sustainability

Review

Future Carbon-Neutral Societies: Minimising Construction Impact on Groundwater-Dependent Wetlands and Peatlands

M. Ehsan Jorat [1,*], Andrew Minto [1], Irene Tierney [2] and Daniel Gilmour [1]

[1] Faculty of Social and Applied Sciences, Abertay University, Dundee DD1 1HG, UK; a.minto@abertay.ac.uk (A.M.); d.gilmour@abertay.ac.uk (D.G.)
[2] IMT Ecological Consultancy, Dundee DD2 3QB, UK; irenetierney@imtecoltd.com
* Correspondence: e.jorat@abertay.ac.uk

Abstract: The decarbonisation of the energy sector through major renewable energy developments in rural areas is one the requirements for sustainable development and future carbon-neutral societies. However, this has resulted in increased construction on peatlands and wetlands and has led to diverse environmental impacts in the affected areas. The overall aim of this project was to review the effectiveness of standard mitigation measures used during construction to maintain the hydrological conditions within peat soils and wetland habitats. This work involved a literature review of the evidence of the impacts of construction on the habitat and groundwater in groundwater-dependent wetlands and peatlands. In addition, developers and contractors were consulted to gain feedback on what practical approaches have and have not been successful and remedial actions taken when monitoring or observation identifies ongoing issues. This research also developed regulatory-relevant recommendations. The main recommendation focuses on the central importance of collecting relevant and detailed site investigation data at an early stage of the application process to enable a full understanding of the site character and to inform a more accurate design process. This will reduce or avoid impacts on the environment, minimise risk, and produce a more informed construction strategy.

Keywords: wetland; peatland; construction; mitigating measures

check for updates

Citation: Jorat, M.E.; Minto, A.; Tierney, I.; Gilmour, D. Future Carbon-Neutral Societies: Minimising Construction Impact on Groundwater-Dependent Wetlands and Peatlands. *Sustainability* **2024**, *16*, 7713. https://doi.org/10.3390/su16177713

Academic Editor: Antonio Caggiano

Received: 28 June 2024
Revised: 22 August 2024
Accepted: 26 August 2024
Published: 5 September 2024

1. Introduction

Research has proven the crucial role of soil in the storage of carbon and contribution towards net-zero targets [1–5]. Peatlands contribute significantly to terrestrial carbon storage both in the UK and internationally [6]. In Scotland, peatlands store a total of 2735 million tonnes of carbon [7] covering more than 20% of Scotland's total land area with approximately 2 million ha, making it one of the richest countries in Europe in terms of peatland area [8]. Peatbogs are ombrotrophic (rain-fed) where a consistently high water table plays an important role in the overall health of peatlands [9]. Healthy peatlands are carbon and nitrogen sinks, primarily due to slow rates of decomposition aided by water saturation [10]. Saturation is maintained by a high water table, which controls both plant and microbial species composition through oxygen availability. Price et al. [11] reported that a water table 400 mm below ground level in summer months is generally accepted as the critical level for the growth of raised bog plant communities. This highlights the significance of the water table in maintaining a healthy peatland.

Areas of land covered by shallow water at or near the surface level including fens, marshes, swamps, and bogs are referred to as wetlands [12]. According to the latest release of the UK Natural Capital Land Cover accounts published in 2007, open wetlands cover around 2,800,000 ha of land [13]. Scotland's Environment [14] describes carbon storage and accumulation, water purification, flood management, and water supply/groundwater infiltration as the primary functions of wetlands and their associated benefits. In addition, an important function of wetlands in urban areas in controlling run-off has been discussed and highlighted (e.g., in [15]). Wetlands often host a unique ecosystem, and any water quality and quantity alteration within wetlands will result in deleterious impacts on the ecosystem. Salimi et al. [16] reported detrimental impacts of drought on the wetland ecosystem, especially for peatlands.

Growing interest in the sustainable development of renewable energy and the decarbonisation of the energy grid has resulted in increased construction on peatlands and wetlands through major infrastructure projects and renewable energy developments in rural areas with consequent negative impacts on peatlands and other wetlands. The impacts include a reduction in permeability and water infiltration and a loss of habitat, carbon storage, biodiversity, and ecosystems.

Although construction on peatlands and wetlands cannot be effectively prevented, mitigation measures can be taken into account before, during, and after the construction to minimise the negative impacts mentioned above. Therefore, the overall aim of this research was to review the evidence of the effectiveness of standard mitigation measures used during construction to maintain the hydrological conditions within peat soils and wetland habitats. This work explored the key challenges when minimising construction impacts on peatlands and wetlands through the selection of appropriate mitigation methods. This research theoretically (through reviewing the literature) and practically (through interviewing with practitioners working on peatlands and wetlands and site visits) contributes knowledge and guidance to developers in relation to appropriate construction techniques to enhance practice around avoidance, impact minimisation, and habitat creation and restoration.

This paper (i) reviews the evidence on the effectiveness of mitigation measures in protecting groundwater-dependent wetlands and peatlands, (ii) consults developers and contractors to gain feedback on successful and unsuccessful methods, and remedies employed, if monitoring or observation identifies that mitigation procedures have not been appropriate, and (iii) provides regulatory-relevant recommendations and disseminates findings to a wider audience to inform future joint actions and approaches.

2. Methods

2.1. Assess the Impact of Construction on Habitat and Groundwater in Groundwater-Dependent Wetlands and Peatlands

A desk-based study was undertaken to source, compile, collate, and review the evidence in reports and the grey literature. This included information from utility companies and any results of existing trials of mitigating measures. A range of scenarios were considered such as disruption to hydrology due to excavation for borrow pits, tracks (cut-and-fill and floating), cable trenches, penstock routes, residential developments, foundations, and drainage installed for water management.

2.2. Consultation and Synthesis of Findings

The review of published research and guidance documents on the impact of construction activities on the hydrological regime of peatlands and wetlands informed the development of a standard list of questions that would form the semi-structured interviews with practitioners with experience of working on peatlands and wetlands.

The semi-structured interviews were undertaken with 17 practitioners (2 contractors, 7 hydrologists/ecologists, 5 environmental consultants, 2 planners, 1 developer) to gain feedback on their experience with techniques and mitigation measures when designing and constructing on peatland or wetland. The interview questions were developed based on the literature review findings. Under each section, a summary of key points related to the level of effectiveness has been compiled and incorporated into an evaluation matrix based on the interviews conducted. Interview questions are presented in Supplementary Information Section SA.

3. Review of Current Challenges Resulting from Construction on Peatland and Wetland

3.1. Construction on Peatland

Construction on peatlands tends to include access tracks, either cut-and-fill or floating track construction, excavation work for sourcing granular material for use as construction fill, excavation for foundations, and trenches for laying utilities. Any construction where lowering the water table of peatlands occurs, either directly for deeper excavations such as borrow pits or indirectly where the groundwater flow is altered or blocked, will result in a loss of carbon given the significance of saturation on limiting peat decay. The abandonment and removal of mesh tracks at a blanket bog were shown to have a wide range of impacts on the physical properties of peatlands, suggesting that only where access is a necessity should mesh tracks be installed [17]. Williams-Mounsey et al. [18] reported the creation of a spatial constraint leading to the poor development of plants and a reduced ability to form characteristic structures which are integral to mire function when mesh tracks are built on peatlands. Liu et al. [19] realised a decrease in daily CH_4 emission and an increase in CO_2 emission with the fall of the groundwater table of peatlands. Any change in peatland hydrology leads to changes in the soil hydraulic conditions in the long term [20]. Browne [21] reported direct and indirect impacts on biodiversity, water quality, carbon storage, historical archive, peat stability, and downstream habitat health as a result of change in the peatland hydrology.

Processes induced by the drainage of peatlands include subsidence, compaction, fissuring through shrinkage, and decomposition where the organic matter in the peat is lost through oxidisation and mineralisation, where organic matter is converted into plant-available forms of nitrogen. These processes may decrease the peatland's ability to store and regulate groundwater flow. The formation of fissures impedes capillary water flow and can lead to the drying out of peat at greater depths. Drained peat soils can become loosened and fine-grained through the increased activity of soil organisms. These may eventually become much more difficult to rewet, given the changes in permeability that have taken place as a result of the processes induced by peatland drainage [20]. Wind farm construction can increase the fluvial macronutrient loading of catchment streams; in particular, forest felling and borrow pits were highlighted as causing significant disruption [22]. Forest felling and borrow pits can alter the hydrological pathways significantly, and even after reinstatement, the ground surface is likely to change permanently regardless of the quality of reinstatement. Dissolved organic carbon and soluble reactive phosphorus increase over the period of wind farm construction. Losses in carbon and other nutrients from the soil have been shown to negatively impact soil fertility and, hence, vegetation growth and peat-forming species [23]. This, in turn, limits plant and animal biodiversity.

3.1.1. Road Construction

Road construction on peat can be categorised into two main construction techniques. In shallower peat depths, cut-and-fill techniques are generally employed where peat is removed until a suitable bearing layer is uncovered. In deeper peat layers, "floating" roads are employed where a mixture of granular fill and geotextile placed on top of the peat layer provides a foundation for the road. Pre-loading is sometimes necessary to allow the peat to consolidate [24], a process in which water is squeezed out of the peat under loading over a period of time to increase bearing capacity. Although dust from gravel roads has been reported by Li et al. [25] as an important localised source of nutrients for adjacent peatlands which influences their vegetation composition and surface chemistry, depending on the amount of road dust and its chemical composition, especially its Ca and P content, the diverse environmental impacts of road construction on peatlands are often substantial. NatureScot and the Forestry Commission have compiled guidance on floating roads. The guidance identifies that floating roads tend to be employed on peat with thickness of more than 500 mm depth, although consideration of other site-specific factors is important [26]. However, the construction of floating access tracks on weak peat could result in initially localised failure and rapidly progress to large-scale peat failure [27].

The impact on water table depth within the peat is determined by the type of construction adopted. NatureScot [28] compiled a report on tracks constructed in the Scottish uplands, where the range of construction techniques and their impacts are discussed. Cut-and-fill tracks are the most disruptive to groundwater [29], as the peat overlying suitable bearing material is removed, and therefore, both subsurface and surface drainage is entirely blocked. Gunn et al. [30] noted that the pre-loading of tracks for floating road construction reduces the volume of the acrotelm by approximately 50% during consolidation, which in turn reduces the permeability, and hence, the subsurface groundwater flow through the acrotelm is slowed down. No values for the amount of material affected, in terms of the distance from the track, were reported, although it is likely that this reduction in permeability will be localised around the track construction and will depend on factors including the footprint of the track, the amount of fill material used, and the anticipated loading conditions. These tracks can also cause ponding on the upslope side which blocks surface water flow. The introduction of alkaline aggregate fill material can have an impact on water quality [31] and typical bog species which require acidic conditions. Given that the footprint of any floating road must consider the ability to spread the traffic load over a larger area, more of the peat is disturbed. Both types of road construction can influence groundwater flow and can result in the drying out of peat and hence oxidisation.

Cut-and-fill tracks result in a complete loss of habitat and can cause large-scale disturbance and the fragmentation of habitats [28]. The fragmentation of habitats is also an issue with floating roads; however, much of the peat stays intact, albeit with a reduced permeability [28]. Imported fill material, depending on its geological origin, can also encourage additional plant species to grow. This may be to the detriment of the existing peatland habitat [29].

3.1.2. Foundations and Borrow Pits

Foundations, either temporary or permanent, are required where structures are constructed on peatlands. In the case of wind farms, foundations are normally constructed by using temporary cofferdams to excavate layers of peat until a suitable bearing stratum is found. Cofferdams, which are enclosures built to create a dry working environment (by pumping water out of the enclosed area), are required to keep the excavation dry [29,32]. The concrete base is cast, and then, more backfill is laid on top of the concrete foundation.

Similarly, with cut-and-fill road construction, by removing the peat layers entirely and using cofferdams, the subsurface flows are blocked entirely. The exposed peat faces will drain and oxidise as a result of being exposed to the atmosphere [29]. Lindsay and Bragg [33] commented that the peat surrounding foundation excavations is also drained to avoid uplift on the foundation. The amount of peat that is dewatered will be site-specific. This is likely to cause further drying out of peat deposits surrounding foundations.

Excavating peat in large volumes causes a direct loss of habitat similar to the loss of habitat associated with cut-and-fill road construction. If concrete pads are left exposed, it is likely that the concrete will attract a bryophyte flora uncharacteristic of the blanket mire. However, this has no potential to spread into peatland areas [29]. Although excavated peat is reinstated following the construction of a foundation, the disturbance to the peat results in negative impact to habitats.

Borrow pits are excavations that are used to source fill material to reduce the reliance on imported fill. Borrow pits are excavated to a depth to access suitable construction material that underlies peat deposits. As with other excavations, lowering the water table during the creation and operation of borrow pits will cause the surrounding areas of peat to dry out, oxidising the upper layers. Exposed faces will also dry out and oxidise. To avoid water ingress to the quarrying area, surface and subsurface water may be diverted, e.g., upslope cut-off drains which carry the water a short distance around to downslope of the borrow pit then discharge to the ground in a diffuse manner via a swale or similar.

Excavation results in a total loss of habitat and can be significant in volume depending on the depth of peat excavation that is required.

3.1.3. Trenches

Trenches can be constructed to lay pipelines or cables or for drainage ditches. Holden et al. [34] suggested that the degradation of peatlands associated with the installation of open-cut drainage ditches has been one of the most significant threats to the sustainability of both upland and lowland peatlands. Trenches often provide a preferential path for the drainage of water from within the peat body, diverting groundwater away from previous flow paths. To avoid this, it is standard practice to install clay plugs at intervals along the trench with the spacing determined by the slope.

Price et al. [11] reviewed studies on the drainage of peat and noted that the depth of the ditch, the distance between ditches, and the permeability of the peat can have a significant impact on the impact on groundwater flow. Boelter [35] suggested that in fibrous peat, water may be drawn to the ditch from up to 50 m away, although there was little to no significant impact in more decomposed peatlands. This is due to the low hydraulic conductivity in more decomposed peat compared with fibrous peat. Smith [36] demonstrated the influence of water table drawdown as a result of trenches and drains. Water table drawdown was apparent at distances of up to 25 m away from trenches.

Excavation can result in a total loss of habitat. There is also a risk with drainage ditches on slopes that the flow can cause significant erosion, causing further habitat loss. Studies have also shown that an increase in the rate of run-off as a result of drainage ditches can severely impact the local water quality, with catchment waters showing a rise in discolouration [37].

3.2. Construction on Wetlands

Wetlands in the wider countryside (non-designated sites) are protected through legislative and regulatory mechanisms established under the European Water Framework Directive 2000/60/EC (WFD), Nature Conservation (Scotland) Act 2004, and Habitats Directives for Natura sites [14]. Construction on or near wetland environments has potential to alter the wetland's physical and chemical balance which, in worst cases, could extend to miles from the construction site and persist for years after the construction. These changes in the physical and chemical balance could negatively impact the biological and ecological processes/functioning of wetlands. Twenty wetland water supply mechanisms have been identified by Wheeler et al. [38], in which the interruption of/reduction in each element could lead to a loss of/change in the type of wetland vegetation. Depending on the type of construction, the impacts can vary.

Monitoring the effectiveness of wetland mitigation measures relies on the collection of data (short- and long-term) related to mitigation measures after construction. Two main approaches have been introduced to monitor the effectiveness of wetland mitigation measures, namely the following:

1. Hydro-GeoMetric (HGM) (classifying the wetlands into a narrowly defined regional subclass according to their common hydrological, soil, and vegetative characteristics). This approach is a practical geomorphologically based design tool that can also assist in the planning of wetland restoration projects and relies on somewhat subjective categorical or qualitative data [39].
2. Ecological Functional Assessment (EFA) is a quantitative functional assessment technique that groups wetland functions into five ecosystem-level categories of (i) hydrologic flux and storage, (ii) biological productivity, (iii) biogeochemical cycling and storage, (iv) decomposition, and (v) community and wildlife habitat. A set of indicators representing the five categories in the impacted wetland are selected and measured. These thresholds are then used to assess whether any form of compensation is required, or not, based on a comparison from reference sites [39].

The above techniques are applied post construction to monitor the effectiveness of mitigation measures applied during construction, or if no mitigation measures were in place during construction, they will inform what compensation is required as a result of wetland habitat loss.

Different types of construction on wetlands and their associated impacts are summarised below. In addition, a discussion is provided summarising the mitigation measures and their associated impact on wetland habitats and groundwater.

3.2.1. Pipeline Construction

Assessing the impact of pipeline construction is of particular importance, as a single pipeline project can cross a number of wetlands, resulting in cumulative impacts on a wide ecosystem. In addition, pipeline construction, if not designed appropriately, could become a preferential drainage path, diverting drainage from previous pathways.

Activities related to the construction of a pipeline increase soil bulk density and reduce porosity and hydraulic conductivity [40]. This in turn affects the soil pH, organic matter content, and nitrogen content at or in the vicinity of the pipeline trench. If not protected, disturbed soil along the pipeline trench is vulnerable to erosion, and this could lead to the destruction of the wetlands' ecological function.

The disturbance of a wide range of plant species due to the construction of pipelines in wetlands has been reported [41]. If hydrological links from base-rich springs or seepages are interrupted, the wetland communities dependent on this would be negatively impacted. According to Olson and Doherty [42], the construction of natural gas pipelines resulted in more compact and drier soils. Similar disturbance to plant species in the vicinity of road construction adjacent to wetlands was reported by Li et al. [43]. Along the trench, the shoots and roots of involved plants are eradicated, and the surrounding plants' roots are affected. Construction workers trampling on plant species in the vicinity of the pipeline area results in the destruction of plant shoots, while roots have been proven to remain active.

Unmanaged pipeline construction in wetlands can result in the total local extinction of rare species or the loss of local genotypes. Conversely, construction can result in the establishment and spread of exotic species which may displace native species [43,44]. Should aquatic species exist in the wetland, pipeline construction can affect the biological habitat and fish behaviour and physiology [45], with changes to groundwater quality also disturbing fish populations [41]. Consequently, this may result in avoidance movement by fish, the altered distribution of populations [46], and a reduction in the population sizes and species numbers.

A change in the hydrologic regime of wetlands was observed after pipeline construction [41]. The construction of a pipeline prevents the hydraulic connection between surface water and groundwater and prevents natural water percolation into the groundwater system. The changes to soil chemical properties described above (e.g., pH, organic matter content, and nitrogen content) also alter groundwater quality.

3.2.2. Road Construction

Richardson et al. [47] identified the short-term impacts of highway construction on wetlands. Impacts were identified on salinity, sediment accretion, phosphorus concentration, macrophyte community composition, algal productivity, macroinvertebrates, and fish. Trombulak and Frissell [48], by revealing a broad view of road construction effects, suggested that it is unlikely that the ecological effects of roads will ever be completely mitigated or remediated.

The road sub-base can act as a preferential drainage route for water, leading to a significant negative impact on wetlands. The contamination of groundwater resulting from road construction along wetlands contributes to the deterioration of water quality. In addition, pollution resulting from road use can enter wetlands and result in the contamination of groundwater. Wang et al. [49] highlighted the importance of roadside groundwater pollution and made recommendations for minimum distances of roadways from wetlands.

3.2.3. Overhead Powerline Construction

For the construction of overhead power lines, the use of piled foundations reduces the overall negative impact; however, some towers are built on concrete platforms which are not piled.

Where power transmission towers are installed along power line corridors, changes in the hydrologic regime of wetlands may occur. The impacts will be similar to the impacts reported for pipeline and road construction projects. However, overhead line towers are spaced at intervals and are not continuous, so the effects on the hydrology may be less than in pipeline or road projects. Nevertheless, without the careful protection of groundwater-fed hydrological pathways, the hydrology could be interrupted during construction and/or operation. El-Bana [50] discussed higher densities of ruderal plant species in gravel pads of powerline towers compared to wetlands and highlighted the possibility of ruderal plants from gravel pads colonising adjacent wetlands.

3.2.4. Foundations and Borrow Pits

The construction of foundations is an inseparable part of any form of construction in wetlands. Permanent foundations include wind turbine foundations, transmission tower foundations, and building foundations for substations, housing, and commercial buildings. Temporary foundations include any form of foundation to provide support for temporary constructions.

Adu Gyamfi et al. [51] described the important role of capillary attraction in the movement of groundwater within the wetlands. The movement of groundwater is an important factor in maintaining soil biology within the wetlands. The construction of foundations may negatively influence the capillary zone and, as a result, adversely affect the soil biology around the impacted area. Also, the associated transportation of materials for foundation construction could result in significant damage to the habitat within the wetlands.

The construction of foundations is often associated with excavation within the wetlands. This creates drainage pockets where water is drained into and results in negative impacts on the groundwater hydrology. Often, concrete is used for the construction of foundations. Depending on the nature and location of the wetland, the cement type could be unsuitable for the local environment's pH. As a result, if consideration is not given to the appropriate selection of cement type, in accordance with the soil pH, harmful chemical reactions between the concrete and the wetland chemical components could take place and may result in the release of toxic material into the groundwater system.

Sourcing fill material for construction purposes within the wetlands results in the creation of borrow pits. Although sourcing fill material from within the wetland eliminates the ecological and biological impacts of transporting unwanted exogenous species into the wetland environment, borrow pits are known to be associated with a negative impact on the habitat and groundwater.

Maintaining a healthy ecosystem within the wetlands relies on maintaining the natural hydrology. Borrow pits change the overall drainage system within the wetland and, as a result, negatively impact the ecosystem. Any negative impact on the natural hydrology may result in a reduction in or even the termination of biological activities that rely on nutrients carried in the water. Additionally, borrow pits if designed inappropriately could become a barrier for wildlife moving across the wetland.

The literature suggests that, often, the groundwater table in the wetland is higher than the water table in borrow pits, e.g., [52]. As a result, water within the wetland drains into the borrow pits until a hydrological equilibrium is reached.

3.3. Mitigation Measures and Their Associated Impact on Construction on Peatland

Where construction on peatland cannot be avoided, there are a number of mitigation measures that contractors use to minimise the impact of construction. As well as design choices at planning stages to avoid the most sensitive areas and areas of deep peat, measures such as the removal and careful storage of acrotelm layers before reinstatement and adequate drainage to allow for water flow paths to be maintained can help reduce the impact of construction. Dargie [53] reports on some of the mitigation measures implemented after construction to allow peatlands to be restored. These include the blocking of drains, a reduction in grazing, and compensation for the loss of habitat by creating new areas of blanket bog nearby. Although peatland restoration measures are not directly discussed as mitigation measures after construction activities, Temmink et al. [54] present creating integrated wet peatland landscapes (wetscapes) as a method for an inevitable, novel, ecologically and socio-economically sound alternative for drainage-based peatland use. Table 1 summarises the mitigation measures outlined in the literature.

Table 1. Common construction activities on peatlands and their potential mitigation measures.

Road Construction	Foundations and Borrow Pits	Cable Trenches and Drainage Ditches
Minimise disruption by ensuring the road alignment avoids the most sensitive areas or features, avoid the deepest areas of peat, design road alignment to coincide with borrow pits for fill materials, and estimate cut-and-fill volumes to estimate imported fill requirements; careful removal and storage of acrotelm to allow for better reinstatement [28]. Reduce potential of floated access track failure by measures such as comprehensive site reconnaissance, adequate ground investigation, and reduced rate of construction in areas deemed with an elevated risk [27]. Excavate in peat only up to 2 m depth to reduce the risk of peat landslides [55]. Decrease in slope angle to reduce soil erosion and hence difficulties with revegetation [56]. Use the constructed road surface as a platform for heavy machinery when building the rest of the road to prevent excessive damage as well as bog mats and low-ground-pressure tracked machinery where this is not possible [57]. Use culverts to maintain subsurface flows across floating roads [57]. Construct tracks to maintain catchment drainage characteristics. This may require more investigation and planning during design phases [36]. Align the road parallel to the local water flow direction, when possible, consider the hydrogeological setting during road design to reduce hydrologic impacts, and increase hydrological flows between up- and downstream by adequate culverts (Saraswati et al. [58]).	Minimise disruption to peatland habitats by planning borrow pits along the line of track construction and using smaller and more frequent borrow pits [28]. Situate borrow pits where peat is relatively shallow to minimise disruption. Put in place planning that also considers backfilling borrow pits. Ensure excavated turves are watered regularly to prevent drying out [36]. Avoid moving excavated peat around site and ensure storage locations are as close to the excavation as possible. Prevent excess sediment run-off from excavations for borrow pits or foundations using silt traps. Maintain silt traps by removing trapped silt particularly after heavy rainfall period. Use submerged foundations for wind turbines so that they can withstand uplift pressures from groundwater as an alternative to peat drainage to maintain natural hydrology [36]. Avoid disturbance near sensitive water courses, avoid disturbing sloped areas, consider importing fill material, adopt run-off, avoid deep areas of peat for borrow pit excavations, and locate these as close to access tracks as possible to avoid increase in macronutrient fluvial loading [22].	Avoid high-density excavations of drainage channels to limit excessive water drawdown. Block up of all historical drainage channels prior to construction. Use vegetation to help slow the flow of water through the drain [36]. Use peat turves to block historic drains providing these are less than 0.7 m^2 with a slope angle of $<3°$ [59,60]. Construct low verges and build them wider to accommodate cable trenches to avoid additional excavation in virgin material. Excavate in sections to reduce the length of open excavations, backfill as soon as possible after installation, and if required, use clay plugs to prevent water flow through cable trenches. Monitor floating roads after construction to assess the influence of settlement on the drainage path as the peat below the road becomes more compressed [28]. Separate construction drainage from natural drainage to prevent deterioration of downstream water quality. Consider the impacts of climate change and the likelihood of more intense rainfall. Consider higher return periods for drainage design (i.e., 1 in 200 as opposed to 1 in 100). Ensure any ditches are a maximum of 0.5 m deep [61]. Orient pipelines parallel to flow direction, where fen intersected the road, and locate along the central axis of the fen. Construct additional culvert in the event of building a pipeline through an already existing road to facilitate flow on either side [40].

The literature also outlines some measures to ensure the restoration of peatlands after construction. Watts [62] demonstrated the effectiveness of heather brash and geotextiles in regenerating bare peat. However, Murray [63] suggests that whilst this can be effective in the short term, brash mulching should be phased out to avoid a reduction in water quality. Also, dense mulching can hinder the regeneration of vegetation [64]. The rewetting of degraded peatlands post construction can potentially restore the physical properties of peat and therefore increase the water storage capacity [65]. Rewetting has been shown to significantly improve degraded peatlands [66]. Other methods of peatland restoration include spontaneous revegetation using indigenous soils [67]. The results showed that the plant communities responded locally to encourage regrowth, although this would likely be improved with a combination of restoration measures, including rewetting. Soil moisture was found to be one of the most important factors in revegetation; other important factors included the soil pH, slopes, and microtopography [67]. Monitoring the restoration of a drained and afforested blanket bog catchment showed that the removal of brash from the site reduced dissolved and particulate organic carbon [68]. From their study, the authors concluded that restoring a small proportion of the catchment (12%) at a time would minimise aquatic carbon export.

In conclusion, the most significant impacts that construction activities will have on peatlands include the following:

- Lowering the water table. This can lead to an increased rate of decomposition and therefore release of stored carbon.
- Changes in or interruptions of the hydrology within the peat from new/deepened drainage ditches associated with roads or other infrastructure.
- Changes in the downstream water quality as a result of changes to run-off patterns.

3.4. Mitigation Measures and Their Associated Impacts on Construction on Wetlands

Mitigation measures during and after construction on wetlands have been identified to reduce the risks and potential impacts on biodiversity and ecosystem services which include avoiding construction on wetland where possible, crossing wetland at its narrowest and shallowest point, reducing soil compaction during construction by minimising the number of construction vehicles and their frequency, marking the route with substantial fencing, and scheduling construction during seasons with least impact.

For mitigation, four areas have been taken into consideration: the avoidance of sensitive habitat, the minimisation of impacts, the restoration of habitat, and offsetting project impacts, if necessary [69]. Furthermore, Table 2 summarises mitigation measures for pipeline and road construction, overhead powerline construction, foundation construction, and borrow pits on wetlands.

3.5. Consultation with Developers and Contractors

The 17 developers and contractors interviewed provided a broad range of experience and observations on the current mitigation methods for construction on groundwater-dependent terrestrial ecosystems. The interviewees identified some of the key challenges relevant to the effectiveness of construction techniques on peatlands and wetlands in terms of the impact on the groundwater and on the habitat. The interviews covered both the impact of construction techniques and experience of mitigation. Combining these interrelated discussions, several key issues arose several times. Detailed findings from the interviews are presented in Supplementary Information Section SB.

Table 2. Common construction projects on wetlands and their potential mitigation measures.

Pipeline and Road Construction after [70]	Overhead Powerline Construction	Foundation Construction	Borrow Pits
Avoid wetland site selection for permanent and temporary infrastructure and access routes.	Inform management of environmental factors that promote the growth and establishment of specific invasive alien species to deter the spread of alien species in powerline servitude corridors [71].	Ensure appropriate design of foundation by considering groundwater regime at the construction site [51].	Creation of artificial wetlands through borrow pits, e.g., [74], as a measure to minimise the negative impact of borrow pits on the wetlands.
Minimise clearing on the Right Of Way (ROW) *. Use existing ROW, if available.	Reroute to avoid species or communities of conservation concern or use established corridors [72].	Prevent the area excavated for foundation construction acting as a drainage pocket for groundwater within the wetlands. This can be performed by installing watertight materials such as a damp-proof membrane around the excavated area.	Consider local typology and hydrology when locating borrow bits to avoid borrow pits becoming a destination for run-off that feeds the wetland.
Design and plan construction to cross wetland at its narrowest and shallowest point to minimise turbidity.	Schedule construction in seasons with least impact [72].	Select appropriate cement type for foundation construction depending on the wetland's pH, as it has been proven that concrete can have a significant impact on wetland water chemistry [73].	Carry out pre-construction monitoring and analysis to avoid the creation of borrow pits along the main corridor for wildlife movement within the wetlands.
Plan construction outside of wildlife breeding seasons.	Use native species seeds for the regeneration of vegetation in affected areas [72].	Reduce foundation construction time and conduct the construction in drier months of the year to minimise impacts of construction on the wetlands [72].	Carry out post-construction monitoring to evaluate impacts resulting from borrow pits.
Carry out immediate stream bank repair following construction to control erosion and saltwater intrusion.	Remove topsoil prior to construction and replace post construction to maintain microbial communities in soil. Where possible, remove turves, store the right way up, and replace as soon as possible [72].	Ensure suitable transportation of the material to the construction site to minimise negative impact to the wetlands. The most suitable method of transportation is using air transport (via helicopter).	
Contour using bulkheads, culverts, earthen dams, wires, etc., to re-establish drainage pattern.	Reduce the size of the disturbed area. Control invasive species throughout the life of a project. Avoid pollution and unnecessary human activities [72].		
Reduce soil compaction during construction by minimising the number of construction vehicles and their frequency of passes.			
Backfill trenches in timely manner to restore contours and avoid canalisation.			
Consider segregating topsoil from the trench spoil and replacing after the completion of construction.			
Revegetate sites in areas disturbed by construction to allow re-establishment of vegetation.			

* ROW—the stretch of land to be used for the construction and operation of the pipeline.

Figure 1 presents the percentages of the combined key challenges related to the effectiveness of construction and mitigation. The figure illustrates that detailed design and careful planning in implementation were emphasised the most during the interviews. The level of experience of the contractor and the competence of the operative were identified as key for the effectiveness of implemented approaches. Communication between all the stakeholders was considered important together with early engagement of all stakeholders throughout the process. The sharing of knowledge and early engagement of the key parties ensured that expertise was applied at the best time to be most effective.

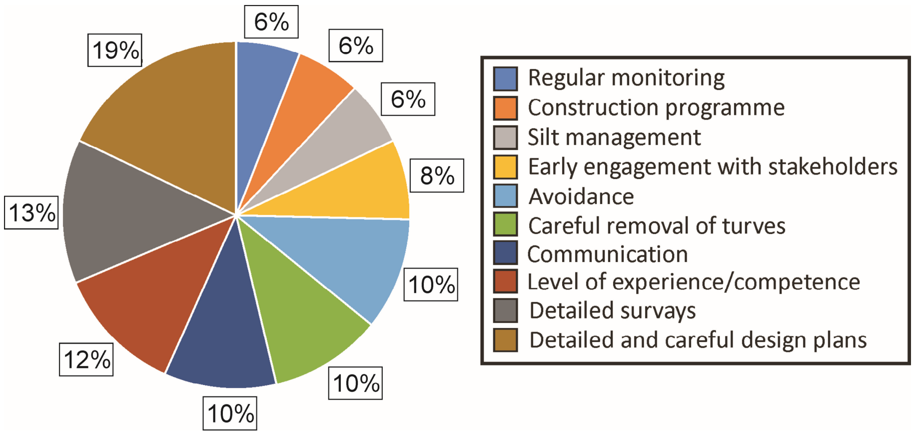

Figure 1. Key challenges related to the effectiveness of construction and mitigation as identified by interviewees.

The avoidance of deep peat and sensitive communities and habitats was identified as a key part of the design process. This involved a full understanding of the site location to determine the orientation, location, access, and borrow pit location. The careful removal, storage, and replacement of turves was identified as key for the successful reinstatement of vegetation. These techniques alongside water management and silt management were all discussed and emphasised as important factors for effectiveness by the participants.

The key determinants of the effectiveness of construction and mitigation techniques identified by interview participants were the following:

- Detailed design and careful planning before implementation. This should include early engagement of the contractor and Environmental Clerk of Works during the design phase and construction programming. Interviewees identified the importance of the level of experience of the contractor and the competence of the operatives.
- Detailed surveys of the site are required to enable effective planning. Construction activity programming and planning contingency are needed to accommodate changes in weather, space to microsite, and temporary access options.
- Communication between all the stakeholders together with early engagement of all stakeholders throughout the process. This sharing of knowledge and engagement of the key parties early ensures that expertise is applied at the best time to be most effective.
- Avoidance of thick peat and sensitive locations during the design process. This involved a full understanding of the whole site to determine the orientation, location, access, and borrow pit requirements.
- Careful removal, storage, and replacement of turves for the successful reinstatement of vegetation. Separating turf, acrotelm, and catotelm for effective reinstatement and revegetation and to ensure that hydrology conditions needs are met for successful reinstatement.
- Water management and silt management. Drainage design and implementation including how to avoid creating preferential flow paths when dealing with slopes for track drainage.
- Monitoring the baseline and post construction in the medium and long term, for reinstatement, mitigation, and habitat restoration.

The key issues identified within the interviews also supported the main findings from the literature review:

- It was emphasised throughout the interviews that there was a need to inform a more accurate design process, which included obtaining detailed site investigation data, ultimately leading to a more robust design at an early stage.

- Detailed site investigation surveys are required to characterise the site and to enable effective planning and implementation.
- The level of experience of the contractor and the competence of the operatives were identified as a key consideration when ensuring the effectiveness of the implementation of approaches contained within the standard guidance from multiple key agencies.
- Early engagement and communication between all the stakeholders throughout the process is a key consideration. Pre-application engagement and the sharing of knowledge at an earlier stage ensured that the right expertise was applied at the right time to be most effective.
- The careful removal, storage, and replacement of turves was identified as a key consideration for the successful reinstatement of vegetation. These techniques, alongside water and silt management, were discussed and emphasised as important factors for the effectiveness of mitigation methods by the participants.
- A more detailed topography and hydrology survey to allow for more accurate mapping (at a pre-determined scale). This is essential to assess the slope, contours, geology, location of flushes, water run-off, catchment areas, and habitat types. This will then inform aspects such as the correct size of culverts and the design of drainage systems and settlement lagoons.
- The track location design should follow that of the topography, where possible, to avoid producing a linear track. Tracks are likely to interrupt the hydrological flow and fragment habitats; therefore, advanced site information can inform the track design and layout to avoid or minimise such impacts.
- Avoidance of thick peat and sensitive locations or receptors during the design process.
- Water management and silt management through detailed drainage design.

4. Discussion

4.1. Effectiveness of Mitigation Measures in Protecting Groundwater-Dependent Wetlands and Peatlands

Construction activities such as linear infrastructure projects, wind farms, housing developments, etc., all have the following techniques in common: a mixture of cut-and-fill and floating tracks, excavations for foundations or to source fill material, and trenching for drainage/laying utilities. All these activities alter the hydrological regime to varying degrees by either blocking or partially blocking surface and subsurface water flows. In peatlands, the lowering of the groundwater table by altering surface and subsurface water flows will result in the oxidisation of the peat and losses in stored carbon (Figure 2).

Linear infrastructure, such as cut-and-fill roads, has the greatest impact on peatland and wetland. By removing the peat, the flow paths of underground water are cut off entirely. The impact of excavations can be varied, mostly depending on the quality of reinstatement as well as the applied mitigation measures, such as separating the catotelm and acrotelm layers (Figure 3a). Any foundation is likely to have some impact, but the impact is much lower than that of linear infrastructure because water tends to flow around the obstruction and therefore some flows are maintained. These impacts are also localised around the foundation, although there is little research to indicate how much of an area surrounding a foundation is impacted. Similarly, with borrow pits, any impacts will be localised. Trenches can have a significant impact, given the likelihood that these will become preferential flow paths for drainage and interrupt existing flow pathways, potentially changing both the volume and chemical characteristics of source water to a wetland (Figure 3b,c). Research has shown that the groundwater table can be affected up to 25 m away from drainage trenches [36].

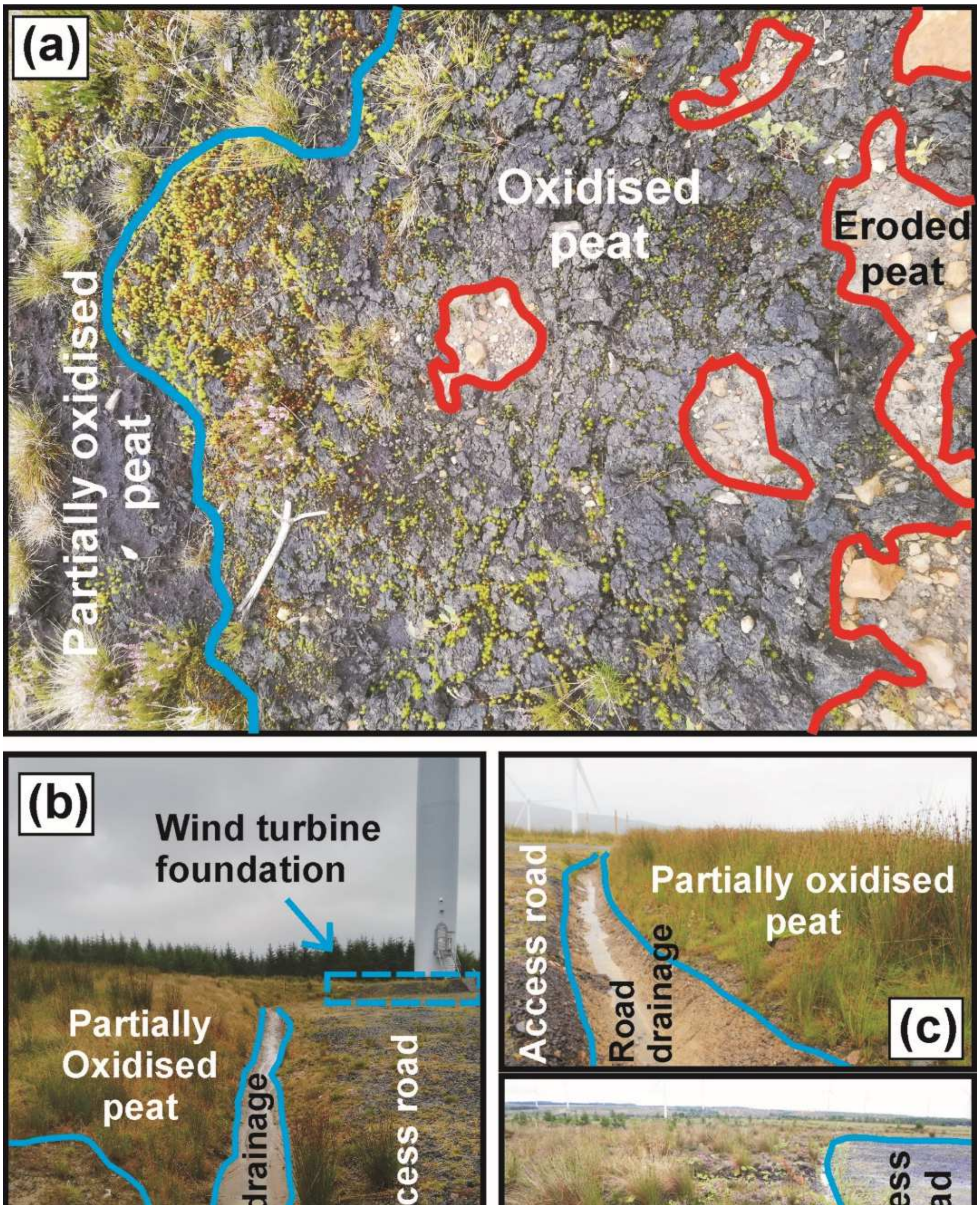

Figure 2. (**a**) Area of peat affected by the lowering of the groundwater table around a wind turbine foundation. More affected areas can be seen on the right side of the picture which is closest to the turbine foundation. (**b**,**c**) Lowering of the groundwater table through construction of road drainage and its impact on peat erosion/oxidisation. (**d**) Access road construction interfering with groundwater flow which results in deteriorating vegetation and exposed and partially oxidised peat.

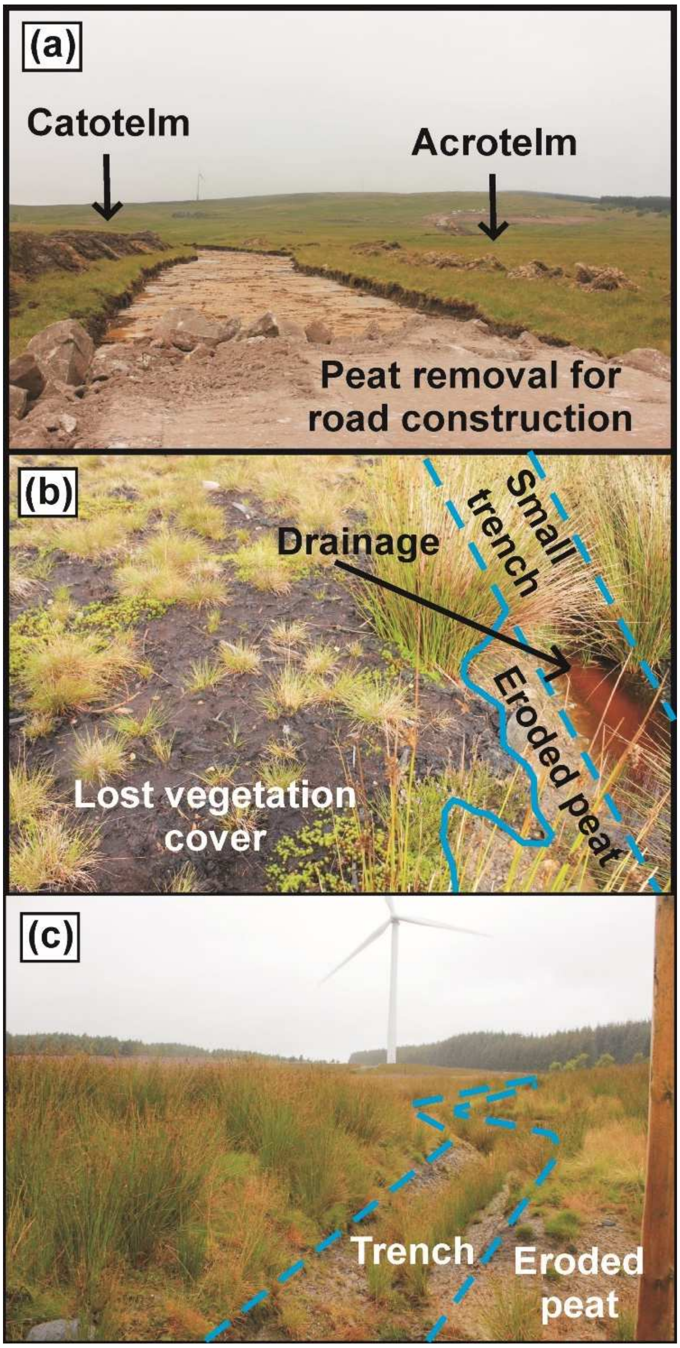

Figure 3. (**a**) Removal of peat for road construction and correct separation of catotelm and acrotelm. (**b**) Small trench impact on deterioration of surrounding peat. Colour of discharge in the drainage is similar to Yli-Halla et al.'s [75] observation of dissolved organic carbon, organic N, nitrate, ammonium, sulfuric acid, and iron in discharge from cultivated organic soil. (**c**) Large drainage trench (which was dry at the time of visit) and its influence in eroding the surrounding peat.

Steep slopes after construction are a barrier to vegetation reinstatement and prevent vegetation growth, which in turn causes erosion in rainfall events due to the lack of vegetation retained on the slope (Figure 4a). Evidence from reinstated slopes after construction has demonstrated that vegetation redevelops on slopes with gradients lower than 30° post construction, while significant soil erosion was observed in slopes with a gradient of 45° (Figure 4b,c).

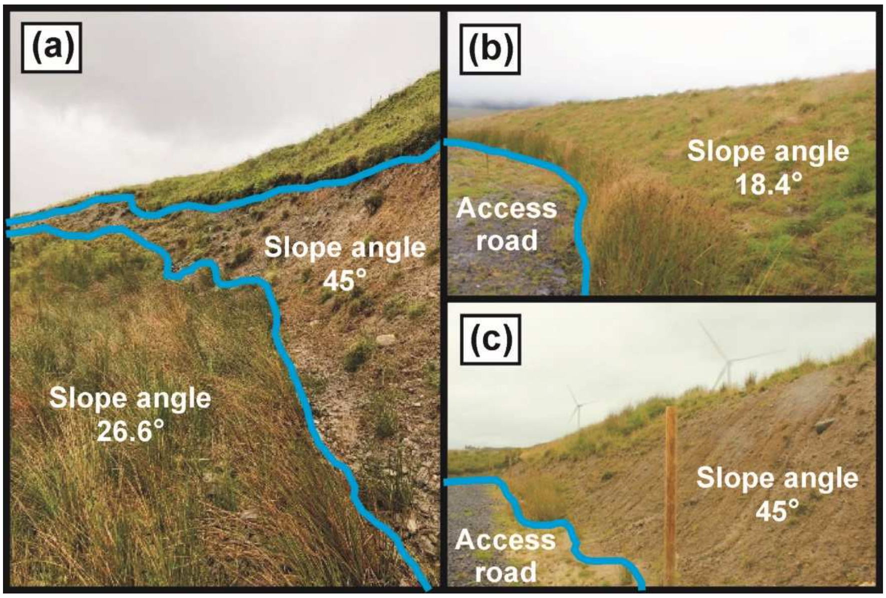

Figure 4. (**a**) Reinstated slope showing vegetation reinstatement in slope with a gradient of less than 30° and significant soil erosion in slope with a gradient of 45°. (**b**) Full vegetation cover on slope with a gentle gradient of less than 20° and (**c**) significant soil erosion on a slope with a gradient of 45° after construction of an access road.

4.2. Recommendations to Inform Future Joint Actions and Approaches

Recommendations have been developed following interviews and the literature review. A synthesis of the data collected on mitigation measures to minimise the negative impact of construction on wetlands and peatlands was undertaken, and the following recommendations can be made.

4.2.1. Planning: Design and Management Stage

In this stage, the following should be considered:

1. Early in the planning process, there should be more emphasis on thorough site investigation prior to the design phase. It was raised in the interviews that some respondents did not feel there was enough site investigation. To ensure compliance, this can be part of planning recommendations where an additional level of (or more detailed) site investigation is carried out to assist the design and locations of turbines, hard-standings, tracks, cables, pipelines, trenches, and other infrastructure. This would ensure that the design considers the avoidance of sensitive areas and maintains the hydrological flow paths on site and follows avoidance in the first instance and not retrospectively.
2. The topography, as well as the hydrology, should be mapped in detail and may require a specified scale. The design of where tracks are to be placed should follow that of the topography, where possible, to avoid producing a track perpendicular to the preferential flow.
3. As part of the pre-planning design, plans, or maps, a more detailed and descriptive Construction Environmental Management Plan (CEMP) and Construction Management System (CMS) should be provided, with detailed maps of all sensitive areas, which may require a specified scale. The CEMP/CMS should include detailed surface water management procedures in order for these to be scrutinised and, where possible, mapped out or installed at the pre-construction stage. It is noted that, as construction starts, this is a fluid process which will require constant review, additions, and improvements. To note, this is mostly conducted after planning has been granted, so the suggestion here is that this is all conducted pre-planning, with scrutinisation and possible conditions applied. The design should include the separation of clean water from "dirty" water created via construction activities, inclusion of lagoons (settlement ponds), silt fencing (Figure 5c–e), etc. It was noted that all interviewees followed the present guidance.

4. Specific types of machinery and size should be specified early in the design and CEMP/CMS process to ensure that the machinery is appropriate for the site conditions.
5. The method statements within the CMS should come under earlier scrutiny, possibly as part of the planning process, as opposed to post planning. This would involve any associated work and how it will be carried out and identify which areas are to be avoided and if mitigation is to be put in place. The methods involved in this process can be detailed, along with how these will reduce the impact on the environment, maintain water flow, and reduce the potential for a pollution event. This is a similar process to the "end of life" removal of infrastructure, which is now asked for on some developments.
6. A more efficient design guidance is required to ensure the understanding and compliance of the design and construction process, which can take the form of a "How To" guide (which will pull in all the current guidance into one document).
7. Costs in planning could be reviewed so that developers have more flexibility at the feasibility stage to ensure that if any changes need to take place to the planned boundary to avoid sensitive habitats, wetter areas, or peat, they can be carried out without the costs associated with the larger boundary required.
8. An experienced Environmental Clerk of Works should be consulted early in the construction design stage to minimise any impact of the development on the ecology and environment. A site walkover is advised during the planning process and not after. This would also be useful when micrositing turbines and tracks, etc. If this is conducted earlier, at pre-planning and not post consent, then a more robust plan can be put in place, as opposed to the possibility of micrositing at a later stage where a consultation process may be initiated, which wastes time and resources.
9. Consolidated guidance should be produced that includes the guidance from all environmental protection agencies, rather than located in separate guidance documents. This can also include a Standard Operating Procedure document as an appendix for contractors.

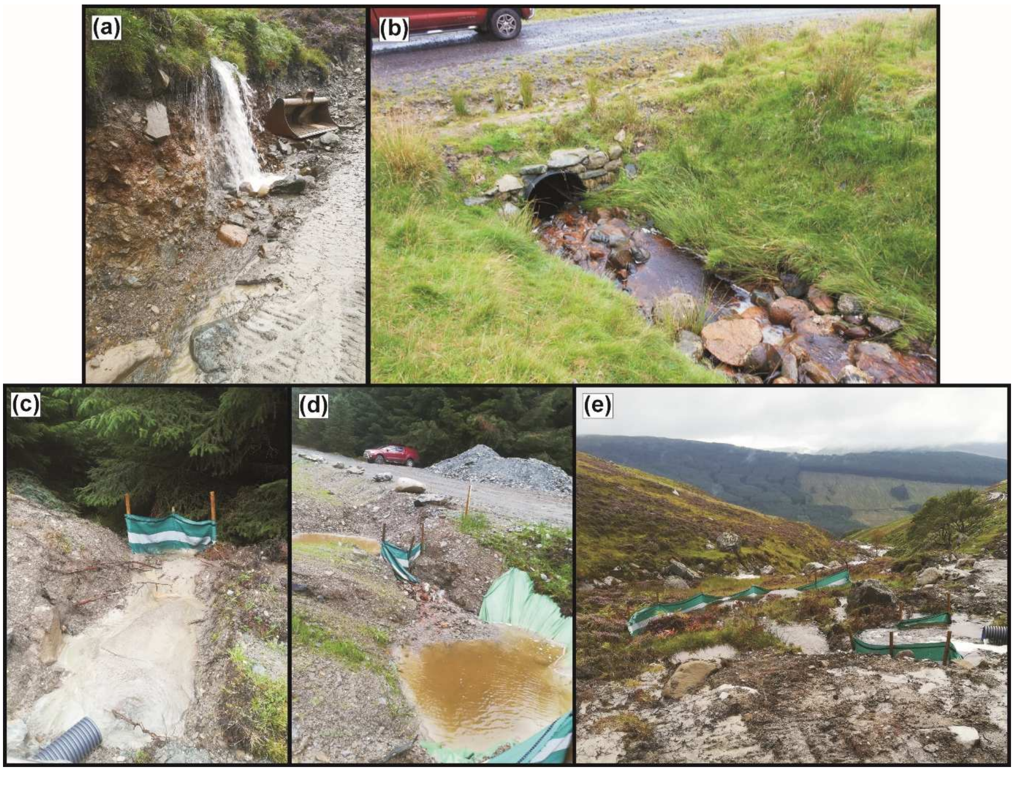

Figure 5. (**a**) Track construction impact on fast dewatering of subflows, (**b**) construction of culvert prior to construction of track, and (**c**) single-level and (**d**,**e**) multi-level silt fencing to reduce suspended particles in run-off from construction before disposal into open water.

4.2.2. Water Quality Baseline Data Collection (Physical/Chemical)

It is recommended that baseline data are collected for a year at the site and at a control site with similar physical/chemical characteristics. This would allow the comparison and determination of water quality at the site throughout a year.

As an example, data will be collected (sampling fortnightly/monthly but possibly more frequently in sensitive areas) during construction and post construction at the site and at the control site. Any changes in the water quality parameters during construction may indicate the impact of the construction activity when assessed with the previous year's data and control site data. This can then be investigated further to determine if site activity is at fault and can prompt remediation if necessary. The appropriate water quality values can be found in the Water Framework Directive and at Marine Scotland Science.

4.2.3. Access Tracks: Cut-and-Fill

It is recommended for access tracks that require to be cut in that a specific type of drainage is required, where shallow drainage ditches are put in place ahead of the track construction to divert the surface water or rainwater away from the track works. This reduces the fast dewatering of subflows (Figure 5a). Where these will be located will be part of the CEMP/CMS and should form part of the earlier consultation and design process. To ensure that the construction drainage dirty water is kept separate from the clean water, culverts can be placed from one side of the track to the other (Figure 5b). This also reduces the load of water to be treated via settling ponds and silt fencing (Figure 5c–e). Surface cross drains/SuDS can also be used for the flow of water on a track during rainfall or heavy traffic use (Figure 6a,b). Some interviewees did not think this was carried out early enough, and many contractors objected to the time involved in this process. This suggests that surface cross drains/SuDS should be designed rather than reactively placed during construction; therefore, the recommendation to measure and maintain hydrological connectivity is advised within the planning section.

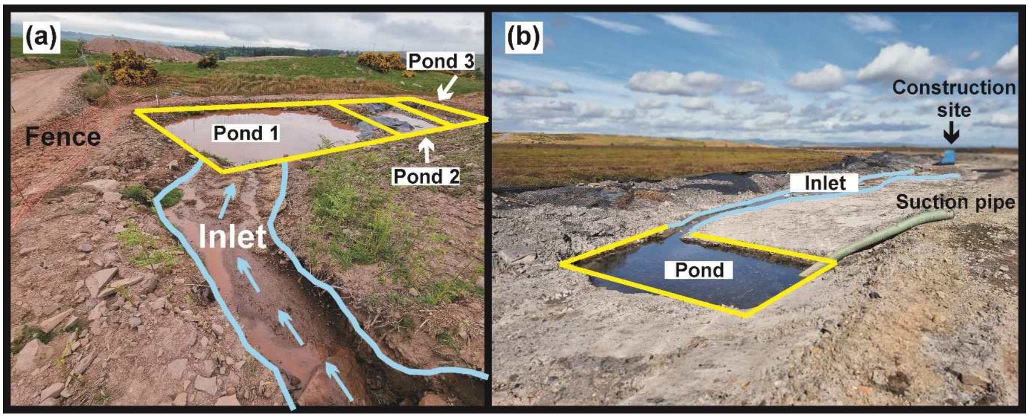

Figure 6. (**a**) Multi-stage and (**b**) single SuDS pond(s) designed close to construction sites to treat run-off during construction and heavy rainfall.

4.2.4. Access Tracks: Floating Tracks

It is recommended that floating tracks should be implemented (Figure 7b), where possible, as these tend to have the least impact on hydrological flows, and they cause less disruption with less material removed. A floating track utilises a 5-degree cross slope as its limit, to avoid slippage, as anything other than this would require a cut-and-fill track. Where there is a subsurface hydrological flow path, a series of small drains can be placed under the track to maintain the hydrological regime. Floating tracks should be designed with a good specification of fill material, as they are known to settle gradually over time and use with site traffic. Where borrow pitting is required to source fill material for construction purposes, reinstatement is required to encourage vegetation and minimise the negative impact on surrounding peatland and wetland (Figure 7a). The possibility of the track becoming a preferential flow path should be avoided by constant monitoring of the track quality and alteration or repair when required. Constant repair is not always preferred, so another design would be a good idea in this instance.

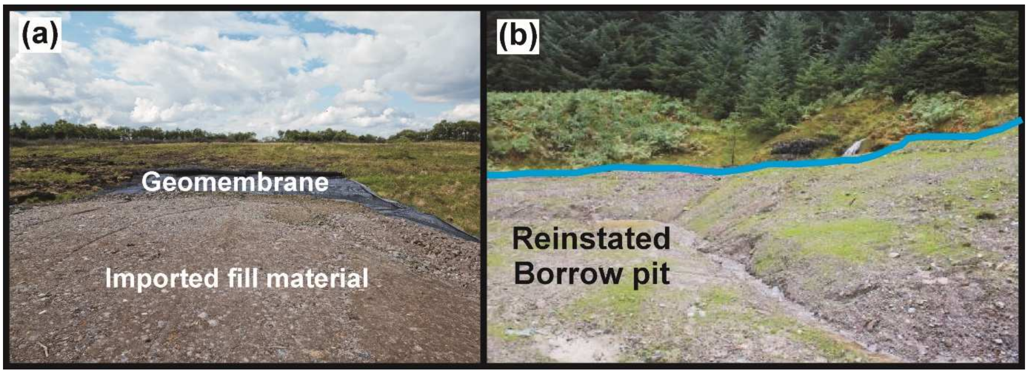

Figure 7. (**a**) Example of a successful borrow pit reinstatement. Restoration shows signs of early recovery with vegetative growth. Gradients of the reinstated ground are less than 20° which prevents soil erosion. (**b**) Floating road under construction showing layer of geotextile under imported fill material.

4.2.5. Penstock

Clay plugs are normally used to stop the penstock from becoming a preferential flow path for water. It is advised that a specified number of clay plugs are recommended by the designer based on drainage surveys. If no clay or other suitable material on site is available, then sandbags can be used.

4.2.6. Storage of Turves

It is recommended that a full Standard Operating Procedure guide is provided for turf removal, as some contractors may struggle with this due to varying skill levels and understanding of the turf management process. Additionally, the top vegetation layer (300 mm approx.) which contains the seed layer should be stripped and placed to the side with the vegetation facing up and in a single layer. This should be kept moist until reinstatement. If there is a peat layer, then this is excavated and laid out beyond the turves (or sometimes on the other side of the track dependent on slopes). Peat and turves should be kept moist at all times. If peat is left to dry out, it will oxidise, and carbon will be released. The early reinstatement of soil and turves is advised.

5. Conclusions

The present guidance documents available to the construction sectors, for a variety of scenarios, such as, wind, hydro, tracks, road, and other infrastructure, are usually informative, generic good practice guidance. However, one of the key considerations that evolved during the interviews was the need for either a "How To" document or a single, easy-to-use source for all guidance documentation. Although it may not be good practice to have a Standard Operating Procedure, the consolidation of the full guidance information in an easy-to-find and retrievable manual would be a beneficial resource.

The combined summary of these research findings from the literature review and consultation with developers and contractors is presented in Figure 8. The main theme from the literature review and interviews is to facilitate earlier site investigation surveys that will inform a more robust design at an earlier stage in the project development process. It is advised that this should be supported by the early engagement of an Environmental Clerk of Works and a detailed site visit to determine sensitive receptors on site, reduce environmental risk, and input into the drainage design plan and that the Construction

Environmental Management Plan (CEMP) and Construction Management System (CMS) plans are properly informed.

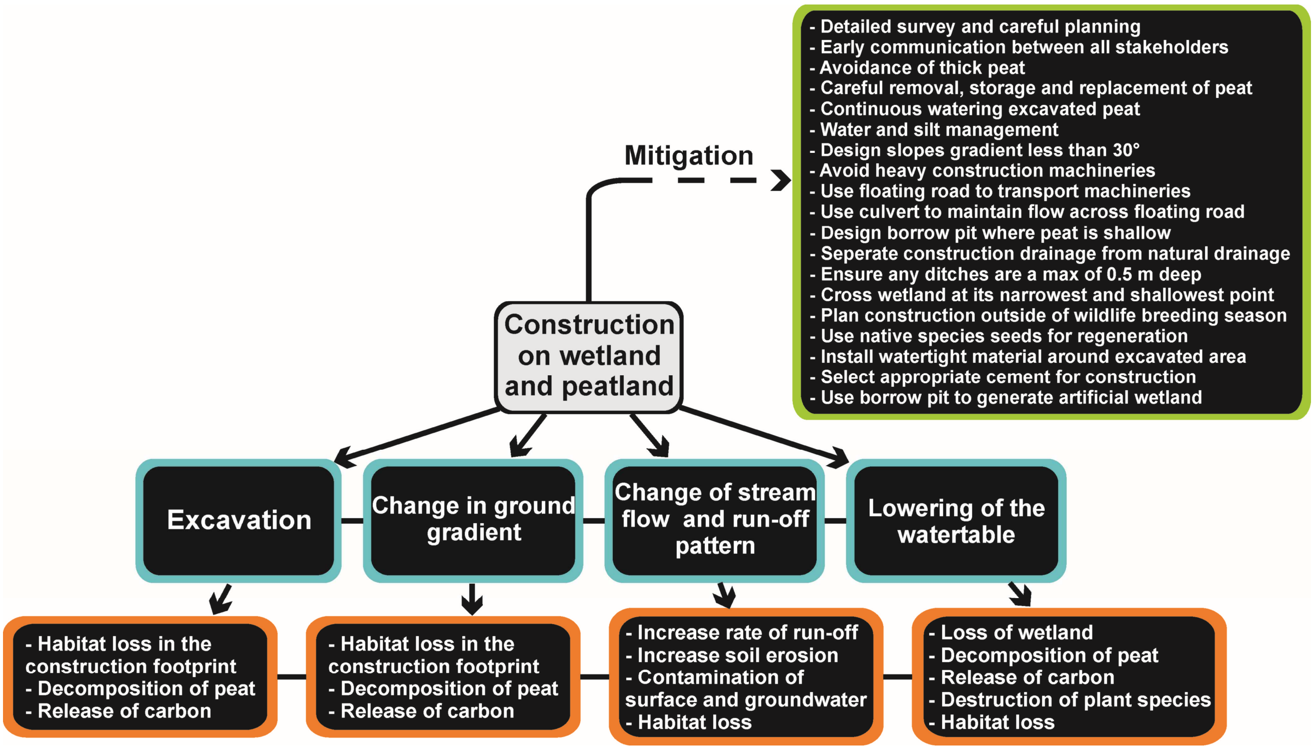

Figure 8. Construction on wetland and peatland impact and mitigating measures combined summary from literature review and consultation with developers and contractors.

This would allow the ability to characterise the site by its physiochemical profile and include a description of the watercourses and their water quality parameters at the pre-construction stage. Baseline data of the site, and the inclusion of a control site, can be used to determine the impact of the development. This set of robust data could be used as an operational tool to determine if the construction mitigation methods are effective on site.

The research developed regulatory-relevant recommendations. The main recommendation outlined above focused on the central importance of collecting relevant and detailed site investigation data at an early stage of the application process to enable a full understanding of the site character and to inform a more accurate design process. Using findings from this study, it is expected that impacts on the environment will be reduced or avoided, risks will be minimised, and a more informed construction strategy will be produced in the future.

For this research, although the review of the literature was global, interviews were conducted with practitioners working on peatlands and wetlands generally in the United Kingdom (particularly in Scotland). In addition, the wetland and peatland sites visited were in Scotland. For future research, this project recommends site visits and interviews with practitioners beyond the United Kingdom, particularly in areas with diverse environmental conditions (e.g., tropical and subarctic peatlands and wetlands).

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su16177713/s1.

Author Contributions: Conceptualisation, M.E.J. and D.G.; methodology, M.E.J., A.M., and D.G.; software, M.E.J.; validation, M.E.J., A.M., I.T., and D.G.; formal analysis, M.E.J.; investigation, M.E.J., A.M., I.T., and D.G.; resources, M.E.J. and D.G.; data curation, M.E.J. and A.M.; writing—original draft preparation, M.E.J., A.M., I.T., and D.G.; writing—review and editing, M.E.J., A.M., I.T., and D.G.; visualisation, M.E.J.; supervision, M.E.J. and D.G.; project administration, M.E.J., A.M., I.T., and

D.G.; funding acquisition, M.E.J. and D.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Scotland's Centre of Expertise for Waters (CREW) (CD2019_03).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The sources of any data reported in this review paper have been appropriately cited. Data related to interviews are fully presented in the Supplementary Materials that are published alongside this paper.

Acknowledgments: We acknowledge financial support from the Scotland's Centre of Expertise for Waters (CREW) (CD2019_03). We would like to thank the following organisations for participating in this study: Green Cat Contracting, RSK, Mac Arthur Green, WSP, Force 9 Energy, Botanaeco, Scottish Power, Perth and Kinross Council, Antorr, LLTNPA, AECOW, MSS, and R J McLeod. We thank Claire Campbell, Deborah Spray, and Nikki Dodd for their support and guidance during this project.

Conflicts of Interest: Irene Tierney was employed by the IMT Ecological Consultancy. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Manning, D.A.C.; Renforth, P.; Lopez-Capel, E.; Robertson, S.; Ghazireh, N. Carbonate precipitation in artificial soils produced from basaltic quarry fines and composts: An opportunity for passive carbon sequestration. *Int. J. Greenh. Gas Control.* **2013**, *17*, 309–317. [CrossRef]
2. Washbourne, C.L.; Lopez-Capel, E.; Renforth, P.; Ascough, P.L.; Manning, D.A.C. Rapid removal of atmospheric CO_2 by urban soils. *Environ. Sci. Technol.* **2015**, *49*, 5434–5440. [CrossRef]
3. Jorat, M.E.; Goddard, M.A.; Manning, P.; Lau, H.K.; Ngeow, S.; Sohi, S.P.; Manning, D.A.C. Passive CO_2 removal in urban soils: Evidence from brownfield sites. *Sci. Total Environ.* **2020**, *703*, 135573. [CrossRef]
4. Jorat, M.E.; Kraavi, K.E.; Manning, D.A.C. Removal of atmospheric CO_2 by engineered soils in infrastructure projects. *J. Environ. Manag.* **2022**, *314*, 115016. [CrossRef] [PubMed]
5. Goddard, M.A.; Glanville, H.C.; Comadran-Casas, C.; Jorat, M.E.; Manning, D.A.C.; Prendergast-Miller, M.T.; Stott, K.D. Soil management and engineering for blue-green infrastructure. In *ICE Manual of Blue-Green Infrastructure*; ICE Publishing: London, UK, 2023; pp. 187–205.
6. Grieve, I.; Gilvear, D. Effects of wind farm construction on concentrations and fluxes of dissolved organic carbon and suspended sediment from peat catchments at Braes of Doune, central Scotland. *Mires Peat* **2008**, *4*, 03.
7. Scottish Executive. *ECOSSE: Estimating Carbon in Organic Soils—Sequestration and Emissions: Final Report*; Climate Change and Air Division, Scottish Executive Environment and Rural Affairs Department: Edinburgh, UK, 2007. Available online: http://nora.nerc.ac.uk/id/eprint/2233/ (accessed on 7 September 2021).
8. NatureScot. Scotland's National Peatland Plan: Working for our Future. 2015. Available online: https://www.nature.scot/scotlands-national-peatland-plan-working-our-future (accessed on 8 September 2021).
9. Rahman, M.M.; Mcdermid, G.J.; Strack, M.; Lovitt, J. A new method to map groundwater table in peatlands using unmanned aerial vehicles. *Remote Sens.* **2017**, *9*, 1057. [CrossRef]
10. Sampson, R.N.; Scholes, R.J. Additional Human Induced Activities—Article 3.4. In *Land Use, Land-Use Change and Forestry*; A Special Report of the IPCC; Cambridge University Press: Cambridge, UK, 2000. Available online: https://archive.ipcc.ch/ipccreports/sres/land_use/index.php?idp=157 (accessed on 8 September 2021).
11. Price, J.; Heathwaite, A.; Baird, A. Hydrological processes in abandoned and restored peatlands: An overview of management approaches. *Wetl. Ecol. Manag.* **2003**, *11*, 65–83. [CrossRef]
12. Office for National Statistics. UK Natural Capital: Ecosystem Accounts for Freshwater, Farmland and Woodland. 2017. Available online: https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/uknaturalcapital/landandhabitatecosystemaccounts (accessed on 8 September 2021).
13. Office for National Statistics. UK Natural Capital Land Cover in the UK. 2007. Available online: https://www.ons.gov.uk/economy/environmentalaccounts/articles/uknaturalcapitallandcoverintheuk/2015-03-17 (accessed on 10 September 2021).
14. Scotland's Environment. Wetlands. 2014. Available online: https://www.environment.gov.scot/media/1201/land-wetlands.pdf (accessed on 10 September 2021).
15. Scholz, M. *Wetland Systems to Control Urban Runoff*; Elsevier: Amsterdam, The Netherlands, 2015.
16. Salimi, S.; Almuktar, S.A.A.N.; Scholz, M. Impact of climate change on wetland ecosystems: A critical review of experimental wetlands. *J. Environ. Manag.* **2021**, *286*, 112160. [CrossRef] [PubMed]

17. Williams-Mounsey, J.; Crowle, A.; Grayson, R.; Lindsay, R.; Holden, J. Blanket bogs exhibit significant alterations to physical properties as a result of temporary track removal or abandonment. *Ecohydrology* **2024**, *17*, e2623. [CrossRef]
18. Williams-Mounsey, J.; Crowle, A.; Grayson, R.; Lindsay, R.; Holden, J. Surface structure on abandoned upland blanket peatland tracks. *J. Environ. Manag.* **2023**, *325*, 116561. [CrossRef]
19. Liu, H.; Gu, Y.; Ge, J.; Yu, Z.; Xu, X.; Zhang, Z.; Cheng, S.; Xie, S. The response of the Dajiuhu Peatland ecosystem to hydrological variations: Implications for carbon sequestration and peatlands conservation. *J. Hydrol.* **2022**, *612*, 128307. [CrossRef]
20. Schumann, M.; Joosten, H. Global Peatland Restoration Manual; Institute of Botany and Landscape Ecology, Griefswald University, Greifswald, Germany. 2008. Available online: http://www.imcg.net/media/download_gallery/books/gprm_01.pdf (accessed on 15 September 2021).
21. Browne, S. Peatlands and Development. International Union for Conservation of Nature, UK Peatland Programme Briefing. 2023. Available online: https://www.iucn-uk-peatlandprogramme.org/sites/default/files/2023-03/2.%20Peatland%20and%20Development.pdf (accessed on 17 September 2021).
22. Heal, K.; Phin, A.; Waldron, S.; Flowers, H.; Bruneau, P.; Coupar, A.; Cundill, A. Wind farm development on peatlands increases fluvial macronutrient loading. *Ambio* **2020**, *49*, 442–459. [CrossRef] [PubMed]
23. Quinton, J.N.; Govers, G.; van Oost, K.; Bardgett, R.D. The impact of agricultural soil erosion on biogeochemical cycling. *Nat. Geosci.* **2010**, *3*, 311–314. [CrossRef]
24. Jorat, M.E.; Kreiter, S.; Mörz, T.; Moon, V.; de Lange, W. Strength and Compressibility Characteristics of Peat Stabilized with Sand Columns. *J. Geomech. Eng.* **2013**, *5*, 575–594. [CrossRef]
25. Li, X.; Talbot, J.; King, J.; Wang, M. Effects of road dust on vegetation composition and surface chemistry of three ombrotrophic peatlands in eastern Canada. *Geoderma* **2023**, *439*, 116665. [CrossRef]
26. NatureScot and Forestry Commission Scotland. Floating Roads on Peat. 2010. Available online: https://www.roadex.org/wp-content/uploads/2014/01/FCE-SNH-Floating-Roads-on-Peat-report.pdf (accessed on 3 September 2024).
27. Kane, G.; Grennan, R.; Jennings, P. Investigation into the likely cause of peat failure at Ballincollig Hill Wind Farm, Ireland. In Proceedings of the XVII ECSMGE-2019, Geotechnical Engineering Foundation of the Future, Reykjavik, Iceland, 1–6 September 2019; ISBN 978-9935-9436-1-3. [CrossRef]
28. NatureScot. Constructed Tracks in the Scottish Uplands. 2015. Available online: https://cairngorms.co.uk/wp-content/uploads/2019/09/CD039-Scottish-Natural-Heritage-Constructed-tracks-in-the-Scottish-Uplands-2015.pdf (accessed on 22 September 2021).
29. Stunnel, J. Investigating Wind Farms on Peat. Report to Natural England No. NECR032. Maslen Environmental. 2009. Available online: http://publications.naturalengland.org.uk/publication/43010 (accessed on 22 September 2021).
30. Gunn, J.; Labadz, J.C.; Dykes, A.P.; Kirk, K.J.; Poulson, S.J.; Matthews, C. Blanket Bog Hydrology at Mynydd Hiraethog SSSI: An Investigation of Peat Properties and Hydrology and Assessment of Effects of Proposed Wind Farm Construction. Countryside Council for Wales Research Report No. 501. 2002. Available online: http://irep.ntu.ac.uk/id/eprint/15341/ (accessed on 23 September 2021).
31. Labadz, J.; Allott, T.; Evans, M.; Butcher, D.; Billett, M.; Stainer, S.; Yallop, A.; Jones, P.; Innerdale, M.; Harmom, N.; et al. Peatland Hydrology: Draft Scientific Review. IUCN UK Commission of Inquiry on Peatlands. 2010. Available online: http://www.iucn-uk-peatlandprogramme.org/sites/www.iucn-uk-peatlandprogramme.org/files/Review%20Peatland%20Hydrology,%20June%202011%20Draft_0.pdf (accessed on 28 September 2021).
32. Lindsay, R.A.; Freeman, J. *Lewis Wind Power (LWP) Environmental Impact Statements (EIS) 2004 and 2006—A Critical Review*; University of East London: London, UK, 2008.
33. Lindsay, R.; Bragg, O. *Wind Farms and Blanket Peat—A Report on the Derrybrien Bog Slide*, 2nd ed.; University of East London: London, UK, 2005.
34. Holden, J.; Evans, M.; Burt, T.; Horton, M. Impact of land drainage on peatland hydrology. *J. Environ. Qual.* **2006**, *35*, 1764–1778. [CrossRef]
35. Boelter, D.H. Water table drawdown around an open ditch in organic soils. *J. Hydrol.* **1972**, *15*, 329–340. [CrossRef]
36. Smith, B.A.V. Assessment of Carbon and Nutrient Export from a Peatland Windfarm Construction Site. Ph.D. Thesis, University of Glasgow, Glasgow, UK, 2016.
37. Wallage, Z.E.; Holden, J.; McDonald, A.T. Drain blocking: An effective treatment for reducing dissolved organic carbon loss and water discolouration in a drained peatland. *Sci. Total Environ.* **2006**, *367*, 811–821. [CrossRef]
38. Wheeler, B.D.; Shaw, S.; Tanner, K. Wetland Functional Mechanisms: A Synopsis of WETMECs. Environment Agency Science Report-SC030232/SR2. 2009. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/291616/scho0309bpof-e-e.pdf (accessed on 28 September 2021).
39. Richardson, C. Highway construction and mitigation: On the road to increasing wetland function? *Natl. Wetl. Newsl.* **2005**, *27*, 17–20.
40. Elmes, M.C.; Petrone, R.M.; Volik, O.; Price, J.S. Changes to the hydrology of a boreal fen following the placement of an access road and below ground pipeline. *J. Hydrol. Reg. Stud.* **2022**, *40*, 101031. [CrossRef]
41. Yu, X.F.; Wang, G.P.; Zou, Y.C.; Wang, Q.; Zhao, H.M.; Lu, X.G. Effects of pipeline construction on wetland ecosystems: Russia–China oil pipeline project (Mohe-Daqing section). *Ambio* **2010**, *39*, 447–450. [CrossRef] [PubMed]
42. Olson, E.; Doherty, J. The legacy of pipeline installation on the soil and vegetation of southeast Wisconsin wetlands. *Ecol. Eng.* **2012**, *39*, 53–62. [CrossRef]

43. Li, Z.; Yu, J.; Ning, K.; Du, S.; Han, G.; Qu, F.; Wang, G.; Fu, Z.; Zhan, C. Ecological effects of roads on the plant diversity of coastal wetland in the Yellow River delta. *Sci. World J.* **2014**, *2014*, 952051. [CrossRef]
44. Findlay, C.S.; Bourdages, J. Response time of wetland biodiversity to road construction on adjacent lands. *Conserv. Biol.* **2001**, *14*, 86–94. [CrossRef]
45. Lévesque, L.M.; Dubé, M.G. Review of the effects of in-stream pipeline crossing construction on aquatic ecosystems and examination of Canadian methodologies for impact assessment. *Environ. Monit. Assess.* **2007**, *132*, 395–409. [CrossRef]
46. Newcombe, C.P.; Jensen, J.O.T. Channel suspended sediment and fisheries: A synthesis for quantitative assessment of risk and impact. *North Am. J. Fish. Manag.* **1996**, *16*, 693–727. [CrossRef]
47. Richardson, C.; Flanagan, N.A.; King, R.S. *Functional Assessment of the Effects of Highway Construction on Coastal North Carolina Wetlands: Comparison of Effects before and after Construction—Phase II (Construction)*; N.C. Dept. of Transportation Research and Analysis Group: Durham, NC, USA, 2003.
48. Trombulak, S.C.; Frissell, C.A. Review of ecological effects of roads on terrestrial and aquatic communities. *Conserv. Biol.* **2000**, *14*, 18–30. [CrossRef]
49. Wang, H.; Nie, L.; Xu, Y.; Du, C.; Zhang, T.; Wang, Y. Effects of highway-related pollutant on the groundwater quality of turfy swamps in the Changbai Mountain Area. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1652. [CrossRef] [PubMed]
50. El-Bana, M.I. Gravel pads of powerline towers as human-made habitats for ruderal vegetation in some Mediterranean wetlands of Egypt: Implications for management. *Egypt. J. Aquat. Res.* **2015**, *41*, 83–91. [CrossRef]
51. Adu Gyamfi, T.; Amo, M.; Osae, S.; Agyeman Junior, A.; Yaw Manu, I. Appropriate construction technologies to control the effect of wet conditions in wetlands in building industry in Kumasi Metropolis. *Int. J. Energy Environ. Res.* **2018**, *6*, 1–18.
52. Skaggs, R.W.; Chescheir, G.M.; Phillips, B.D. *Determination of Lateral Effects of Borrow Pits on Hydrology of Adjacent Wetlands (No. FHWA/NC/2006-50)*; CTE/NCDOT Joint Environmental Research Program; North Carolina State University, Department of Biological and Agricultural Engineering: Raleigh, NC, USA, 2007.
53. Dargie, T. Windfarm Impacts on Blanket Peat Habitats in Scotland. In Proceedings of the 19th Conference of the Institute of Ecology and Environmental Management (CIEEM 2004), London, UK, 18 May 2004.
54. Temmink, R.J.; Robroek, B.J.; van Dijk, G.; Koks, A.H.; Käärmelahti, S.A.; Barthelmes, A.; Wassen, M.J.; Ziegler, R.; Steele, M.N.; Giesen, W.; et al. Wetscapes: Restoring and maintaining peatland landscapes for sustainable futures. *Ambio* **2023**, *52*, 1519–1528. [CrossRef] [PubMed]
55. MacCulloch, F. *Guidelines for the Risk Management of Peat Slips on the Construction of Low Volume/Low-Cost Roads over Peat*; Forestry Commission: Inverness, UK, 2006.
56. Kapolka, N.M.; Dollhopf, D.J. Effect of slope gradient and plant growth on soil loss on reconstructed steep slopes. *International J. Surf. Min. Reclam. Environ.* **2001**, *15*, 86–99. [CrossRef]
57. Department of Housing, Planning and Local Government. Draft Revised Wind Energy Development Guidelines. December 2019. Available online: https://www.gov.ie/en/publication/9d0f66-draft-revised-wind-energy-development-guidelines-december-2019/ (accessed on 8 October 2021).
58. Saraswati, S.; Xu, B.; Strack, M. Presence of access roads results in reduced growing season carbon uptake in adjacent boreal peatlands. *J. Geophys. Res. Biogeosci.* **2023**, *128*, e2022JG007206. [CrossRef]
59. Armstrong, A.; Holden, J.; Kay, P.; Foulger, M.; Gledhill, S.; McDonald, A.T.; Walker, A. Drain-blocking techniques on blanket peat: A framework for best practice. *J. Environ. Manag.* **2009**, *90*, 3512–3519. [CrossRef] [PubMed]
60. Armstrong, A.; Holden, J.; Kay, P.; Francis, B.; Foulger, M.; Gledhill, S.; McDonald, A.T.; Walker, A. The impact of peatland drain-blocking on dissolved organic carbon loss and discolouration of water; results from a national survey. *J. Hydrol.* **2010**, *381*, 112–120. [CrossRef]
61. Natural England. *Investigating the Impacts of Windfarm Development on Peatlands in England (NECR032)*; Natural England: York, UK, 2010.
62. Watts, S. Revegetation of upland eroded bare peat using heather brash and geotextiles in the presence and absence of grazing. *Mires Peat* **2020**, *26*, 29. [CrossRef]
63. Murray, H. Assessing the Impact of Windfarm-Related Disturbance on Streamwater Carbon, Phosphorus and Nitrogen Dynamics: A Case Study of the Whitelee Catchments. Ph.D. Thesis, University of Glasgow, Glasgow, UK, 2012.
64. Moffat, A.J.; Jones, W.M.; Mason, W.L. *Managing Brash on Conifer Clearfell Sites. Forestry Commission Practice Note (FCRN013)*; Forestry Commission: Edinburgh, UK, 2006.
65. Ahmad, S.; Liu, H.; Günther, A.; Couwenberg, J.; Lennartz, B. Long-term rewetting of degraded peatlands restores hydrological buffer function. *Sci. Total Environ.* **2020**, *749*, 141571. [CrossRef]
66. Renou-Wilson, F.; Moser, G.; Fallon, D.; Farrell, C.A.; Müller, C.; Wilson, D. Rewetting degraded peatlands for climate and biodiversity benefits: Results from two raised bogs. *Ecol. Eng.* **2019**, *127*, 547–560. [CrossRef]
67. Johansen, M.D.; Aker, P.; Klanderud, K.; Olsen, S.L.; Skrindo, A.B. Restoration of peatland by spontaneous revegetation after road construction. *Appl. Veg. Sci.* **2017**, *20*, 631–640. [CrossRef]
68. Gaffney, P.P.J.; Hancock, M.H.; Taggart, M.A.; Andersen, R. Restoration of afforested peatland: Immediate effects on aquatic carbon loss. *Sci. Total Environ.* **2023**, *742*, 140594. [CrossRef]

69. Sahley, C.T.; Vildoso, B.; Casaretto, C.; Taborga, P.; Ledesma, K.; Linares-Palomino, R.; Mamani, G.; Dallmeier, F.; Alonso, A. Quantifying impact reduction due to avoidance, minimization and restoration for a natural gas pipeline in the Peruvian Andes. *Environ. Impact Assess. Rev.* **2017**, *66*, 53–65. [CrossRef]
70. Krone, M.A. *Pipeline Emplacement: Mitigating Environmental Impacts on Wetlands*; International Right of Way Association: Gardena, CA, USA, 1985. Available online: https://eweb.irwaonline.org/eweb/upload/web_0485_Pipeline_Emplacement.pdf (accessed on 28 September 2021).
71. Dalu, T.; Stam, E.M.; Ligege, M.O.; Cuthbert, R.N. Highways to invasion: Powerline servitudes as corridors for alien plant invasions. *Afr. J. Ecol.* **2023**, *61*, 379–388. [CrossRef]
72. Richardson, M.L.; Wilson, B.A.; Aiuto, D.A.S.; Crosby, J.E.; Alonso, A.; Dallmeier, F.; Golinski, G.K. A review of the impact of pipelines and power lines on biodiversity and strategies for mitigation. *Biodivers. Conserv.* **2017**, *26*, 1801–1815. [CrossRef]
73. Wright, I.A.; Khoury, R.; Ryan, M.M.; Belmer, N.; Reynolds, J.K. Laboratory study of impacts of concrete fragment sizes on wetland water chemistry. *Urban Water J.* **2017**, *15*, 61–67. [CrossRef]
74. Kuczynski, E.C.; Paszkowski, C.A. Constructed borrow-pit wetlands as habitat for aquatic birds in the Peace Parkland, Canada. *Int. Sch. Res. Netw.* **2012**, *2012*, 217357. [CrossRef]
75. Yli-Halla, M.; Lötjönen, T.; Kekkonen, J.; Virtanen, S.; Marttila, H.; Liimatainen, M.; Saari, M.; Mikkola, J.; Suomela, R.; Joki-Tokola, E. Thickness of peat influences the leaching of substances and greenhouse gas emissions from a cultivated organic soil. *Sci. Total Environ.* **2022**, *806*, 150499. [CrossRef]