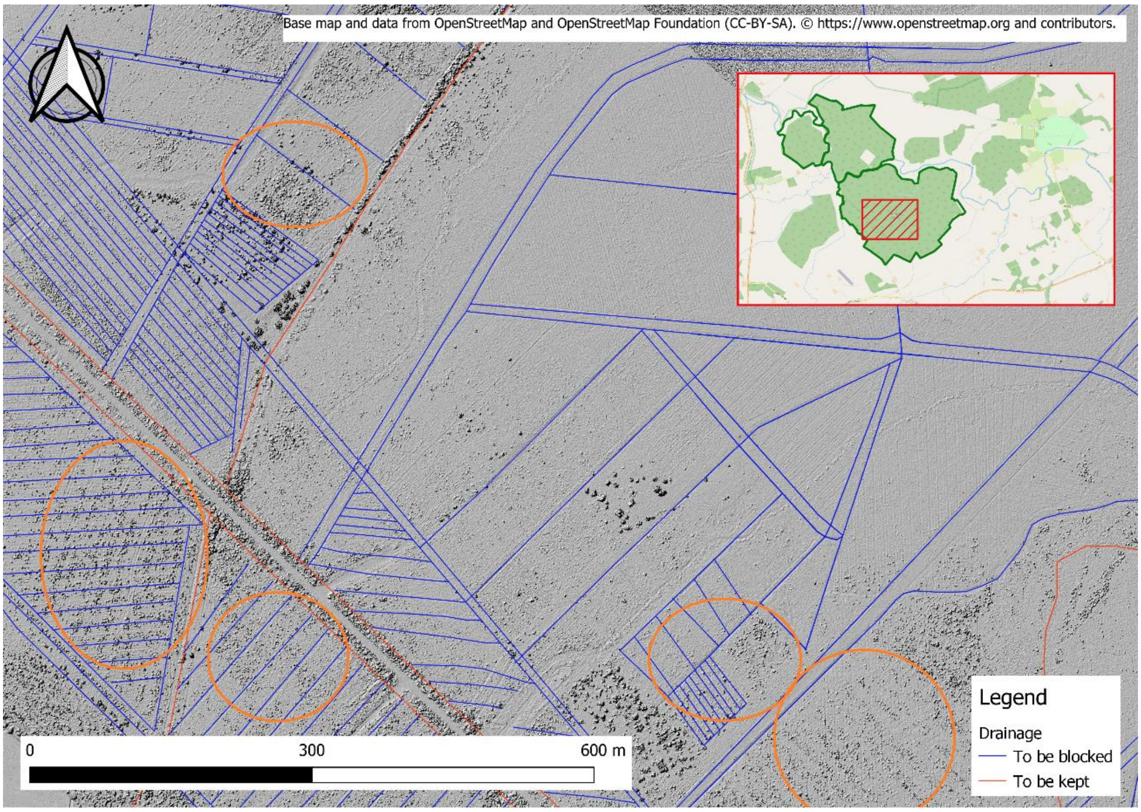

Figure C-2 – Examples of areas of regeneration in southern Flanders Moss shown on the DSM, circled in orange.

C.3. Existing drainage network

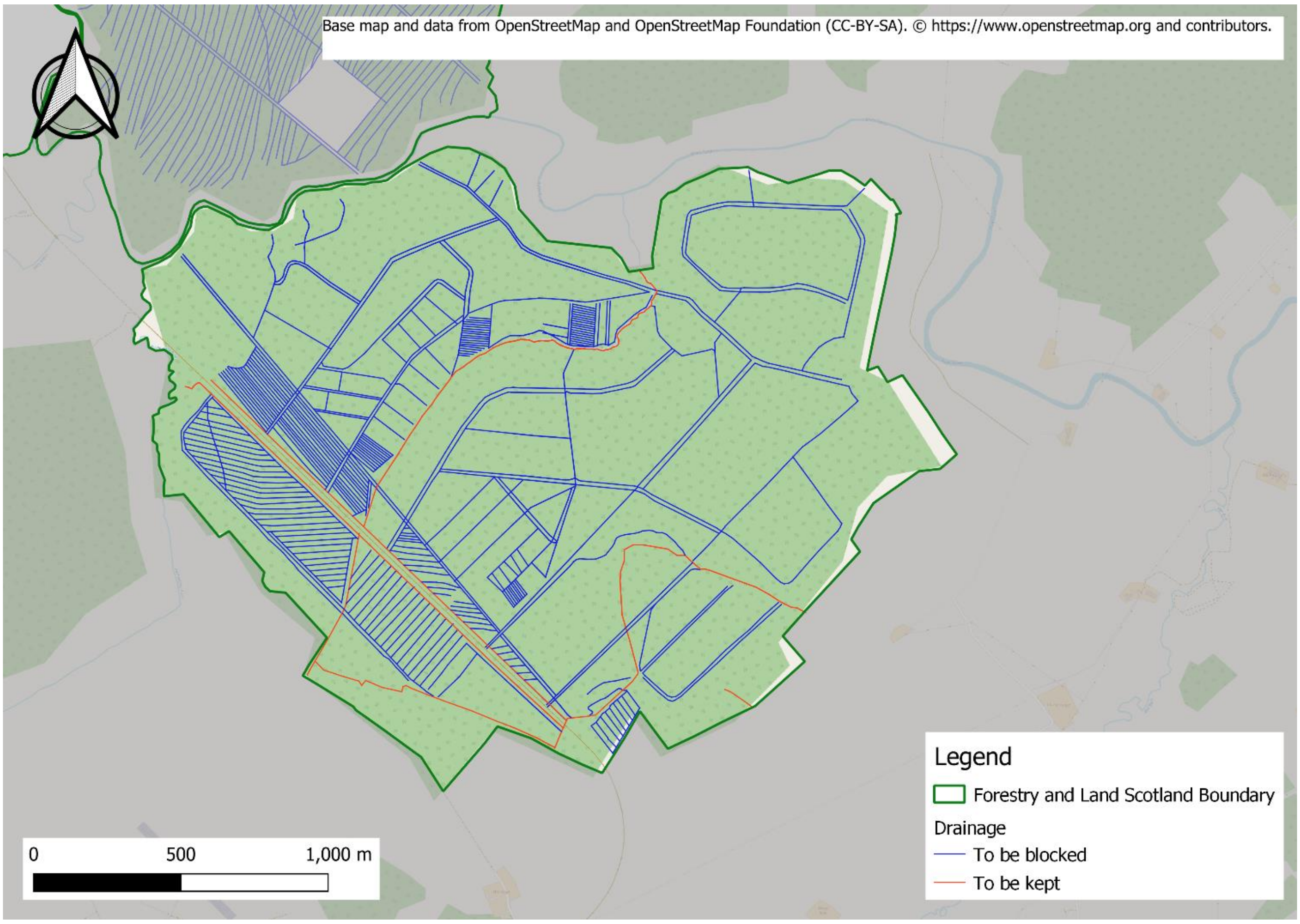

Figure C-3 - Existing drainage map of Flanders Moss

To the northwest, Flanders Moss drains directly to the River Forth. To the west, south and east it drains down a steep slope into drainage ditches in adjacent farmland. Large artificial drainage ditches are present on the farmland outwith the FLS boundary.

The spacing of artificial drains is highly variable across Flanders Moss as shown above in Figure C-3. In some areas a very dense artificial drainage network exists, especially close to the road in the west, while drains larger and less regularly spaced on the eastern side of the block. However, as the impacts of artificial drains can extend for hundreds of metres across the water table in a raised bog, it is likely that the entire block has an altered hydrology due to the artificial drains.

A larger, likely natural watercourse drains the block to the north. This is marked as to be ‘retained’ but is joined by artificial drains and likely carries greater peak flows than would occur prior to drain cutting. Two large drainage ditches are located on either side of the road which will be retained.

C.4. Flow path analysis

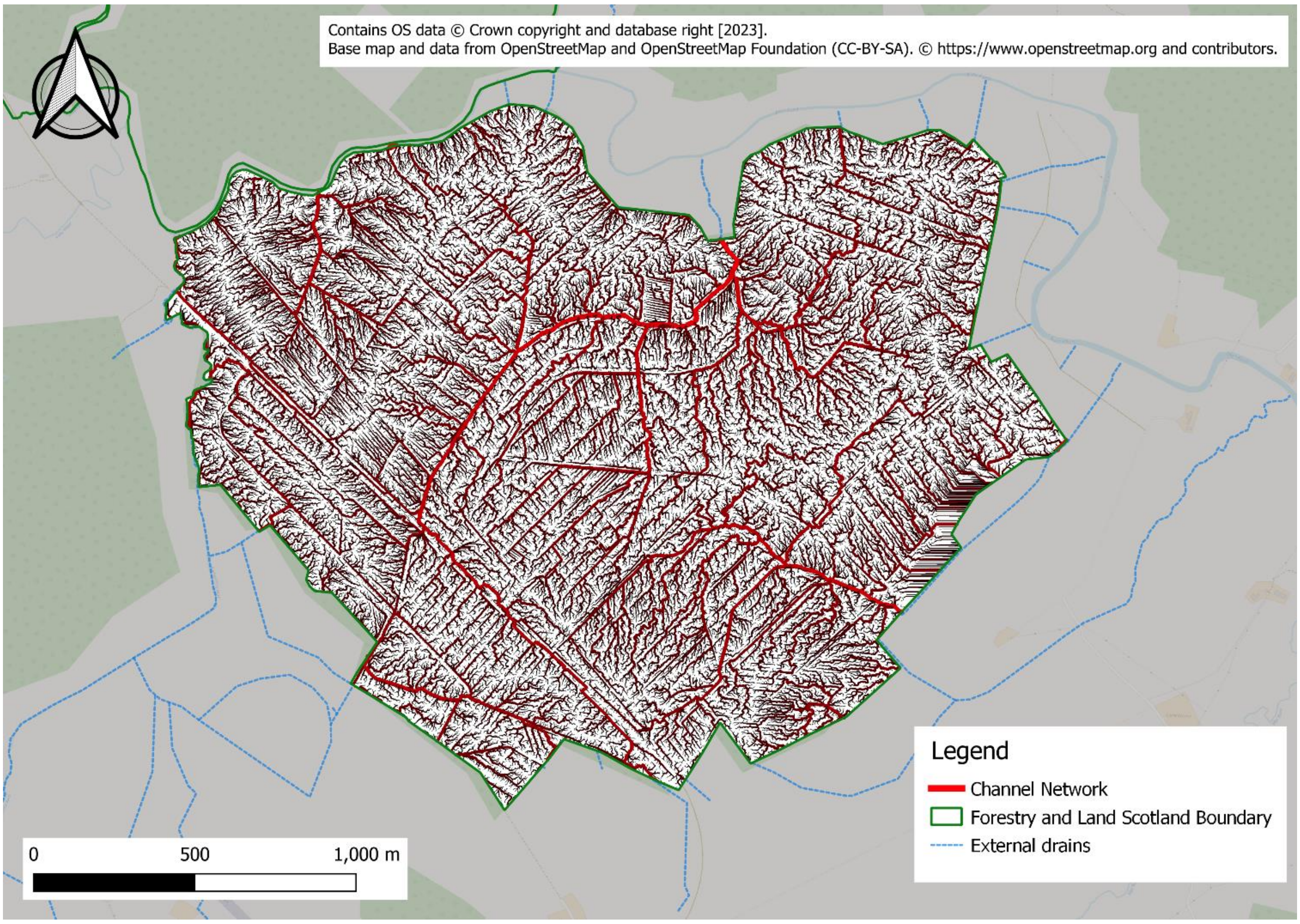

Figure C-4 - Flow channel network for Flanders Moss

As shown above, drainage from Flanders Moss is dominated by a larger natural watercourse located to the north, which drains through farmland after leaving the FLS boundary. It is clear from Figure C-4 that the drainage network of Flanders Moss has been heavily altered by the artificial drain cutting and follows a regular pattern similar to the other two blocks for most of the area of the block. To the north and west, several drains directly discharge to drainage ditches in surrounding farmland after running in a downslope direction, which is likely to result in rapid runoff following rainfall.

C.5. Restoration potential

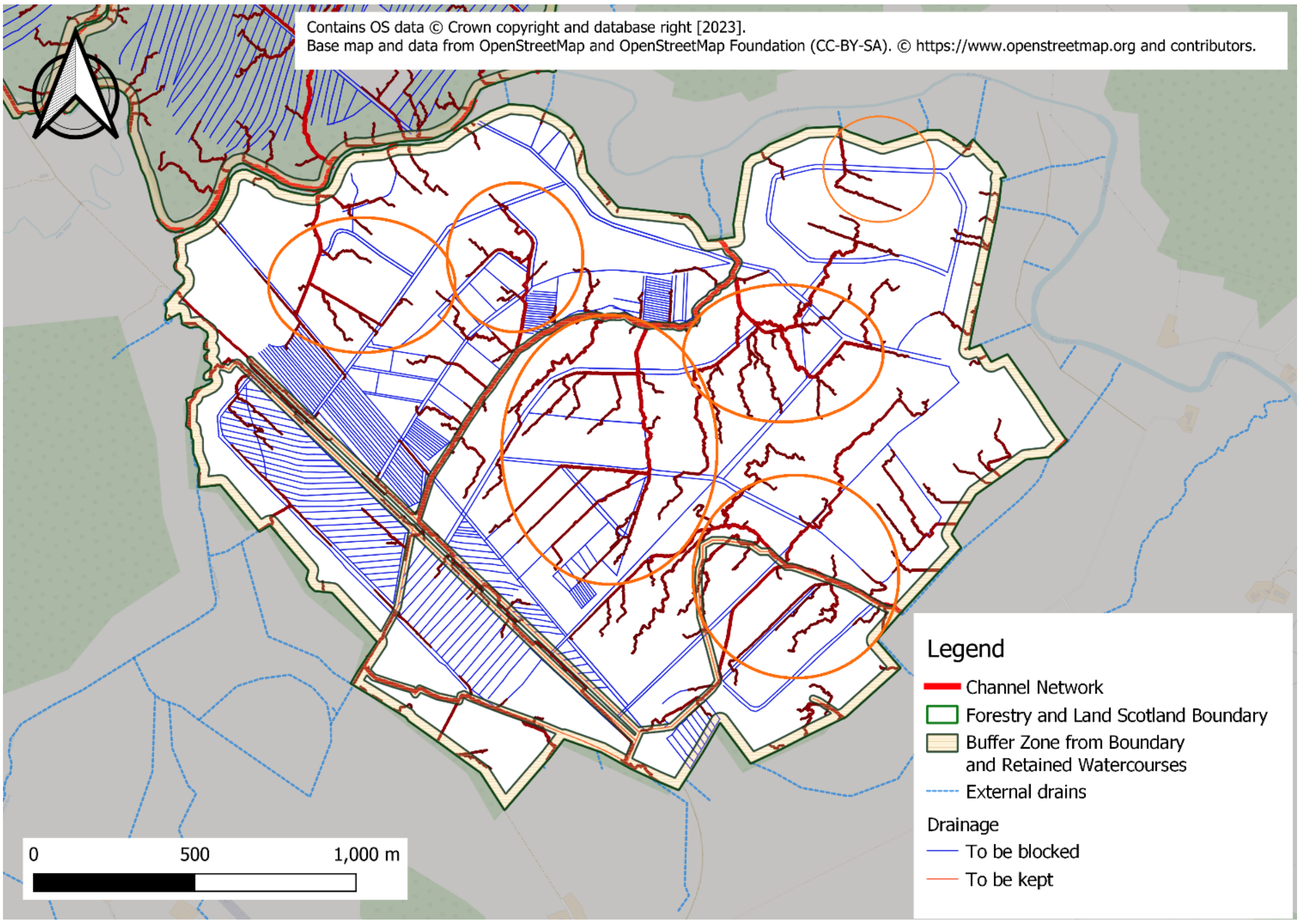

Figure C-5 - Comparison of the artificial drainage network at Flanders Moss to the major flow channels. Areas with significant overlap are circled in orange.

As shown above by Figure C-5, many of the major flow paths at Flanders Moss follow the artificial drainage network and damming them will be effective for slowing runoff. Particularly in the circled locations, water 'cuts through' the artificial drains so the flow paths are shortened than they would be in natural state.

As most of Flanders Moss drains to the surrounding farmland, it is likely that damming along these ditches would result in lower peak runoff and improved water quality in the runoff entering the ditches in adjacent farmland. Particularly for the north-eastern and eastern edges of the block, peat dam construction along the ditches located in a downslope direction would provide additional temporary storage following rainfall, which would be expected to attenuate flood peaks. By 'spreading' a portion of the water carried by the ditches over the rougher peatland surface away from the dams, runoff to farmland would be expected to be further slowed. Overall flow volumes discharged to the surrounding area would not be expected to see significant change.

Notably, artificial drainage ditches lie just outside the FLS boundary to the west and southeast and restoration will be limited in these areas as they will not be blocked. It should be expected that the steeper edges of Flanders Moss will remain in a heavily degraded state even after restoration actions, although the flatter central plateau will recover to some degree, but water table recovery will be more limited in closer proximity to the retained drains.

The buffer zone around the road will provide a constraint on potential restoration, as these areas contain some of the densest drain networks in the entirety of the site and the drains by the road have been identified as major flow channels. Restoration is therefore likely to be limited closer to the road. It should be noted that the long flow pathway running along the ditch east of the road to the natural watercourse is completely marked as 'to be retained'.

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