CENTRE OF EXPERTISE FOR WATERS

Understanding the relationship between water scarcity and land use in private water supply catchments – a review

Josie Geris, Eva Loerke, Diana Valero, Keith Marshall, Jean-Christophe Comte, Mike Rivington, and Mark Wilkinson

Report and Appendices

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Declaration: The authors were commissioned by CREW to carry out an independent review on the relationship between water scarcity and land use in private water supply catchments. The steering group directed the scope of this work and reviewed the outcomes but did not influence the research process. The steering group consisted of representatives from the Scottish Government, the Drinking Water Quality Regulator (DWQR), and the Scottish Environment Protection Agency (SEPA). Input from the land use sectors was provided via contributions to a policy and practice workshop developed as part of the project and via correspondence with steering group members. Scottish Forestry subcontracted Forest Research to provide a review of an earlier version of this report. This report includes revisions based on some of their feedback along with feedback received from the steering group.

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Acronyms

BFI	Base flow index
EIA	Environmental Impact Assessment
FAO	Food and Agriculture Organisation
NWRM	Natural Water Retention Measures
NbS	Nature-based Solutions
PWS	Private Water Supply
RBMP	River Basin Management Plan
SUD	SUstainable Drainage
UKFS	UK Forestry Standard
LA	Local Authority

Executive Summary

Project aim and objectives

This project aimed to collate an evidence base and provide recommendations for land use change effects on water scarcity in private water supply (PWS) catchments. It focussed on emerging land use change trends in Scotland that include tree planting and management (afforestation and agroforestry), and wind farm development. Specific project objectives were:

1. To collect and review the available evidence on the effects of tree planting and wind farm development and management on water availability.
2. To carry out an international review of PWS policy and practice in relation to these land use change effects.
3. To consult with stakeholders to identify and co-create recommendations for PWS protection, policy and implementation solutions in relation to the land use changes that might operate at different scales.

Key findings

Effects on water availability

- While studies that directly monitor the effects on PWS are lacking, overall, the evidence review revealed that tree planting and wind farm development could both result in a decrease in water availability in PWS catchments. Whether and how this relates to PWS water scarcity will also depend on PWS water demand and local PWS logistics.
- For tree planting, the local effects on water availability can be highly variable, and are a complex function of time, the spatial orientation and extent of tree planting, the type of tree species, and other local factors such as the land use prior to planting, soil and geological properties, and site management. The effects of agroforestry on water availability are similar to those of afforestation, although typically smaller in magnitude and more sensitive to the orientation and extent of the planting.
- The international literature on wind farm development indicates that, in addition to landscape factors, wind farm characteristics, including type, number and density of turbines, are key local factors that contribute to the magnitude of effects on water availability. Literature on the effects of wind farm development on water availability for Scottish landscapes is generally scarce.

Practice and policy review

- The practice and policy review revealed that most of the measures identified aiming to protect water supplies from impacts associated with land use change are preventive. The two most significant policy instruments in play are 1) defining forestry standards and the issues to be included in the impact assessments, particularly those required for wind farm development, and 2) the establishment of effective buffer zones around water supplies.
- There is a lack of information on how these instruments are used after the approval for the land use change (what happens during and after implementation). Documentation of the whole EIA process (reports, consultation statements, decisions) is critical as a source of information for identifying impacts and existing measures, but these documents are not always publicly available or accessible. Relying mostly on documentation referring to initial EIA reports could bring bias that has to be considered as a limitation of this study.
- The practice and policy review has also highlighted the need for integrated and up-to-date information on conditions and locations of the water supplies, catchment conditions and potential impacts of the different land uses in order to assist decision-making.
- The design phase of land use change developments needs to include rigorous and effective consultation and where necessary mediation, with PWS users.
- Overall, literature exploring measures safeguarding water supplies from impacts of wind farms is very limited, with most information coming from the study of environmental impact assessments and planning and guidance documentation. The majority of these focus on water quality issues, with only limited references to sustainability of water quantity. Documents referring specifically to private water supplies are scarce. The management of impacts of afforestation and agroforestry is better documented, particularly through the outputs of EU-funded projects in

the last 10 years exploring how to reconcile the protection of drinking water sources with land use activities, although these are mainly focused on water quality as well.

Stakeholder consultation

- Stakeholders expressed a need for improved policy and associated legislation relating to PWS owners' rights, responsibilities, and protections. There was a perception that different sectoral policies (e.g., climate change, agriculture, water resources) affecting land use decision making were not always coherent. Stakeholders flagged the lack of cross-sectoral understanding, and the need for developing and sharing good practice and awareness of PWS considerations in the context of both wind farm and afforestation developments (covering scoping, planning, implementation and ongoing management phases).

Recommendations

1. **Careful consideration of local assessment and management strategies** for tree planting and wind farm development, both at short- and longer-term scales. This requires site ground truthing of desk-based assessments, monitoring of impacts of primary and subsidiary works, and processes for agreeing actions to mitigate impacts. While water availability could decrease in response to tree planting and wind farm development, the relevance and magnitude of effects for PWS depend on various local factors. PWS that could be expected to be most affected are those that rely on relatively shallow sources on thin soils or superficial geology located downstream of large wind farm developments or coniferous plantations. In these and other places, provision of risk mitigation options could involve improving catchment storage potential with nature-based solutions that also improve wider ecosystem resilience. There is also scope for these risks to be mitigated by attention to land use change design, scale and management.
2. **Addressing the lack of integrated land use planning and management that accounts for private water supply.** Specifically, this requires cross-sectorial and cross-project coordination and involves a coherent consideration of wind farm and forestry policy and appraisals alongside agricultural policies, across scales. This should include reference to existing guidance within the UKFS, relevant practice guides, and specific Forestry and Water Scotland guidance on protecting PWS during forestry activities. It is essential to consider catchment scale pressures on water availability for PWS in the context of broader landscape and climate characteristics.
3. **Addressing knowledge gaps:**

Water scarcity:

A) The literature reports predominantly on the effects of tree planting and wind farm development on catchment scale water balance components, but studies that monitor the effects on PWS directly are lacking. Monitoring and research that considers water demand factors would be required to be able to quantify associated PWS risks to land use change. B) Especially for the effects on groundwater resources, and subsequently, on groundwater sourced PWS, more evidence is needed, as much of the evidence for Scotland has been collated indirectly (i.e., effect on potential groundwater recharge not actual recharge or storage), or from modelling results. C) Literature on the effects of wind farm development on water availability is also scarce. More empirical research is required to address these fundamental knowledge gaps. Monitoring of wind farm effects on water stores and flows, including PWS, is critical to characterizing the relative controls on water availability and scarcity.

Policy and practice:

A) Assessment of the implementation and efficacy of the measures currently being implemented in Scotland, or the UK more widely, would be necessary to fully consider measures already in place and the potential for consolidating existing good practice and learning from other experiences. B) Improvements are recommended to regulations of PWS users' rights and responsibilities to enable the development of policy coherence and integration with other policies and legislation governing land use change developments, climate change adaptation and mitigation, river basin management, and water policy. This would help provide clarification for decisionmakers and consultive and regulatory bodies, including local authorities fulfilling their statutory responsibilities, when considering trade-offs and mitigation options.

4. **A shared repository of data and information** is critical for addressing the points above and will help to create shared understanding of the potential impacts of land use changes on PWS. A more complete register of location and type of PWS and related infrastructure (including both regulated and unregulated supplies) would provide a fundamental resource to inform land use planning. This should be complemented by a spatial database that assimilates already existing data relating to land use planning, PWS catchment hydrology, and be enhanced as further data becomes available (e.g., from ground truthing work, effective monitoring of development and management processes). Likewise, easily accessible support and consistent guidance for PWS users in line with their rights and responsibilities needs to be provided.
5. **A continued process of stakeholder involvement and knowledge sharing.** Building on the project workshop as a forum to outline future pathways, participants expressed a strong desire for a continuation of this process and thereby improve knowledge sharing, good practice examples and guidance, and regulatory oversight, and public awareness raising around PWS management and land use change.

1 Introduction

1.1 Background

As part of Scotland's path to net zero, the development of wind farms and tree planting are two emerging land use change trends that address renewable energy and carbon storage targets aimed at addressing the climate crisis. Among these and other benefits, tree planting can also make an important contribution towards addressing the biodiversity crisis. In turn, the impacts of climate change and other environmental policies on land use pose various challenges around the balance between targets, different land uses, and resources. Land use changes are known to affect water storage and flow. They can thereby be considered as nature-based solutions for water management problems. For example, afforestation has been attributed to reducing flood risks (Bulygina *et al.,* 2011; Collins *et al.,* 2023; Mansour and Hughes, 2014; Monger *et al.,* 2022; Stratford *et al.,* 2017). However, there are also anecdotal reports that tree planting and wind farms may affect water availability for private water supplies (PWS).

PWS numbers (Figure 1A) vary from year to year but generally serve approximately 3% of the resident population in Scotland and potentially many thousands of tourists (DWQR, 2019), in addition to numerous agricultural, distilling and other businesses. PWS thereby plays a vital role in the local economy of remote rural communities in Scotland, which are vulnerable where PWS is unreliable (Teedon *et al.,* 2020). Climate change poses increased drought risks for water resources across Scotland (Boca *et al.,* 2022) with various sectors exhibiting a range of preparedness (Glendell *et al.,* 2024; Gosling *et al.,* 2024). There is a high probability that increasingly drier and warmer summers will result in increased water deficits for PWS, particularly those more reliant on surface water (Rivington *et al.,* 2020). Interactions between various personal, social, environmental, and institutional factors interact to either enhance or reduce PWS users' vulnerability to drought (McClymont and Beevers, 2022). By comparison, the effects of climate change are likely to be greater than to those of land use change on water resources in the UK (Buechel *et al.,* 2022). Within this wider context, the PWS concerns in relation to tree planting and wind farm development are multifaceted. In addition to uncertainties around reductions in water availability, challenges include; shortcomings in the regulation and general resilience of PWS, issues with land use change risk assessment processes, lack of integrated planning, limited knowledge and awareness of land use effects on PWS, and challenges around engagement with PWS users (Appendix 1).

1.2 Private water supply and land use in Scotland

Within the Scottish context, there are spatial patterns in terms of the PWS types and demand (Figure 1A, Appendix 2 – Figure A1), potential risks of PWS in the context of future climate projections (Figure 1B), and physiographical characteristics that affect water storage and flow, which include soil and geological properties (Appendix 2 – Figure A1), and dominant land use (Figure 1C), including current and planned wind farm developments (Figure 1D).

The East and North-East of Scotland have a relatively high density of PWS, mostly from (shallow) groundwater sources in agricultural areas, which are vulnerable under high to very high risk to meteorological drought. In the South-West and Central Belt, the demand of private water supplies is relatively high in terms of abstractions, while these sources are under low to moderate drought risk in the future. This region has a relatively high density of installed and planned wind farms as well as woodland creation schemes in Scotland.

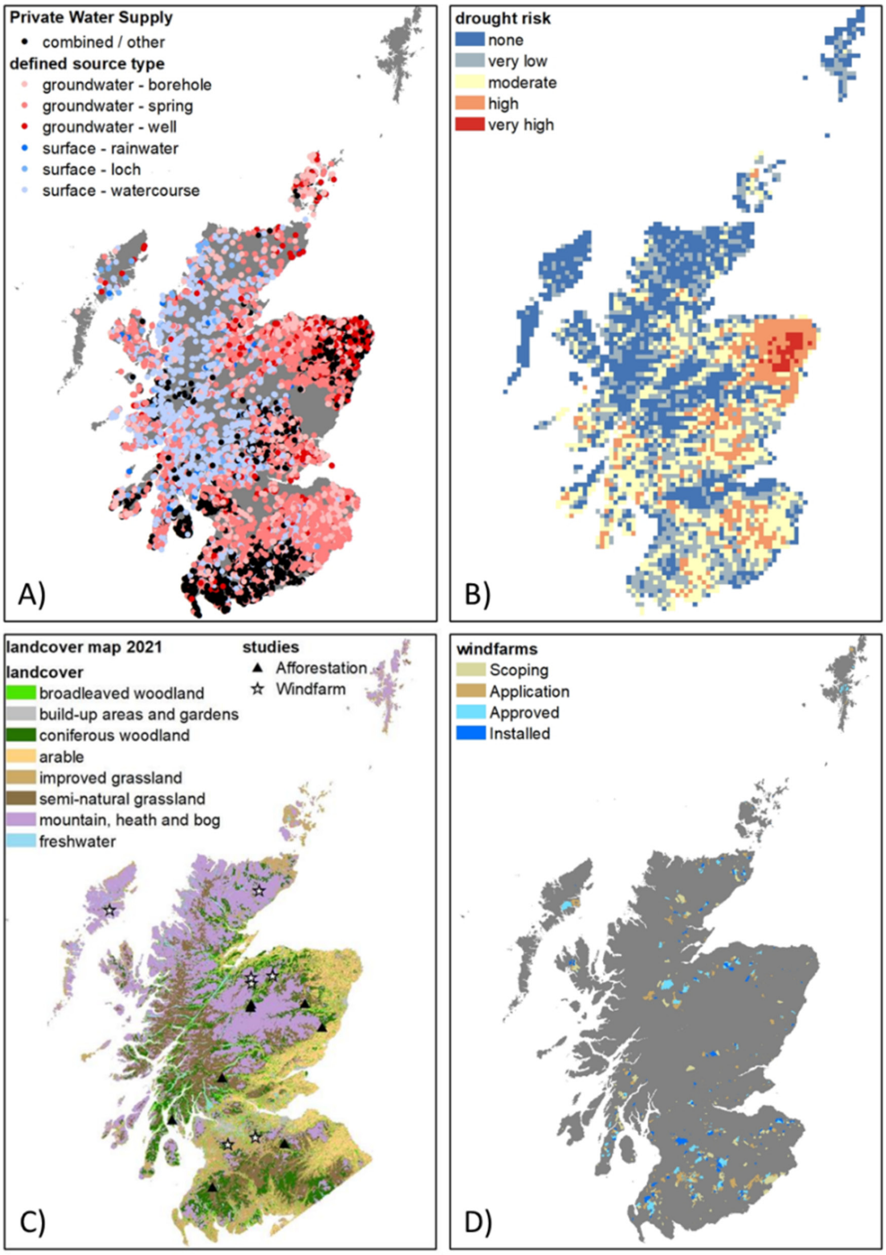

Figure 1: Scotland's A) private water supply source types, B) mean drought risk map for private water supply, based on future (2020-2050) annual mean precipitation of 12 climate model ensembles for Met Office (2019) RCP8.5 (Rivington *et al.,* 2020). C) key land covers (UK CEH, 2021), superimposed by location of afforestation and wind farm studies based in Scotland and included in this review, and D) installed and planned distribution of wind farms (Scottish Government, 2023).

While aquifer productivity in Scotland is generally low to moderate, there are also clear spatial patterns in the shallow subsurface soil and hydrological properties (Appendix 2 – Figure A1). Freely draining soils towards the East potentially favour groundwater recharge, as also indicated by a relatively high base flow index (BFI). BFI provides a measure of the proportion of the river runoff that derives from stored sources; the more permeable the subsurface, the higher the BFI and the more likely river flow is sustained during periods of dry weather. In the North-West of Scotland, the surface water supplies are under relatively lower risks of water scarcity because of the low risk of meteorological drought and overall low water demand in relation to the water availability. However, there is still vulnerability to drought in these areas due to low subsurface (soil and aquifer) water availability associated with dominant thin or poorly draining soils, thin superficial glacial/alluvial formations and poorly productive bedrock aquifers. The major land uses are moorland and semi-natural grasslands, which are interspersed with woodlands.

Afforestation, in principle, does not require planning permission and only requires compliance with what the “prior notification procedure” set down in the Consolidated Circular on Non-Domestic Permitted Development Rights (Scottish Government, 2021). Nevertheless, Scottish Forestry has a statutory duty to screen and consider afforestation proposals with requirements for full Environmental Impact Assessments (EIA) for all projects in sensitive areas, for those >2 ha in National Scenic Areas, and for planting of >20 ha elsewhere (Scottish Forestry, 2021). The screening must include details on the existing public and private water supplies in the area that are likely to be affected. Guidance on Forestry activities near PWS was developed through the “Forestry and Water Scotland” initiative supported by various organisations involved in Scotland’s forestry sector and by the Diffuse Pollution Management Advisory Group. However, it has been suggested that there is a lack of consolidation and knowledge of practice under existing policy measures aimed at monitoring and offering guidance beyond the EIA process.

Regarding wind farm development, SEPA, which consults on wind farm development and development plans, offers planning guidance on onshore wind farm developments (SEPA, 2017a) and on developments that might impact on groundwater abstractions, including wind farms (SEPA, 2017b). Their latest guidance assessment checklist (SEPA, 2017a) includes among the issues to consider buffers to private and public supplies and the requirement for applications to contain site layout plans which illustrate the location of all built elements in relation to public and private supplies.

Some Local Authorities have elaborated supplementary guidance to their local development planning on the development of onshore wind energy, which offers guidance or establishes requirements for the planning and doing impact assessments of wind farm developments (e.g., Angus Council (2017), East Ayrshire Council (2017), The Highland Council (2011)). While most of the focus is on quality impacts on PWS, some guidance documents explicitly mention the impacts on quantity and ask for full risk assessment of PWS to be included in the proposals that include appropriate mitigation and contingency measures (see for example East Ayrshire Council (2017)). However, there seems to be inconsistency regarding the requirement of PWS risk assessments across Scotland, and their requirements and scope of these risks assessments, particularly regarding the consideration of impacts on water quantity.

1.3 Aim and objectives

This project aimed to collate an evidence base and provide recommendations for land use change effects on water scarcity in private water supply (PWS) catchments. It focused on emerging land use change trends in Scotland that include tree planting and management (forestation and agroforestry) and wind farm development. Specific project objectives were:

1. To collect and review the available evidence on the effects of tree planting and wind farm development and management on water availability.
2. To carry out an international review of PWS policy and practice in relation to these land use change effects.
3. To consult with stakeholders to identify and co-create recommendations for PWS protection, policy and implementation solutions in relation to the land use changes that might operate at different scales.

The report specifically focusses on land use change effects on water availability, the role of catchment characteristics and the nature of change therein, and the policies and practices to address any negative impacts. There are two key points in relation to the scope:

Firstly, when interpreting the effects of water availability in terms of effects on PWS water scarcity, they should be evaluated in the context of future PWS demand and climate risk, as well as logistical challenges. Figure 2 summarises the key controls and links between factors that ultimately determine water scarcity in PWS catchments. Primarily, water scarcity for PWS is a function of both water availability and water demand. Water availability depends on climatic factors and catchment characteristics. It is well established that climate change can pose significant risks for water scarcity in the future, affecting both water availability and demand in Scotland (Rivington *et al.,* 2020). While the land use changes considered in this review are implemented to help reduce or mitigate against the impacts of climate change, they can also affect water availability. In turn, the extent and timing of these impacts will depend on catchment characteristics and the nature of change. In addition, there are many site-specific and logistical challenges that can potentially affect water scarcity for PWS. These include, for example, tank leakage, or damage to pipes as part of access road construction. Such aspects are not considered as part of the review here, but it is acknowledged that for individual PWS sources, these factors could have a dominant role in determining water availability/scarcity locally.

Secondly, the report specifically focuses on addressing knowledge gaps related to wind farm and afforestation effects on *water quantity*. Nevertheless, there are inherent links between water quantity and water quality issues; for example, as water availability reduces, this could be paired with an increase in concentration of contaminants. Increasingly drier conditions might also involve changes in the proportion of different water sources to PWS, which again could have implications for water quality. Although the direct water quality impacts on PWS depend on local factors such as forest management, the variety of effects on water quality may be inferred from water quality data from catchments typical for PWS (see e.g., Shah *et. al.* (2021, 2022) and Duffy *et. al.* (2020) for the effects of forestation and Heal *et. al.* (2020) and Millidine *et. al.* (2015) for the effects of wind farms).

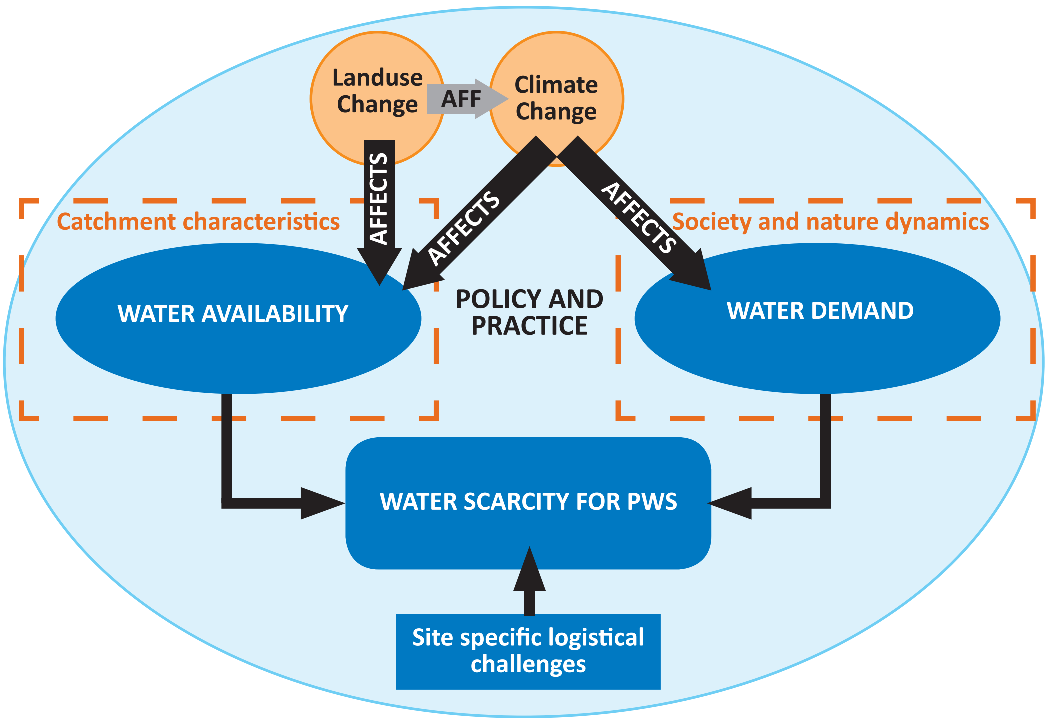

Figure 2: Schematic representation of the key controls and links between factors that ultimately determine water scarcity in PWS catchments.

2 Methodology

2.1 General approach

The evidence reviews on land use change effects on water availability (objective 1) and good policy and practice strategies (objective 2) considered international peer-reviewed scientific literature and governmental technical reports, complemented by grey literature and interviews. Reviews focused on water availability effects of different land uses, implications for PWS water scarcity, current policy measures in Scotland, and (good practices in) other countries. Preliminary results of the first two objectives were then presented at a workshop with a variety of stakeholders from across Scotland. The focus of the workshop was to address objective 3 and co-create recommendations for PWS protection, policy and implementation solutions in relation to the land use changes.

2.2 Literature review on land use change effects on water availability

Water availability, or water storage (i.e., the amount of water stored in surface water bodies, soils and aquifers) in PWS catchments is a function of the balance between inputs via rain and snow, and outputs via evaporation and plant water use (i.e., evapotranspiration), river flow, and abstractions (Equation 1):

Water availability = Rain + Snow – Evapotranspiration – River flow – Abstractions

Equation 1

While the literature rarely reports on water availability for PWS directly, impacts on soil moisture and groundwater levels both provide indications of water storage changes in the shallow and deeper subsurface. Much of the evidence relates directly to individual components of Equation 1, or specific hydrological processes that affect these components (Appendix 3 – Table A1). In addition, because river flow can be described as a function of catchment storage, the effects on river flow can also provide an indicator of the integrated effects on catchment storage, representing the overall effect of complex processes and flow pathways within the catchments.

For planting trees, the literature review focused on studies based in Scotland, countries in similar hydrological settings and those countries identified for the good practice and policies review (see 2.3). For tree planting, we considered the most emerging trends appropriate for Scotland. This included, firstly, farmland conversion to forests (conifer plantations and forest restoration), specifically grassland (rough and permanent grazing) to forest. The review focused on the effects of planting and managing trees rather than deforestation as this land use change aligns with Scotland's Net Zero plans. Secondly, we considered integrating trees on farmland (agroforestry) and explored literature for silvo-pastoral and silvo-arable systems. Google Scholar was used to identify peer reviewed literature. This involved a combination of different search terms relating to "afforestation", "agroforestry" and "hydrology" by combining the keywords summarised in Appendix 3. The literature was analysed with an emphasis on exploring the role of factors including tree species (deciduous vs coniferous), historic land use, temporal and seasonal effects, catchment size, soil type and geology. Additional information was gathered based on study period, depth of observational measurements, and methodology. Where possible, information on the magnitude of change was extracted to allow comparison between different studies.

For wind farm development, fewer studies are available and therefore the literature review was broadened to gather sufficient data to explore for trends. We therefore gathered information from international peer-reviewed studies, as well as grey literature and reports, irrespective of geographical location on an international basis. Google Scholar and Google were used to identify peer reviewed and grey literature sources. This involved a combination of different search terms relating to "wind farm development" and "hydrology" by combining the keywords summarised in Appendix 3. The literature was analysed with an emphasis on wind farm area, number of turbines, historic land use, temporal and seasonal effects, soil type and geology. Further information was gathered based on study period and methodology. Where possible information on the magnitude of change was extracted to allow comparison between different studies. The review focused on the effects of constructing and operating rather than decommissioning of wind farms as this land use change aligns with Scotland's Net Zero plans.

2.3 International PWS practice and policy reviews

The international policy and practice review focused on policy measures to protect and conserve water supplies around the development of afforestation and wind farms, with specific attention to decentralised, off-grid or small-scale supplies. Such information is typically published in national languages, which slows down the identification of sources of information and analysis. Thus, we followed a dual approach combining a the review of documentation collected via a literature search, identification of EU funded projects working on relevant topics (e.g., through the databases KEEP, CORDIS and LIFE Public), and targeted national policy programmes and regulations (e.g., RBMP and EIA regulations) and media news, with interviews with experts from initiatives representing PWS initiatives or research projects that could provide good practice examples or identification of relevant policies. Experts consulted are listed in the acknowledgments section.

For the international review, in addition to the UK, we targeted countries and regions with characteristics of relevance for understanding the management of water in Scotland, identified based on similarities to Scotland regarding climate, water stress challenges, level of water governance, and extent of small water supplies akin to PWS. The list of countries targeted in the review includes Austria, Canada, Ireland, Portugal, Austria, Switzerland, New Zealand, Norway, Belgium, Germany and Spain, with specific focus on Austria, Ireland, Norway, New Zealand and Spain as agreed in discussion with the project steering group.

The topic of land use effects on PWS sits at the intersection of several policy areas (i.e. water, environmental, land use, forest, energy, development, and climate change policies) which all require consideration of different scales regarding objectives and impacts and management of risks (Orru and Rothstein, 2015). In addition, there are also complex interactions among local, regional and national levels (and in some cases European level) (Garnier and Holman, 2019). Within each of these policies, there are different objectives and programmes that ultimately translate into policy measures. Measures typically refer to specific on-the-ground policy levels, and usually contain at least one of two important policy components: specific targets or specific policy tools (Howlett, 2009). Here we provide an illustrative inventory of policy measures and wider management measures (e.g., those developed by developers).

We differentiate between three types:

1. Preventive measures (also referred to as proactive or anticipatory) that are focused on saving and holding water available and to increase the buffering capacity of the soil and water systems;
2. Adaptive measures (sometimes called concurrent) aimed to “accept the limitations of the natural system and adapt the water use to the scarcity risks that the system generates”;
3. Reactive measures to “bend the water system in the desirable direction” (Bressers *et al.,* 2019; Garnier and Holman, 2019).

Preventive or proactive adaption measures are considered more effective and less expensive in the long term (Garnier and Holman, 2019).

2.4 Co-creating recommendations for PWS protection, policy and implementation solutions

A one-day workshop was the main mechanism for consulting with stakeholders to identify and co-create recommendations for PWS protection, policy, and implementation solutions in relation to land use changes. Key stakeholders including representatives from relevant Scottish Government departments and agencies, local authorities, and land use sectors attended an in-person workshop in Perth on 18th January 2024 (see Appendix 1 for the workshop report including details of stakeholders, methods, outcomes, and feedback). It should be noted that some invitees were unable to attend, and input from additional voices, particularly from the commercial forestry sector, would have been valued on the day. Those unable to attend were invited to respond in writing to the day’s questions, and the draft workshop report was shared with attendees to check for misrepresentation or needs for clarification.

During the workshop, interim findings from the project’s evidence-review were presented, after which a series of plenary and breakout group discussions were facilitated to discuss and outline:

- Coherent policy and regulatory pathways for wind farm development and afforestation that support the provision of private water supplies
- Good practice land use development and management strategies, particularly those in relation to wind farm and forestry expansion, that may maintain water availability for private water supply security

- Recommendations on where and what mitigation strategies might be appropriate in cases where potential negative effects on water availability may arise.

There were four activities around which engagement was encouraged: attendees recorded what they personally considered to be key challenges for PWS and land use change; facilitated discussions around wind farms and afforestation lead to suggestions for improvements to relevant policy and practice; likely dependencies were identified in relation to these improvements; and good practice examples that might inform progress were recorded.

3 Land use effects on water availability

3.1 General overview of evidence base

The review on afforestation (grass-/farmland to forest) involved scientific literature sources from 75 studies, 38 of which from the UK, including 12 from Scotland with a wide geographical spread (see Figure 1C). Appendix 4 – Table A2 provides a summary of all afforestation studies included in this review, including results and key information on the study context. There is some duplication in study sites; in addition to several meta-analyses across many sites, the evidence base covers results from 49 regions across 12 countries. Most of the studies report on the effects of tree planting on a combination of river flow (>50% of studies), evapotranspiration (>50% of studies), groundwater levels, or soil moisture (~40% of studies in each case). 60% of studies are based on observed data, while the others present results from modelling studies. The review on agroforestry involved 25 scientific literature sources from 19 sites across 10 different countries, in addition 2 multi-site studies. Most of these studies report on the effects of agroforestry on a combination of soil moisture (~80% of studies), evapotranspiration (>40% of studies), river discharge (>40% of studies) or groundwater levels (~20% of studies). 76% of studies are based on observed data, while the others present results from modelling studies. Appendix 4 – Table A3 summarises all studies with evidence on agroforestry effects.

We identified 21 studies and reports from 20 different locations on the effects of wind farm developments that address the effects on water availability. Ten were from the UK, of which eight reports were based in Scotland with a good geographical spread, although studies from the NE are missing (Figure 1C). Peer reviewed literature on wind farm effects is limited and most sources found are grey literature reports where effects are largely unquantified. Where effects were quantified in the international literature, these were mainly for wind farms with > 300 turbines and extending > 200 km^2.

Most evidence is available on wind farm effects on evapotranspiration and soil moisture (>50% of studies report on these); less than half report on the effects on river discharge and groundwater. Appendix 4 – Table A4 summarises all studies with evidence on the effects of wind farms, including results and key information on the study context.

3.2 Tree planting – Grassland to forestry

Together, the results indicate that, given certain rainfall inputs, water availability is likely to decrease in PWS catchments following tree planting (afforestation and agroforestry). Overall, the literature review consistently indicated that in response to planting trees on grassland, soil moisture, groundwater recharge/groundwater levels and river discharge decrease and evapotranspiration increases (Figure 3). These effects can be mainly attributed to trees and forests using more water than grass and other shorter vegetation (Birkinshaw *et al.,* 2014; Houghton-Carr *et al.,* 2013; Nisbet, 2005) predominantly via increased canopy evaporation, which is highest during wet conditions and high flow events (Momiyama *et al.,* 2023; Page *et al.,* 2020).

There has been a longstanding and ongoing debate about the link between forest cover and rainfall (see e.g., Bennett and Barton (2018) and Sheil (2018) for an overview). In a recent study across Europe, Meier *et. al.* (2021) revealed that forests could increase precipitation, specifically summer precipitation in the downwind direction. This can generally be explained by forest increased evapotranspiration removed from a particular catchment contributing to precipitation events and increasing water yield in downwind locations. It is important to recognise this connectivity, as the focus on single catchment water balances alone may not fully capture the effects of afforestation on water quantities. This is especially important for wider policy and practice implications (Creed *et al.,* 2019). Furthermore, it has also been described that large areas of tree cover may actively draw in air and moisture from elsewhere and increase precipitation locally (Sheil, 2018). Nevertheless, both processes typically take place over large distances (up to hundreds or thousands of kilometres) and involve significant forest cover. The majority of the international evidence supports that trees reduce runoff at the catchment scale (e.g., Filoso *et al.,* 2017), while at larger scales, trees are more clearly linked to increased precipitation and water availability (Ellison *et al.,* 2012). Therefore, care must be taken with interpreting these results for rainfall in the context of afforestation in PWS catchments locally, especially when facing potential water scarcity.

There is strong agreement between different evidence sources in terms of the direction of change for specific hydrological stores and flows (Appendix 4 – Figures A2, A3 and Table A2). There are a few exceptions, especially for soil moisture, where 40% of studies showed that soil moisture was not affected, or, in some cases, increased. This could be attributed to increased infiltration (Chandler *et al.,* 2018; Kleine *et al.,* 2021; Monger *et al.,* 2022; Mongil-Manso *et al.,* 2022; Revell *et al.,* 2022) or improved water holding capacity with increased organic materials (James *et al.,* 2003; Monger *et al.,* 2022; Revell *et al.,* 2022). Afforestation can thereby improve soil hydrological functioning and provide natural flood management services (Murphy *et al.,* 2021). How increases in infiltration and recharge balance with interception losses and increased evapotranspiration will determine the local effect on soil moisture, groundwater and water yield. Despite increases in infiltration, recharge of deeper (ground)water still predominantly reduced for the studies included in the review, because of increased vegetation water uptake (Calder, 2004; Gribovszki *et al.,* 2008; Kleine *et al.,* 2021; Mansour and Hughes, 2014). While these studies are typical for the Scottish context, it should be noted that especially during intense rainfall, the benefits of trees to increased recharge are typically larger (Archer *et al.,* 2016), and such events are more likely to occur in the future for Scotland. In addition to more winter precipitation increasing recharge, a wetter and warmer climate is likely to enhance evaporation losses from forest canopies (Nisbet, 2002, 2005), and the relative offsets will vary between sites. Especially in the context of a warming climate, the temperature regulation effect of trees is also worth noting. Forests can remain cooler due to shade and the role of evapotranspiration in reducing sensible heat, especially during summer (Ellison *et al.,* 2017). In addition, in line with relatively high evapotranspiration, European forests have been shown to increase cloud formation (Teuling *et al.,* 2017), which in turn provides shade and affects rainfall dynamics.

While the evidence base is mostly consistent, generalisation of tree planting effects to specific locations or times of the year is difficult, especially with regards to the expected magnitude of change. Factors that control the effects of tree planting on water availability include the tree species; local factors such as the land use prior to planting, and soil and geological properties; maturity, seasonal growth cycles and varying hydro-climatological conditions (i.e., time); and the spatial orientation and extent of planting and site management.

The relative dynamics and magnitude of tree planting effects on water availability is species dependent; coniferous trees typically exert larger effects than deciduous species, as they use more water overall (Coble *et al.,* 2020; Lawson *et al.,* 2019; Markwitz *et al.,* 2020; Salazar *et al.,* 2013). The changes in water availability will also depend on the land use prior to tree planting. We have focussed mainly on conversion from rough grazing, and within that, it has been found that effects on water availability may be larger for afforestation of grassland than heath or arable lands (Farley *et al.,* 2005; Mansour and Hughes, 2014; Parkin *et al.,* 2003). The relative impacts of tree planting for water availability ultimately also depend on subsurface (soil and aquifer) hydraulic properties, which have a dominant control over land use on water availability across Scotland (Geris *et.al.,* 2015; Peskett *et al.,* 2023, 2021). In catchments with low storage and poorly productive properties, tree planting could have a proportionally larger effect on water availability. For plantations of conifers, Nisbet (2005) also summarises that the proportional effects for lowlands may be larger than for uplands, because of the closer match between rainfall and evaporation totals and the much lower water yields in the former compared to the latter.

There are both short- and long-term variations in the effects of tree planting with time. Over longer time scales, this is associated with the establishment and growth of trees (Johnson, 1998). During the early stages, effects are often related to ground preparation work (not canopy closure (Nisbet and Stonard, 1995)), where soil compaction and increased drainage typically leads to increased discharge (Kleine *et al.,* 2021; Robinson, 1986; Robinson *et al.,* 1998) including low flows (Johnson, 1998). Here, it is important to note that since 1998, drainage is not a common practice anymore and mounding is more common now than creating ditches and banks. There are also variations between the early growing years and after the forest has matured (Calder *et al.,* 2002; Kleine *et al.,* 2021; Lewis *et al.,* 2013; Neill *et al.,* 2021; Salazar *et al.,* 2013). For example, after initial increases, there may be decreases in water use with forest aging. Soil infiltration rates have also been reported to increase over time with forests maturing (Archer *et al.,* 2016), so that the potential for trees to facilitate rainfall recharging shallow and deeper groundwater resources will increase with forest age.

At shorter timescales, there are notable differences between the effects of trees under varying hydro-climatological conditions. The effects of afforestation on low flows are most relevant in the context of water scarcity for PWS. The literature predominantly indicated that low flows decrease in response to planting trees on grassland, and this is also supported by observations of increased low flows following harvesting (e.g., Robinson and Dupeyrat, 2001). Several studies have suggested that proportional decrease in water availability during relatively drier periods (i.e. low flows) is greater than that in high and/or average flows. Similarly, others have also found that for afforestation of grasslands, absolute reductions in annual runoff are greatest at wetter sites, but proportional reductions are significantly larger in drier sites (Farley *et al.,* 2005), suggesting that trade-offs should be considered for forest planting in catchments with known pressure on water resource systems. While depending on local properties, low flows across many parts of Scotland may still be predominantly sustained by relatively shallow sources and flow pathways. Shallow sources generally are more quickly affected by drought than deeper sources (van Loon, 2015), which could be amplified by tree water use. However, if replenishment of deeper groundwater sources is enhanced by increased infiltration following afforestation, this could potentially increase levels of low flow. In the context of PWS, these differences between relatively shallow and deeper sources could be equally important. There is an overall lack of studies focusing on the direct impacts on deeper groundwater sources, as these are typically implied or inferred from other datasets. Locally, the balance between increased infiltration and tree water use effects on low flows, including any reversals in the balance, will also depend on other local factors, and may change as trees mature (Bruijnzeel, 2004; Filoso *et al.,* 2017), as also outlined above.

The effects of tree planting generally increase with the proportion of the catchment affected, and for small catchments, the location and spread of planting may also play a role (Buechel *et al.,* 2022; Fennell *et al.,* 2023). With increasing catchment scale, disentangling the role of different land use changes and at different times does become more difficult (Collins *et al.,* 2023; Lewis *et al.,* 2013; Sonnenborg *et al.,* 2017).

Finally, how tree planting is established and managed locally can make a difference. As mentioned above, access roads, ploughing, or drainage were found to increase runoff where these were applied (Calder, 1993; Robinson, 1998, 1986; Birkenshaw *et al.,*2014). There is little evidence on the effects of more recent management practices such as mounding. Forest thinning can mitigate the decrease in water yield and has especially positive impacts on low flows (Duncan, 1995; Hughes *et al.,* 2020). While clear-cutting in combination with site preparation has shown only a small decrease in ground water availability (Mannerkoski *et al.,* 2005), clear cutting without site preparation and forest thinning are known to increase river discharge and groundwater levels for a short period of time until crown closure rates are similar to the pre-thinning state (Bent, 2001; Yang *et al.,* 2019). Whereas current Scottish Forestry Policy for new woodland is to avoid ground disturbance from ploughing, felling and restocking operations can still employ trench mounding, which causes soil disturbance and water pathway alterations. The role of access tracks and ground disturbance on water availability as part of the felling procedure requires further research.

In summary, given the complexities that the various factors as mentioned above bring, careful consideration of local assessment and management strategies of tree planting would be advised in PWS catchments, both at short- and longer-term scales. While we found consistent evidence for the direction of change, the magnitude of tree planting effects on water availability will depend on the interplay between local factors. PWS that could be expected to be most affected by tree planting are those that rely on relatively shallow sources on thin soils or superficial geology located downstream of large coniferous plantations (Robinson *et al.,* 2003). In these cases where water trade-offs need to be made in terms of the potential for trees to reduce water availability, there is scope for these to be mitigated by attention to woodland type (e.g., species choice), design (including tree densities), scale and management (Nisbet *et al.,* 2011; Ellison *et al.,* 2017).

The literature reports widely on tree planting effects on catchment scale water balance components, but studies that monitor the effects on PWS directly are lacking. Especially for effects on groundwater sources, more evidence is needed, as most studies report either indirect evidence (i.e., effect on potential groundwater recharge rather than directly actual recharge or groundwater storage/availability), comparisons between sites with different physiographic characteristics or modelling results.

3.3 Tree planting – Agroforestry

The review revealed that the effects of agroforestry on water availability are comparable to those of afforestation in terms of the direction of change, but these are generally less pronounced. Appendix 4 – Figure A4, Figure A5 and Table A3 provide an overview of results from individual studies and show that there is strong agreement between

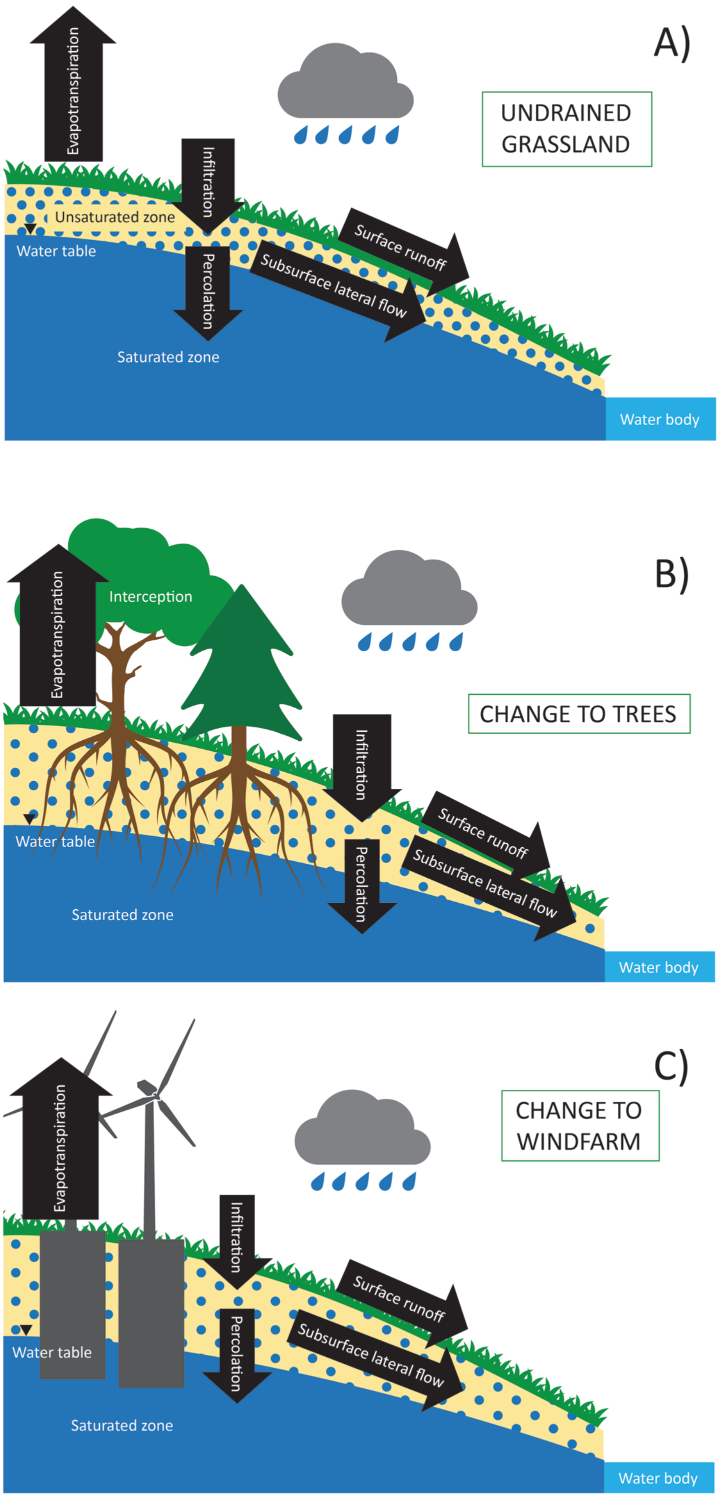

Figure 3: Schematic representation of the general impacts of implementing trees or wind farms, demonstrated by the major hydrological flows and stores in A) grassland B) after tree planting, and C) after wind farm development. The differences in the size of the arrows reflect relative increases or decreases in the fluxes.

different sources in terms of the direction of change. There are a few exceptions, especially for soil moisture, where 32% of studies showed that soil moisture was not affected, or, in some cases, increased. This could be attributed to increased infiltration or improved water holding capacity with increased organic materials (Inurreta-Aguirre *et al.,* 2022; Kumar, 2009; Seobi *et al.,* 2005). Also, although overall relatively smaller than for afforestation (see e.g., Coble *et al.,* 2020), the effect of agroforestry on evapotranspiration appears to be variable with 36% of studies indicating increased evapotranspiration while 27% indicate a reduction in evapotranspiration because of land use change to agroforestry. More research would be required to understand these differences, but they may be attributed to the variety of different agroforestry forms and the individual configurations.

Despite increases in infiltration, recharge to deeper (ground)water is typically locally reduced because of increased vegetation water uptake (Bharati *et al.,* 2002; Fernández *et al.,* 2002; Kay *et al.,* 2018; Pollock *et al.,* 2009). Again, there are several factors that determine the magnitude of effects, whereby the spatial orientation of tree planting appears to have a more dominant role for agroforestry. Dense strips of trees have shown stronger reductions in surface runoff (Bharati *et al.,* 2002; Kumar, 2009; Kumar *et al.,* 2012; Sharrow, 2007) than sparser configurations of trees. More concentrated grazing under trees has even been reported to locally lead to increases in surface runoff for silvo-pastoral systems (Mackay-Smith *et al.,* 2022). On the other hand, for forest strips, relatively stronger increases in infiltration rates could be expected for silvo-pastoral systems (Bharati *et al.,* 2002; Kumar *et al.,* 2012) compared to silvo-arable systems (Lawson *et al.,* 2019; Miller *et al.,* 1998; Wang *et al.,* 2011). In Wales, strongest reductions in peak flows were observed when tree strips were located in the uplands of a catchment (Marshall *et al.,* 2009).

Reductions in groundwater levels have been observed at local scales (Fernández *et al.,* 2002; Pollock *et al.,* 2009), including for cross-slope forest strips in Scotland where lower groundwater levels were reported beneath and downslope of tree planting (Peskett *et al.,* 2020). In some cases, increased water retention capacity has been linked to increased soil moisture locally, attributed to deeper rooting systems leading to higher potential infiltration (Kumar *et al.,* 2012; Wang *et al.,* 2011) and increases in organic material. Nevertheless, increased water demand of trees compared to crop- or grassland alone can counteract these effects in agroforestry systems (Bharati *et al.,* 2002; Coble *et al.,* 2020; Fernández *et al.,* 2002; Mackay-Smith *et al.,* 2022; Wang *et al.,* 2011). Together, these effects result in reduced river flow, especially of peak flows (Lawson *et al.,* 2019; Udawatta *et al.,* 2010; Wang *et al.,* 2011). Again, stronger reductions in water availability have been observed for integrating coniferous trees compared to deciduous trees on farmland (Lawson *et.al.,* 2019; Markwitz *et al.,* 2020). Pruning and thinning can reduce the impacts on water availability (Coble *et al.,* 2020; Mackay-Smith *et al.,* 2022).

3.4 Wind farms

Overall, the evidence for the effect of wind farms on water availability is low Appendix 4 – Figure A6, Figure A7 and Table A4. Appendix 4 – Table A4 provides a summary of the wind farm studies and reports included in this review. Most of the literature reports an increase in evapotranspiration by locally altering air temperature and humidity (e.g., Armstrong *et. al.* (2013), Baidya Roy *et. al.* (2004), Henschen *et. al.* (2011)). In addition to different geographical settings, the effects are scale-dependent because of the number, the size, density, height, and rotor diameter of wind turbines (Qin *et al.,* 2022). Armstrong *et. al.* (2016) found a very small increase (3%) in evapotranspiration for an upland wind farm (54 turbines) with forest and grassland, while Henschen *et. al.* (2011) reported up to 52% of increases in evapotranspiration a lowland site of the USA with 303 turbines. For a comparison study in China, Qin *et. al.* (2022) observed relatively larger effects on evapotranspiration where wind farms were built on grassland and cropland than in forested areas. For a study in Scotland, Heal *et. al.* (2020) reported reduced evapotranspiration after wind farm development, which was attributed to the felling of trees which were located at this site before. Effects are also spatially variable depending on the dominant wind direction, and relatively larger in the middle, then downwind, followed by upwind regions (Armstrong *et al.,* 2016; Fiedler and Bukovsky, 2011; Wang *et al.,* 2022).

Increased evapotranspiration is paired with reductions in water availability and reflected in reduced soil moisture (Baidya Roy *et al.,* 2004; Wang *et al.,* 2022) and groundwater levels (Gomes *et al.,* 2019), although evidence for this is sparse. Environmental impact studies by EnergieKontor (2020) for Craiginmoddie Wind Farm, South Ayrshire Scotland, and by Multiconsult (2020) for the Kuślin Wind Farms Project in Poland, both reported a potential risk of reduced groundwater levels and storage caused by land drainage or dewatering associated with excavations and access tracks during and after construction. Natural England (2010) drew similar conclusions specifically for wind farms located on blanket bogs. The foundation of turbines can also alter subsurface flow regimes and groundwater (Gomes *et al.,* 2019).

We found two studies in Scotland that report unquantified increases in discharge (Heal *et al.,* 2020; Millidine *et al.,* 2015) and three more reports mention potential increases (Fred. Olsen Renewables, 2023; ITP Energised, 2022; LUC, 2018). Such increases have been attributed to compaction of soil, artificial drainage of the site, and increased areas of temporary and permanent hardstanding increasing runoff. These effects could already be noticeable during the early stages of wind farm development during ground preparatory work (Headley, 2020; Heal *et al.,* 2020; LUC, 2018; Multiconsult, 2020), especially in areas of poorly draining soil (i.e., peat) (EDF Renewables, 2022; Millidine *et al.,* 2015).

While the overall evidence on the effects of wind farms is low, the literature suggests that water availability for PWS is likely to decrease (Appendix 4 – Figure A6, Figure A7 and Table A4). As for the effects of tree planting, local factors are likely to play a role, as has been evidenced for the effects on evapotranspiration internationally. Monitoring of wind farm effects on water stores and flows, including PWS, will be critical to characterizing the relative controls of local factors on water availability in Scotland.

4 Practice and policy review

4.1 General overview of policy guidance and recommendations

Appendix 5 – Table A5 includes a summary of the reviewed documents.

Literature exploring measures and guidance on preventing or mitigating impacts of land-use change on water supplies is limited. In the case of wind farms particularly, the most significant insights come from EIA documentation (e.g., (McKenna *et al.,* 2022; Wawrzyczek *et al.,* 2018) and other grey literature, including guidance documents, EIA technical reports, consultation statements and decisions, and associated policy documents. It should also be noted that full documentation of the EIA process is a critical source of information, but not all these documents are publicly available, limiting efforts to achieving a comprehensive understanding of impacts and action taken.

The management of impacts of afforestation and agroforestry is better documented, particularly via international collaborative projects. During the past decade there have been several projects from different EU programmes (e.g., INTERREG, LIFE, HORIZON) exploring how to minimise conflicts between the protection of drinking water resources and land use activities. Summary findings from some of these projects are included among the case study highlights in this report, and ongoing work in current projects will provide further insights (see Table 1).

Until recently, the focus of water protection in small supplies in Europe has focused on quality issues, rather than quantity (e.g., Rickert *et. al.* (2016)). For example, the Horizon 2020 project "WATERPROTECT" delivered an inventory of available mitigation and good practice options for the protection of drinking supplies from agricultural pollution (Marcinkowski *et al.,* 2019), with no reference to water quantity issues. This focus on water quality also applies to the Horizon 2020 project "FAIRWAY", the Interreg VA "Source to tap", and the JPI-Water "REFORMWATER". However, this might be changing, driven by the pressures on water scarcity associated with climate change. For example, in the EU, the 2019 Fitness Check of the Common Implementation Strategy (CIS) for the Water Framework Directive and the Floods Directive found that an increased focus on water quantity management was needed for climate change adaptation. Consequently the 2022–2024 work programme seeks to "help guarantee a stable

Table 1: Ongoing international projects that might deliver relevant advancements regarding measures to protect water quantity for drinking water supplies	
Project name and details	**Expected contributions**
LIFE URBASO: Forest based solutions for surface drinking water protection, biodiversity, bioeconomy and climate resilience (LIFE20, 2021–2025). https://lifeurbaso.com/en/	The project, set in the Vasque Country in Spain, is working on the development and implementation of forest management protocols and a network of nature-based solutions to optimize interactions between forests and water and protect both quality and quantity of water supplies in forested areas, including a novel approach to safeguard zoning around supplies ("PROSILVA").
BIOCONSENT: Decision-making Support for Forest Biodiversity Conservation and Restoration Policy and Management in Europe. Trade-offs and Synergies at the Forest-Biodiversity-Climate-Water Nexus (Biodiversa+, 2022–2025). https://www.bioconsent.eu/	The project will explore forest owners and land managers behaviour scenarios and developed integrated modelling tools that account for biophysical, social, economic and policy/governance drivers to quantify and assess the outcomes of alternative conservation and restoration measures on the provision of forest ecosystem services. From the documentation available, the extent of the water supplies focus is currently uncertain, but the integrated modelling and the ecosystem services approach make this project one to look forward to.
OPTAIN: Optimal strategies to retain and re-use water and nutrients in small agricultural catchments across different soil-climatic regions in Europe (Horizon 2020; 2020-–2025). https://www.optain.eu/	This project explores Natural Small Water Retention Measures (NSWRM) for adapting to drought and extreme weather events that might exacerbate conflicts between different land uses in agricultural catchments, including forestry and agroforestry, and other human and environmental demands for water, including drinking water supplies. The project, which builds in consolidated referent catalogues of water retention measures, is modelling scenarios with an optimisation approach for combining NSWRM and it counts with 14 cases, all using the same participatory methodology.
SOS-Water -Water Resources System Safe Operating Space in a Changing Climate and Society (Horizon Europe, 2022–2026). https://sos-water.eu/	It aims to define a "safe operating space" for water resources co-creating management pathways. The documentation available is still limited, but the project seems to have a clear focus on water scarcity and domestic water supplies appears as one of the thematic challenges addressed. Altogether with the integrated modelling and the development of advance indicators make this project one to look forward to.

and secure supply of drinking water, by encouraging the incorporation of the risks of climate change in risk analyses of water management", and to "ensure the availability of adequate quantities of clean tap water, through inclusion of climate change considerations in existing water management plans, the implementation of the revised DWD, and encouraging Member States to include climate change considerations in the DWD's risk-based approach" (CIS, 2021). Environmental organisations have called for a "new water and climate resilience law" that requires Member States to "create EU Natural Water Reserves to protect critical water supplies and their catchments in water-stressed areas" (Living Rivers Europe, 2023).

When focusing on wind farms and afforestation and their effects on water supplies, there is a qualitative difference that separates them: while the impacts of wind farm development on water provision are considered negative, and so to be prevented and mitigated (Wawrzyczek, *et al.,* 2018), afforestation is understood to also have positive and desirable impacts by securing water supplies (particularly improving quality if managed correctly) (FAO *et al.,* 2021; Mansourian *et al.,* 2018). Thus, while policy and practice measures on wind farms tend to be management measures focused on minimising negative effects on supplies, for afforestation there are also enabling policy and practice approaches focused on fostering and supporting positive impacts (e.g., schemes of payment for ecosystem services).

The country insights (see Appendix 6) cover a range of contexts (e.g., extent of PWS, different water scarcity pressures) in relation to the impacts of different land use changes on PWS. These range from small water supplies in northern Spain experiencing the effects of wind farm developments (similar to PWS in Scotland), to a focus on forestry related impacts on water supplies (centred around water quality) in Norway, Austria and Ireland. Concerns around the need to protect water quantity are emerging in Ireland and New Zealand that could lead to changes to policy and practice.

Alongside the sectoral-focused measures around wind farm development and afforestation projects detailed in the next sections, our policy review has identified several general policy measures that would help mitigate land use impacts on water supplies. These are:

- Enhanced policy coherence, with frequent cross-referencing of regulations and policies, particularly regarding roles and responsibilities of authorities (Cvejić *et al.,* 2023; Čenčur Curk *et al.,* 2019; Schmidt *et al.,* 2022).

- Integration of spatial plans and data (including catchment modelling) (Lukač Reberski, 2018; Čenčur Curk *et al.,* 2019).
- Integrated catchment-based policy, regulation and planning (FAO *et al.,* 2021 ; Rolston *et al.,* 2017; Vande Velde *et al.,* 2023) that also accounts for the buffer zones for water supplies (Courseau and Bojanowski, 2022).
- And enhancement of buffer zones (Schmidt *et al.,* 2022) and strict observance of regulations and implementation and inspection of restrictions in such protection zones (Vande Velde *et al.,* 2021; Čenčur Curk *et al.,* 2019).

Specific measures related to small water supplies, and relevant to PWS, include:

- Registration of all supplies to improve data availability (WHO, 2018; Schmidt *et al.,* 2022).
- Enhancing centralised support/supervision of supplies (WHO, 2018).
- Development of checklists and guidance material for monitoring the supplies (WHO, 2018).
- Building awareness at community level about impacts of daily practices and land use on their drinking water source (Deane and Mac Domhnaill, 2021).

4.2 Management and prevention of forestry impacts

A summary of measures identified regarding afforestation and forest management is provided in Table 2, with details provided in the subsections below.

In general, afforestation is seen as a desirable land-use practice and it is seen as an adaptation strategy to address drought risks and protect groundwater (Marcinkowski *et al.,* 2019; Mansourian *et al.,* 2018). Although with variations in species and afforestation design, it is being used as such in countries such as Austria, Germany, Spain, Hungary, Ireland, Italy, Latvia, Portugal, and Sweden; and planned in several others (Belgium, Bulgaria, Cyprus, Czechia Greece, Croatia, Lithuania, Luxembourg, Portugal, and Slovakia (Schmidt *et al.,* 2023). However, it is recognised that "if applied in drought-prone areas and depending on the previous land use, it can increase net water consumption and deteriorate the water balance" (Benitez Sanz *et al.,* 2023: 52).

Good forest management practices are necessary for protecting drinking water supplies (Brandstetter 2018) however, research has tended to focus on water quality. For example, there have been several research projects (Reducing the Effects of Forest

Table 2: Summary of measures identified regarding afforestation and forest management

Type of measure	Policy measures	Sectoral Measures
Preventive	• Requirement of good practice standards for the forestry industry • Requirements of harvest plans that account for PWS • Increased requirements regarding the environmental information that is required for an afforestation application • Enabling and flexible policy framework for adaptive forest management	• Use of appropriate broad-leaf species or other native species • Diversification of tree species and forest age • Change to chalk grassland • Appropriate buffers, exclusion zones and setbacks. • Limitation of forest roads, and when necessary, properly designed • Minimising soil erosion: avoiding tractor-skidder method, use of cover crop • Appropriate plans for harvesting • Observance of good practice standards for the forestry industry • Use of science-based tested checklists and decision-support tools to assist/orient actions • Increase engagement of consultant ecologists. • Exhaustive mapping that includes drinking water sources. • Reduction of tree density
	• Water-focused training to foresters and consultant ecologists. • Integration of data for supporting evidence-based planning and adaptation • Development of PES and PES-like schemes	
Adaptive & Reactive		• Implementation of NWRM • Reduction of tree density

Management to inland Waters (REFORMWATER), JPI-Water, 2019-2022; Surface waters: The overlooked factor in the forestry climate mitigation debate (SURFER), Research Council of Norway, 2017-2020) and several catalogues of good practice for water protection in forestry, agro-forestry, and agriculture:

- PROLINE-CE list gaps and Best Management Practices in the Strategy for the improvement of policy guidelines (Lukač Reberski, 2018). This catalogue includes measures for the protection of drinking water resources in relation to forestry and agriculture. The measures in this catalogue, along with those from other projects are integrated in the CC-ARP-CE tool (see box 1).
- Source-to-tap list of existing best practice in commercial forestry operations (McIntosh *et al.,* 2022) that reviews measures on afforestation, harvesting and replanting.
- OPTAIN catalogue of promising natural water retention measures (Lemann *et al.,* 2022).

Specific references to forest management for small water supplies catchments remain scarce: a 2008 FAO report (Hamilton *et al.,* 2008) noted that local impacts within small catchments receive little attention, despite this scale being appropriate for understanding the land-use and water interactions, and more effectively engaging stakeholders. However, four preventive or enabling measures identified in the afforestation and agro-forestry review that relate to water quantity were: consideration of tree species and number; zoning; forestry practices; and good governance and capacity building.

Box 1: Case study highlight on decision support tool for land use and water management

The toolbox CC-ARP-CE

Innovative online platform focused on adaptation of water management to climate change to support stakeholders in the integrated consideration of different fields of action in water management affected by climate change.

The CC-ARP-CE toolbox, which has been tested in nine pilot actions in 8 countries, aimed to integrate and harmonize results from previous projects on climate-proof management of water related issues in a unique toolbox that is useful for stakeholders in their adaption processes. The tool includes issues and measures for different types of land use, including forestry and agriculture, and in 7 fields of action that include among others drinking water supply management, water scarcity and drought management, and groundwater management. The catalogue includes It includes a catalogue of 163 measures that are shown according to filters and selection of weights of criteria (e.g., cost, multi-functionality, complexity of implementation) allowing to identify the measures that are most appropriate measures to support the stakeholders in their decision making.

The toolbox also includes a web map service with spatial orientation and information about expected variations induced by climate change in weather forcing, impacting water related issues by means of widely consolidated climate indicators, and also information related to the national tools for water management (Praprotnik Kastelic *et al.,* 2022).

This toolbox is a step-forward in the consolidation and harmonisation of data and results from different sources and projects in order to provide an integrated vision and advice to support land use and water management action.

Developed in the Interreg Central Europe project TEACHER-CE (2020–2022), led by the University of Ljubljana.

Available at: http://teacher.apps.vokas.si

Preventive measures

Types and number of trees:

The importance of planting species appropriate to the climate, and preferably native, and in the temperate European cases reviewed broad-leaf species are recommended rather than coniferous (Caretta *et.al.,* 2022; Nisbet *et.al.,* 2021; Stacey *et. al.* 2020; Van der Biest *et. al.* 2019). Tree species diversity is important (Boljat, 2018), as is diversifying forest age (Nisbet *et. al.* 2021).

Forestry and forestry management:

In planning and decision-making stages, observation of established and recognised good practice standards is recommended (Ministries for the Environment and Primary Industries, 2017; Skarbøvik, n.d.). These commonly include minimising the number of forest roads (Boljat, 2018), and where necessary, design these to a high standard (FAO *et al.,* 2021). Decision-making tools to assist forest management include the CISA field sheet/Blue Targeting tool (see Box 2), or decision matrix tools like the one developed by HOBO (Forest Management in Climate Change – Safeguarding the Soil Functions of Forest Ecosystems through Site-appropriate Timber Harvesting), funded by the Austrian forest Fund, for to help select harvesting technology (Kitzler and Walli 2022). Regarding actions on the ground, measures are oriented to minimising soil erosion (FAO *et al.,* 2021), for example by avoiding tractor-skidder method (Lukač Reberski, 2018) and using cover crop (Gallagher, 2018). For harvesting, measures recommended include thinning and appropriate plans for small coup felling (avoiding even-aged forests) (Natural Resources Wales, 2023) and incorporating water setbacks (Government of Ireland, 2021) and no clear-felling within protected zones. In Ireland, harvest plans should have maps detailing private water supplies (Department of Agriculture, Food and the Marine, 2019).

Zoning:

Emphasis was placed on the importance of appropriate buffers (particularly in riparian zones) (FAO *et al.,* 2021; Gallagher, 2018), exclusion zones (where felling and extraction operations are restricted) and water setbacks (Government of Ireland, 2021) and it is important that forestry operators know the exact location and extent of exclusion zones (Department of Agriculture, Food and the Marine 2019). The width of buffer zones will depend on site conditions (e.g., soil type). In the UK in buffer zones permit natural ground vegetation and the planting of suitable riparian tree species, but ground preparation and other forest operations are restricted to protect water quality, and the Forestry Standard (Forestry Commission, 2017) recommends minimum buffers of 50 metres around abstraction points for public or private water supply. Water maps developed using machine learning (e.g., wet area maps) might optimise the design of buffer zones, so they are adapted for local hydrology rather than having a fix width (WAMBAF n.d.).

Governance and capacity building:

Enhancing the information available for adequate planning is seen as vital. This includes locally relevant baseline information and resources required to support evidence-based plan and adaptation (FAO *et al.,* 2021; Creed and van Noordwijk 2018), that critically includes exhaustive mapping of drinking water supplies (Ministry for the Environment, 2023). The use of appropriate models also helpful to estimate effect of forests on water yield is recommended (Nisbet *et al.,* 2021) and new generation LIDAR can help delineate maps and buffer zones (WAMBAF, n.d.) (see Box 3).

Information is considered critical for planning, and so good practice measures could include increasing the scope of environmental information required for an afforestation application, resulting in increased engagement of consultant ecologists (Government of Ireland, 2021).

The review revealed the need for a flexible policy framework, based on science-based principles, that enables the selection of "the right tree at the right place at the right time", that is: adaptive forest management practice to respond to land use change and site-specific contexts, to ensure sustainability of downwind water supplies (Creed *et al.,* 2019; Mansourian *et al.,* 2018, Nisbet *et al.,* 2021). Such framework requires simple rules and regulations that can be applied consistently in different contexts and that are agreeable to all stakeholders (FAO *et al.,* 2021).

A potential good practice approach to governance would be to consider of payment for ecosystem services schemes (PES) and PES-LIKE schemes where consumers' payment is not voluntary (Nisbet *et al.,* 2021; Van de Velde *et al.,* 2023). However, it should be noted that most of the PES described in the documentation relate to the water quality benefits provided by forests, and that refer to large water supply catchments where private drinking water companies are the ones paying landowners, and so not directly comparable to PWS catchments. In any case, Vande Velde *et. al.* (2021) note that it is possible for PES to involve public sector as

Box 2: Case study highlight on tools for supporting forest management

Blue Targeting

Blue Targeting is a tool for best management practice for forestry along small streams. It was originally developed by WWF Sweden in collaboration with the Swedish Forest Owner association in the years 2007-2011 as the checklist for assessment of Conservation values, impacts, sensitivity and added value of streams (CISA checklist). Swedish companies owning large forest areas implemented it at a landscape level in pilot studies and since 2017 it is used by the Swedish Forest Owners Association when developing forest management plans (Henrikson, 2018).

Originally it was design for boreal and Scandinavian conditions and in 2019 was adapted for other forest conditions in Finland, Poland and the Baltic countries as part of the EU Interreg Baltic Sea Region project Water Management in Baltic Forests (WAMBAF). Within this project, the checklist was digitalised as a mobile app available on Google play in 7 languages. The app works as a checklist for the inventory of stream sections that can be filled while walking along the stream in a forest, and it provides an assessment of how wide the riparian buffer zone must be in order to ensure ecosystem services, including the protection of water supplies (Eriksson *et al.,* 2018). A continuation project, WAMBAF Toolbox (2019–2021) worked in extending the use of the tool among wider groups of stakeholders.

Available at: https://play.google.com/store/apps/details?id=com.lv.ces.silava.bluetargeting buyers, if proven that there is no private economic benefit or disturbance of international markets as a consequence.

Capacity-building measures include water-focused training to foresters and consultant ecologists (Government of Ireland, 2021) and Hamilton et al. (2008) noted the need of capacity building around PES, with guidance for stakeholders involved in schemes, and awareness-raising among the public.

Adaptive and Reactive measures

The implementation of Nature-based Solutions (NbS) or natural water retention measures (NWRM) in forestry and agroforestry developments is considered desirable to address impacts in groundwater levels (Courseau and Bojanowski, 2022; Van der Biest *et al.,* 2019). There are catalogues of cases studies of NWRM such as the nwrm.eu catalogue (Fribourg-Blanc and Bressan, 2017), that includes up to 14 forest sector measures; and the catalogue developed in the project OPTAIN that considers existing case studies within the database of technologies of the World Overview of Conservation Approaches and Technologies (WOCAT) (Lemann *et. al.,* 2022). In cases where afforestation has already had negative impacts on small water supplies, measures recommended are reducing tree densities, prolonging rotation cycles and conserving native trees in riparian buffer zones (Springgay, 2019).

4.3 Management and prevention of wind farm impacts

Table 3 provides a summary of preventive, adaptive and reactive measures for wind farms, with details provided in the subsections below. Several strategies can be considered in more than one category, depending on the timing of the implementation.

Preventive measures

Most of the measures are preventive and aimed at protecting at-risk water supplies from impacts. In most cases, the wind farm developer manages the activity, with relevant public body(ies) in a regulatory or oversight role. The main policy measures that consider impacts of wind farms on water supplies involve EIAs and associated regulations (e.g., zoning and buffer zones). However, the methods and level of detail expected from those assessments regarding impacts on water supplies seem undefined, with most of the detail being configured as guidance or recommendations, which sometimes use ambiguous terminology regarding the level of expectation of the action. We have identified preventive measures along the whole lifecycle of a wind farm development (from territorial planning and project design to decommissioning).

Territorial planning might enable, inform and guide the construction of a wind farm in specific spaces and set up the conditions for their development.

- Key instruments are **local development plans** and associated documents, which might include specific considerations regarding the development of wind farms and water supplies, to protect specific catchment areas around specific supplies (e.g., Donegal County Council, 2022).

The *design of wind farms* needs to conform to any regulations and planning specifications expected for the development of specific spaces. While the design of wind farms depends on the developers, it is guided by set criteria fixed in regulations and guidance.

Box 3: Case study highlight on integrated data portal

KliWES 2.0 Water Balance Portal and assessment of the impact of the climate changes predicted on the water and material balances in the catchment areas.

Portal on water resources that includes the model-based mapping of the water balance river catchments in Saxony including the influence of climate change on different water balance variables based on scientific models to evaluate scenarios.

The purpose of Kliwes is to enable decision-makers and stakeholders to identify the areas in need of adjustment strategies for water resources, agriculture and forestry. The portal allows to classify catchment areas by their water balance's sensitivity to the climate change and to give region-specific management recommendations to ensure sustainable management of the surface and groundwater resources. The user has the possibility to make direct calculations of the effects of specific land use changes on the water balance. (Probst and Schafranek, 2012)

The portal, which was first developed in 2008, requires regular adjustments and updating, with the last revision being done in 2019–2021 (Hauffe *et al.,* 2022) to ensure that the data is available online in an up-to-date and technologically sustainable way through a web application accessible at https://whh-kliwes.de/

Action details: Saxony, Germany. Since 2008. Developed by the Technical University of Dresden, with VISdAT and the Office of Applied Hydrology BAH (Büro für Angewandte Hydrologie) for the State of Saxony.

Table 3: Summary of measures identified regarding wind farm development		
Type of measure	**Policy measures**	**Sectoral Measures**
Preventive	• Zoning -regulating where wind farms can be developed or not, including the regulation of buffer zones. This includes local development planning considerations for specific areas • Requirement of EIA (details) and guidance and recommendations on EIA, engagement with stakeholders and continued monitoring	• Detailed understanding of the landscape and potential impacts. Identification and mapping of water resources and water supplies and users downstream. • Holistic consideration of impacts using integrated approaches, and monitoring of baseline conditions. Including consultations as appropriate • Identification of appropriate remediation or mitigation measures in place. • Training staff on water impacts. • Minimise drying out during construction. • Continuous monitoring and update study on hydrology and water use changes before decommissioning • Continued monitoring
Adaptive and Reactive	• Guidance and recommendations on peatland restoration, monitoring	• Continued monitoring • Rewetting (including naturalisation of channels, peatland restoration and other nature-based solutions)

Policy measures identified for this phase include specifications for the type and level of detail of information developers are required to collect related to the projected development site, including groundwater, abstraction points, and downstream users including PWS (e.g., in MITERD (2020), NatureScot (2019), Scottish Renewables (2015), Vasco (2021)). This is an important step towards assessing the **potential impacts of projects on water resources and existing water supplies**, in terms of water quality and quantity as part of EIAs (MITERD, 2020; NIEA, 2015; Scottish Water, 2022; Wawrzyczek *et al.,* 2018) and then translated into effective project planning to minimise impacts on existing water supplies (MITERD, 2020). This includes the identification of appropriate remediation or mitigation measures (MITERD, 2020; NIEA, 2009) that would be assessed by the competent authorities. **EIAs** in Northern Ireland, for example, require a detailed baseline survey of site conditions; identification of potentially sensitive receptors, including PWS, and assessment of potential impacts to groundwater, and proposed mitigation measures (NIEA, 2015). However, the language used is that all those elements "are expected" in the EIA, with little awareness of what happens if they are incomplete. McKenna et al. (2022) point out that EIAs for wind farms should draw up a complete balance sheet within a system framework, and that although there are promising examples, "these are limited in number as well as in terms of their focus on specific impact categories" (McKenna *et al.,* 2022).

A critical policy measures guiding wind farm design is the **requirement of buffer zones for water features**. In Northern Ireland and Scotland there is an established 250 m buffer for water features used for both private and public drinking water supplies (NIEA, 2009; SEPA, 2017a) which has been criticised for overlooking regional differences (McKenna *et al.,* 2022). It is noted that these buffer distances

Box 4: Case study highlight on identifying and documenting PWS.

Methodology for identifying and mapping PWS and developing tailored sustainability plans.

Building on insights from a previous LIFE project, the council of Abegondo (Galicia, Spain) aimed to strengthen the sustainability of rural water supplies that were facing quality issues. It developed a methodology to map and identify PWS and assess their risks. And in a second phase, it supported and funded the development of improvements in the supplies that committed to the sustainability plan.

Development of tailored sustainability plans for PWS to secure the water supplies (Life Rural Supplies, 2018). These plans are focused on technical and economical sustainability of the supplies and included participatory processes.

Although the main focus of this project was on managing quality risks, the methodology for identifying and mapping PWS might be useful.

Initially EU funded through the Life project "Rural Supplies" (LIFE12 ENV/ES/000557), the project included the regional government a key stakeholder. The project methodology has since been transferred to other local authorities in Galicia and the regional government is providing some funding to help PWS communities to adopt sustainability plans.

for wind farms are generally larger than for woodland creation and felling/restocking. In addition, regarding public supplies, Scottish Water (n.d.) asks that all infrastructure and activities should be located 100 m from any watercourse where possible, and a minimum of 50 m distant where 100 m can be demonstrated to be undeliverable; and it also recommends applying 50 m buffers to watercourses and to springs, wells or boreholes rather than 10m buffers (Scottish Water, n.d.). Regarding zoning (protected areas and safeguard zones), it is important to note possible inconsistencies in the use of the terminology as highlighted by the CIS in the EU. The CIS highlighted the need for more clarity, particularly "concerning the further explanations of the expression "identification" CIS (2021), p. 24), and it also denotes that "a large variety of delineation criteria's (vulnerability, catchment area, model, residence times) are applied in the different countries, but that within the same criteria there are significant differences".

Reviewed guidance advises **consideration of sustainable drainage** (SUDs) options for safe-guarding water resources (e.g., settlement ponds and designated filtration areas) during project design (Scottish Water (n.d.)).

Stakeholder engagement is another measure advised in the policy documentation reviewed. Scottish Water recommends effective **planning consultation** during the design phase (Scottish Water, n.d.) and to develop detailed **specific site planning (including Peat Management Plan, Drainage Plan) to be shared with other land-users** in advance to the works (Scottish Water, n.d.). However, while this might be feasible when planning the work with a public water supplier, engagement with an uncertain number of PWS users might be not so straight-forward. Scottish Renewables also recommends the production of a water management plan at this stage (Scottish Renewables, 2015).

In the *implementation stage* of a project, including construction, the policy measures identified are the responsibility of the developers.

Several actions are focused on the **prevention of the drying out of peatlands and wetlands during construction** (Scottish Renewables, 2015; Statkraft, 2022). Project design should encourage diffuse movement of water across the site to preserve local hydrology (NatureScot, 2019; Scottish Water, 2020). Scottish Water (2020) recommends, for example, the construction of floating access tracks with adequate provision for maintaining existing drainage patterns. Scottish Water (n.d.) also recommends the **provision of specific induction training** to on-site staff regarding site sensitivities in relation to drinking water catchments and infrastructure.

Continued monitoring, including groundwater monitoring, is a necessary instrument to enable risks assessment and adaptation requirements (RenewableUK, 2022).

For *decommissioning stages* of a project:

The measures identified highlight the need for **updating the understanding of a site's hydrology** and any changes since construction (regarding rainfall, hydrological and hydrogeological settings and habitats on site and downstream, and **water users** to determine the appropriate decommissioning strategy and mitigation measures (Welstead *et al.,* 2013). The EIA included in the original planning application should include impacts regarding decommissioning, but Welstead *et. al.* (2013) flagged up that "a more detailed RDP would be beneficial to understand the impacts and options more fully" (Welstead *et al.,* 2013).

Adaptive measures

So far, the review identified two types of adaptive measures: monitoring and different types of rewetting. In both, the policy role is limited to offering guidance.

- **Continued monitoring**, including groundwater monitoring, would be a necessary instrument to facilitate any adaptation or restoration needed (RenewableUK, 2022).
- **Rewetting** (see Box 5), including **naturalising channels** (e.g., creation of irregular streambeds that favour the concentration of flows in low water, alternating water retention areas with areas of current movement), would be advised where works involve the alteration of water courses (MITERD, 2023). It is noted that in Scotland any form of engineering of water courses would require appropriate formal authorisation from SEPA. **Peatland restoration** (see Box 6) is another specific measure widely encouraged (e.g., Scottish Water (2022) and for consideration by wind farm developers, but this "needs to be more widely applied and better enforced" (Bain *et al.,* 2011). Lunt *et. al.* (2010) pointed out the need to improve knowledge on the impacts of peatland restoration as "claims of minimal impact are not supported by consistent, long-term monitoring of

hydrological impacts and there is an urgent need for the renewable energy sector to address this" (Lunt *et al.,* 2010). (RenewableUK, (2022) recommends that to ensure that best practice is used on wind farm sites, "a reference to the Peatland Code booklet Conserving Bogs: The Management Handbook should be added to the good practice guidance". Examples of peatland restoration include the Vattenfall's Pen-y-Cymoedd onshore wind farm in Wales and Quantans Hill in Scotland (Vattenfall, 2022), and the Glendevon Wind farm (Scottish Water, 2022), although we do not know yet about the presence of PWS in these areas. Scottish Water encourages the consultation of stakeholders when planning peatland restoration projects (Scottish Water, 2022).

Reactive measures

- The review so far has identified only one type of reactive measure, which is **rewetting-, linked to critical cases of peatland restoration** (Boxes 5 and 6, respectively). Statkraft (2022) mentioned significant peatland restoration in the case of a wind farm extension following a wildfire across the site in 2019 (Berry Burn Wind Farm). Their management plan aims to raise the water table by using several techniques that includes the use of peat excavated during the construction of the development for blocking a network of drainage grips located within the site.

The review did not identify any policy measures relating to water scarcity affecting water supplies linked to wind farm development.

Box 5: Case study highlight on implementation of nature-based rewetting solutions with a preventive/ adaptive approach.

Leaky barriers at Glenlivet.

Implementation of leaky barriers – a Nature-based Solutions (NbS) approach – in the Blairfindy catchment to provide resilience to low water availability for PWS that supplies the Glenlivet distillery and several private users.

The whisky industry in Scotland is growing as demand for the product increases. Glenlivet distillery has recently increased its production capacity and the distillery is also mindful of future climate projections which show water scarcity could be an issue in the summer. They are interested in NbS measures which could help improve low flows but also keep the water cooler during summer months. As a result, they have invested in a trail of leaky barriers as NbS measures which hold water temporally (Roberts *et al.,* 2023). The study benefited from a UKRI funded PhD research project. Scientists at University of Aberdeen and James Hutton Institute have monitored and modelled these measures, and the results show a positive benefit to low and high flows (Fennell *et al.,* 2022). They have also conducted a cost-benefit analysis (Fennell *et al.,* 2023). Chivas Brothers funded the implementation of the measures (privately funded). They engaged with nearby landowners and other stakeholders.

This is a rare empirically informed experiment located in Scotland that assesses how NbS approaches impact on low flows. The research has shown that the role of place (i.e. placing measures on correct soil types) and size (i.e. dispersed storage across a landscape) are important considerations for planning NbS approaches.

This project has been developed by Chivas Brothers, Glenlivet Distillery, Moray, in collaboration with the University of Aberdeen and the James Hutton Institute since 2018.

Box 6: Case study highlight on peatland restoration in Scotland.

Peatland Action Restoration.

The Peatland Action Programme, in development since 2012, has developed a wealth of case studies of peatland restoration across Scotland and provides an experience-based compendium of techniques describing best practice and associated guidance and training material. The compendium (NatureScot 2022) is accessible online along with other resources at https://www.nature.scot/climate-change/nature-based-solutions/peatland-action/peatland-action-resources/peatland-action-project-resources

The Peatland Action Programme also involves a varied number of key stakeholders in afforestation issues. For example, Forestry and Land Scotland, is one of such agencies involved of Peatland Action, and it is also actively involved in developing peatland restoration projects. Forest Research is currently monitoring the water quality changes in freshwater at one of those projects in southwest Scotland (Shah, n.d.) for which results are expected soon.

5 Workshop summary

While discussions were focussed on mitigating impacts on PWS from wind farms and afforestation, many suggestions related to improved approaches to land use planning more broadly, and PWS related risk awareness and management. The policy and practice improvements discussed during the workshop tended to align with those identified in Section 4 (Practice and Policy Review) indicating shared issues and associated opportunities for improvements to policy and practice. The overarching themes that emerged from the workshop were:

Climate change, and integrated land use policy and planning

The workshop attendees acknowledged the overarching challenge of current and predicted climate change impacts on water availability in Scotland, and that elements of Scotland's climate change mitigation policies influence land use decision-making, the implementation of which can subsequently impact on PWS. Consequently, there is a desire for wind farm, forestry, and agricultural policy that is coherent across scales, and importantly, that considers catchment scale pressures on water availability for PWS in the context of broader landscape and climate characteristics. There was a commonly expressed need for: policy to better define good practice for land use change implementation; a strengthened legal framework defining reporting requirements for the design, construction, and management phases of wind farms (including associated infrastructure); improved enforcement of existing regulations relating to development impacts; and provision of risk mitigation options in relation to land use change development impacts on PWS.

Improved legislation to enable local authorities to compile more comprehensive registers of PWS, and to provide easily accessible support and guidance for PWS users in line with their rights and responsibilities

While most PWS users are exposed to risks related to both water quantity and quality, many are being impacted by developments associated with land use change. Discussions highlighted the need for legislation and resources to allow local authorities to provide improved risk assessments for PWS users, more effective technical and financial assistance, and clarification of PWS users' rights and responsibilities in relation to PWS. Support for local authorities to compile more complete registers of location and type of PWS and related infrastructure (including both regulated and unregulated supplies) would provide a valuable resource to inform land use planning specific to the needs of their location and form a key component of a PWS related data repository (see below). Ideally, changes to PWS legislation would align with the development of more coherent policy and practice around the planning and implementation of land use change.

Local Authorities to be able to more effectively fulfil their statutory risk assessment role in relation to wind farm and forestry developments

The delegates flagged shortcomings in Local Authorities' ability to implement statutory risk impact assessments in relation to wind farm developments and afforestation. While acknowledging issues around resourcing these activities and balancing trade-offs, several needs were identified including improved: cross-project coordination; ground truthing of desk-based site assessments; monitoring of impacts of primary and subsidiary works; processes for agreeing actions to mitigate impacts; and cross-sectoral understanding of the vulnerability of groundwater resources and PWS to land use change associated impacts.

Shared understanding of policy and practice needs across LAs, sector operators (including contractors, consultancies, funders (government and private), and regulators

Several local authorities have significant experience of land use change related impacts on PWS. These are often related to a project's development phase where mechanical damage to PWS infrastructure can occur due to insufficiently detailed maps, lack of understanding of risks, ineffective monitoring, and poor communication between stakeholders on the ground. This was thought to be exacerbated by a lack of shared cross-sectoral knowledge and awareness of land use impacts on PWS and inconsistent use of PWS terminology. These experiences form a basis for improvements to knowledge sharing, practice, and regulatory oversight, and recognises the need for specific training for PWS related staff, more effective use of existing guidance including **relevant UKFS practice guides and the specific Forestry & Water Scotland guidance on protecting PWS**

during forestry activities production of practical guidance, and public awareness raising around PWS management and land use change.

Developing a repository of spatial information to underpin cross-sector policy and practice in relation to land use planning and management and considering PWS

Most discussions referred to the need for a spatial database accessible to all relevant stakeholders. This would assimilate already existing data relating to land use planning, improved mapping of data relating to all PWS infrastructure, PWS catchment hydrology, and be enhanced as further data became available (e.g., from ground truthing work, effective monitoring of development and management processes). As data types and layers were incorporated, they would inform cross-sectoral decision-making across scales and stages of land use change.

Ongoing collection of new data would allow the repository to improve in its use, and fitness for purpose. This links to discussion around the requirement for improved monitoring of wind farm developments, to build a more robust evidence base relating to impacts on water availability, and to inform decision-making and policy implementation.

Caveats and considerations

While the workshop focused on challenges to PWS from land use change, and recommendations for resolving these, there were two notes of caution in relation to managing expectations. One related to managing trade-offs between national level policies and strategic objectives in relation to governing water rights, climate change mitigation and associated land use changes, which might impact on local level decision-making and differently aligned stakeholder priorities. The second was more prosaic: many of the recommendations require input of resources (particularly personnel and funding) to allow local authorities to fulfil their statutory duties, collect and manage PWS information, engage with land use development operatives and consultants.

Evaluation of the workshop revealed a strong desire to continue the conversations and build cross-sectoral engagement (including additional stakeholders) to progress coherent strategies for managing water availability in PWS catchments subject to land use change.

6 Other projects and initiatives

There are several ongoing projects and initiatives that are relevant to this work. These include:

- CRW2023_05: Future predictions of water scarcity in Scotland: impacts to distilleries and agricultural abstractors
- RESAS JHI-D2-1 Emerging Water Futures: Resilience of Private Water Supplies – Understanding of rural communities' vulnerability and risk perceptions to water scarcity and variable water quality (2022-2027)
- RESAS JHI-D2-2: Achieving multipurpose nature-based solutions
- RESAS JHI-D5-2 Climate Change Impacts on Natural Capital – includes high spatial resolution assessments of potential changes to water availability due to climate change.
- RESAS JHI-C3-1 Land Use Transformations – considering how land use can transform to meet multiple objectives, particularly for Net Zero aims.
- RESAS JHI-C5-1 Integrated socio-environmental modelling of policy scenarios for Scotland – includes on-going development of the Land Capability for Agriculture classification systems under future climate projections.
- MDT Fellowship on Rural Water Security by Diana Valero at the James Hutton Institute
- FARM TREE project, funded by the UKRI Treescapes programme (FARM TREE) which explores the socio-economic and environmental effects, including water availability, of agro-forestry in Scotland (University of Aberdeen, James Hutton Institute)
- Hydro Nation PhD Scholar 2023–2027 on the role of groundwater in adapting to climate change and increasing resilience to drought in Eastern Scotland (University of Aberdeen, British Geological Survey, James Hutton Institute)
- The development of the 'Woodland water code (+)' by Forest Research
- Forest Research is also working on a project that explores the impact of woodland on water resources for the Environment Agency. This includes a literature review, a set of conceptual models, a spatial mapping report, an R-shiny app for estimating impacts (drawing on gridded data derived from the JULES model) and draft guidance.

7 Recommendations

1. **Careful consideration of local assessment and management strategies** for tree planting and wind farm development, both at short- and longer-term scales. This requires ground truthing of desk-based site assessments, monitoring of impacts of primary and subsidiary works, and processes for agreeing actions to mitigate impacts. While water availability could decrease in response to tree planting and wind farm development, the relevance and magnitude of effects for PWS depend on various local factors. PWS that could be expected to be most affected are those that rely on relatively shallow sources on thin soils/superficial geology located downstream of large wind farm developments or coniferous plantations. In these and other places, provision of risk mitigation options could involve improving catchment storage potential with nature-based solutions that also improve wider ecosystem resilience.

2. **Addressing the lack of integrated land use planning and management that accounts for private water supply.** Specifically, this requires cross-sectorial and cross-project coordination and involves a coherent consideration of wind farm and forestry policy and appraisals alongside agricultural policies, across scales. This should include reference to existing guidance within the UKFS, relevant practice guides, and specific Forestry and Water Scotland guidance on protecting PWS during forestry activities. It is essential to consider catchment scale pressures on water availability for PWS in the context of broader landscape and climate characteristics.

3. **Addressing knowledge gaps:**

Water scarcity:

A) The literature reports predominantly on the effects of tree planting and wind farm development on catchment scale water balance components, but studies that monitor the effects on PWS directly are lacking. Monitoring and research that considers water demand factors would be required to be able to quantify associated PWS risks to land use change.

B) Especially for the effects on groundwater resources, and subsequently, on groundwater sourced PWS, more evidence is needed, as much of the evidence for Scotland has been collated indirectly (i.e., effect on potential groundwater recharge not actual recharge or storage), or from modelling results. C) Literature on the effects of wind farm development on water availability is also scarce. More empirical research is required to address these fundamental knowledge gaps. Monitoring of wind farm effects on water stores and flows, including PWS, is critical to characterizing the relative controls on water availability and scarcity.

Policy and practice:

A) Assessment of the implementation and efficacy of the measures currently being implemented in Scotland, or the UK more widely, would be necessary to fully consider measures already in place and the potential for consolidating existing good practice and learning from other experiences. B) Improvements are recommended to regulations of PWS users' rights and responsibilities to enable the development of policy coherence and integration with other policies and legislation governing land use change developments, climate change adaptation and mitigation, river basin management, and water policy. This would help provide clarification for decisionmakers and consultive and regulatory bodies, including local authorities fulfilling their statutory responsibilities, when considering trade-offs and mitigation options.

4. **A shared repository of data and information** is critical for addressing the points above and will help to create shared understanding of the potential impacts of land use changes on PWS. A more complete register of location and type of PWS and related infrastructure (including both regulated and unregulated supplies) would provide a fundamental resource to inform land use planning. This should be complemented by a spatial database that assimilates already existing data relating to land use planning, PWS catchment hydrology, and be enhanced as further data becomes available (e.g., from ground truthing work, effective monitoring of development and management processes). Likewise, easily accessible support and consistent guidance for PWS users in line with their rights and responsibilities needs to be provided.

5. **A continued process of stakeholder involvement and knowledge sharing.** Building on the project workshop as a forum to outline future pathways, participants expressed a strong desire for a continuation of this process and thereby improve knowledge sharing, good practice examples and guidance, and regulatory oversight, and public awareness raising around PWS management and land use change.

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Appendix 1 – Workshop report

Report: CREW Workshop on 'Land use effects on water availability: policy and practice implications in relation to Private Water supplies'

Date of workshop: 18th January 2024

Introduction

The workshop is an essential part of CREW project 'Understanding the relationship between water scarcity and land use in private water supply catchments – a review'. The overall project aims to collate an evidence base and provide recommendations for land use change effects on water scarcity in private water supply (PWS) catchments. It focuses on emerging land use change trends in Scotland that include tree planting and management (afforestation and agroforestry) and wind farm development. Specific project objectives are:

1. To collect and review the available evidence on the effects of tree planting and wind farm development and management on water availability.
2. To carry out an international review of PWS policy and practice in relation to these land use change effects.
3. To consult with stakeholders to identify and co-create recommendations for PWS protection, policy, and implementation solutions in relation to the land use changes that might operate at different scales.

Hereby, the workshop focused specifically on objective 3.

This workshop enabled the participants to hear about the interim findings from the project's evidence-review and to engage in discussion around what improvements might be required in relation to policies and practice relating to private water supplies (PWS) and land-use change (LUC). The discussions involved facilitated sessions to:

- Identify coherent policy and regulatory pathways for wind farm development and afforestation that support the provision of private water supplies.

- Identify good practice land use management strategies, particularly those in relation to wind farm and forestry expansion, that may maintain water availability for private water supply security.
- Provide recommendations on where and what mitigation strategies might be appropriate in cases where potential negative effects on water availability may arise.

Venue and organisation

The workshop took place in Perth, a central location that was purposively selected to make it easier for stakeholders from across Scotland to travel and participate in the day. The workshop was held in two rooms at the AK Bell Library, which is located within five minutes' walk from the railway station. The Sandeman room was used as main venue and hosted the registration, plenary sessions, coffee-breaks and the discussions of two breakout groups. The smaller Mackenzie room was used as a quiet room when needed and hosted the discussions of the third breakout group. There were dedicated boards for parking spaces in the main room and the small room, to note points of importance but beyond the scope of the workshop.

The workshop was organised and lead by Keith Marshall (Hutton). The facilitator team included Diana Valero (Hutton), Eva Loerke (UoA), and Rebekah Burman (CREW). The project PI (Josie Geris – UoA) and project manager (Maureen Whalen – CREW) were also present and supported the running of the workshop.

Selection and engagement of participants

In consultation with the Project Steering Group (which involves representatives for Scottish Government, DWQR, and SEPA), we identified policy and practice stakeholders representing a range of relevant views and sectoral interests. They included those concerned with site specific issues (e.g., Local Authority environment officers) and those with a strategic understanding relating to their sites (e.g., Scottish Water), and government agencies responsible for providing guidance and regulatory oversight.

Following a review of the workshop plans by the James Hutton Institute Research Ethics Committee (JHI-HRE-0201–333), stakeholders were invited to the workshop by email, which included an information sheet about the project's remit. Prior to the workshop a summary of the project's preliminary findings, a consent form, and instructions for a brief task were sent to those who had agreed to attend.

Consent forms captured the participants understanding of how the workshop was going to be developed and agreement for contributions to be processed in the form of notes and photos. Consent forms also offer the possibility for participants to choose how they wanted to be identified or not in the project outputs as participants in the workshop: by real name and role, only by role, or with their participation kept confidential.

Participants in the workshop included representatives from Scottish Government (Water Policy) and national public bodies (DWQR, SEPA, Scottish Forestry, Scottish Water), Local Authorities (Highland, Argyll and Bute, South Ayrshire and Scottish Borders), and several sectoral organisations (e.g. SP Energy networks), related CREW research (University of Dundee) and consultancy.

Several other stakeholders were invited to the workshop but were unable to attend. These included other local authorities, and organisations representing landowners with development interests and PWS on their land. Following the workshop, these stakeholders were contacted on January 23rd and given the opportunity to contribute, in writing, to the questions that were discussed in the workshop via an electronic involvement form. We received one written response from a Local Authority by our 5th February deadline. This has been reviewed, and where appropriate incorporated into this draft report.

Methods

Workshop tools and approach

The workshop combined plenary sessions and group activities with focused discussions first in relation to wind farm development and PWS, and then afforestation and forest management, as detailed in the participant's agenda. An information sheet outlining the project findings to date, which were presented in more detail in the first session of the workshop, was sent to participants in advance, along with a request to think about what they perceived to be key challenges in relation to managing land-use change impacts on PWS.

For thematic discussions, participants were split into three groups. The distribution of groups was prepared in advance to ensure a mix of stakeholder types in each. Two of the groups had their discussions in the Sandeman room, and the third one was held in the smaller Mackenzie room.

Upon arrival, participants were welcomed and provided with a summary agenda for the day, a CREW notebook, a badge with their name, organisation, indication of the groups they were assigned for the morning and afternoon breakout sessions, six coloured dots, and three post-its. Stakeholders were given different coloured post-its (green for Local Authorities, blue for Scottish Government and related public bodies, and red for sectoral representatives).

Sequence of Activities

3 key challenges task

Participants were asked to use their coloured post-its to record their three key challenges regarding land use and water scarcity for PWS, and to place them on a board located at the entrance of the main room. A member of the team grouped the challenges during the presentation time and participants could make additions and edits during the day.

Presentation of interim findings (biophysical and policy) – plenary questions

Members of the research team provided an overview of the project scope, its interim findings, and answered questions. Dr Sarah Halliday, PI of a closely related CREW project (CRW2022_07 - Climate Crisis: informing Scotland's actionable mitigation and adaptation response to water scarcity) gave a summary of their work to help contextualise current CREW research around water scarcity and availability.

Good practice examples

During the policy presentation, participants were pointed towards the board provided for capturing good practice examples and asked to use post-its to add examples of cases and/or measures that they considered relevant. Participants were reminded of the board during the group discussions and made additions and edits during the day.

Wind farm and forestry breakout sessions

Specific land-use discussions (the first around wind farm developments and the second focussing on forestry and afforestation) were held to identify practice and policy actions required to improve outcomes for PWS. These discussions responded to the same questions posed in three parallel breakout groups of five-seven participants each, plus facilitator (breakout questions are detailed in the results section below).

The three breakout groups were facilitated by a member of the research team (Marshall, Valero) and a member of CREW (Burman). Participants were encouraged to write their inputs on post-its and share them on a dedicated flipchart for discussion in the group. Facilitators took general notes about the discussion where possible.

Priority actions

At the end of each discussion session, after practice and policy were discussed, participants in the groups were asked to use two or three of their coloured dots to identify the measures that they considered priorities, or more critical to progress.

Plenary feedback

Feedback on key points was provided at the end of breakout sessions by a participant from each group, followed by a brief discussion (facilitated by Marshall and scribed by Valero).

Pathways

Following the land-use-focused discussions and prior to the final plenary discussion participants the breakout groups were asked to reconvene for 20 minutes to discuss what changes might need to occur first to facilitate subsequent improvements. Using a simple 'timeline', they were asked to write actions they felt were necessary for implementing change, and if possible, indicate the order in which they should happen so that dependencies might be explored.

Workshop findings

Stakeholders' key challenges

Participants three key challenges, as provided with post-it at the beginning of the workshop on a dedicated board, captured a wide range of issues regarding impacts of land use changes in PWS and water scarcity more generally. These insights capture the range and complexity of the issues at play.

The issues identified on the board as written down by participants are arranged here under general themes:

- **Climate change impacts on water resources,** and in particular water scarcity even if contrary to the perception of not being an issue, and the compound effects of heavy rainfall events after prolonged drought.
    - o Sleepwalking into scarcity
    - o Climate change projections + impacts on PWS + on measures to protect them

- Long periods of drought then heavy rainfall events creating more run off. Scouring of topsoil and sediments due to soil dehydration
  - The perception that water scarcity is not an issue or that it exists in Scotland
- The **impacts of climate change policies** (and other environmental policies, e.g., biodiversity) on land use and indirectly on water resources, and the need to establish some sort of hierarchy and balance between targets, different land uses, and resources.
  - Determining the balance for forestry and wind farms when it comes to achieving our climate change targets - hierarchy of need
  - Defining what is proportionate in terms of land use change for bigger picture (national) priorities and (versus locations with) small number of PWS
  - Understanding of how land use change will interact with water resource challenges and how effective adaptation will be
  - Comparing potential effects from wind farms compared to existing land use (forestry, farming, etc)
  - Challenge in determining a balance of appropriate nature-based solutions (forestry) that can address flood and water scarcity. Look at hydrological extremes together and not in isolation
  - Biodiversity measures now required on projects, but this may interfere with PWS
- **Shortcomings on integrated planning** that integrates national, and local scales, wind farms, forestry and agricultural policies, and that considers catchment pressures, landscape and climate characteristics.
  - No overall national strategy for wind farms, forestry or agricultural sustainable management based on catchment pressures. Right tree, right place? Right wind farm, right place? No assessment of cumulative impacts of such developments, very much standalone site appraisals
  - Integrated planning policy: local, national, forestry, energy
  - Coordinated planning: how can competing demands be balanced in an equitable way
  - Tailoring land use planning to reflect regional climate variability and landscape characteristics. One size may not fit all
- **Shortcomings in Local Authorities' statutory risk impact assessment[1] processes and following development** of wind farm or forestry projects: lack of cross-project coordination; shortcomings relating to impacts of subsidiary works; lack of ground truthing assessments; limited understanding of vulnerability of groundwater resources, monitoring needed for mitigation.
  - Lack of integration: Permitted developments adjacent to wind farms but different assessments, identification, etc
  - Monitoring: What effective monitoring we can propose as part of mitigation
  - Risk Assessing catchment areas in a meaningful way, that also demonstrates impact or otherwise on individual supplies, and carrying out of mitigation and acceptance of impact by large organization's when things go wrong, and supplies are affected
  - Risk impact assessment - first joint visit crucial. Informs, stops time wasting. Ground truth for all
  - Installation of permanent features such as concrete foundations, roads, etc. causing changes in the water table and/or inhibiting movement completely
  - Better understanding of implications for groundwater resources/vulnerability of groundwater resources
  - Linear developments cut off/transfer water from PWS
  - Resolution for loss of supply - lack of mains infrastructure, no options for connection (Reliance on replacement PWS with associated costs, timescales, health impacts (physical and mental) practicalities, permissions and future resilience).
  - Investigation of complaints involving loss or contamination of the supply. Typically, no baseline or detailed appraisal of supply characteristics to measure or identify impact
- **Shortcomings in the general resilience of PWS**, not only regarding water scarcity but also water quality issues, linked to elevated costs and lack of awareness of risks and guidance.

[1]The term 'risk assessment' refers to that which it is the statutory duty of the local authority to undertake on regulated PWS

- o Need to address poorly set up PWS systems with no resilience built in for land use change or climate changes. Householder awareness + education via simplistic PWS handbook or guide would help. Tie in with legal home sale obligations (Home Buyers Report and legal title deed search of burdens and servitudes) and improved Grant Scheme accessibility to resolve the issue
- o Maintenance and management of a PWS due to elevated costs - lack of possible policy and legislation
- o Removing the public's (and others) reliance on sampling as an indication of compliance or risk: "end product testing" does not ensure safety of product (water)
- o Including quality issues
- o Are there also quality issues?
- o PWS becoming contaminated with bacteria, parasites, etc. due to potential land use and climate change

- **Limited knowledge and awareness of PWS issues and land use impacts on PWS**, flagging the need for specific training for PWS related staff, the production of practical guidance, and public awareness raising in general regarding pressures and land use changes.
  - o Training/education as new officers coming through often not met a PWS before
  - o Ensuring all involved fully understand the vulnerabilities of PWS and the difference between them and mains supplies, throughout organisations and their contractors, right down to ground/field level
  - o Producing practical guidance
  - o Need to address public distrust of land use changes + pressures + poor consultation communication. Use of social media to "sell" the benefits and rationale behind national targets urgently required. Education + communication issues apparent.
- **Public distrust** of land use changes and **challenges of engaging** with PWS users.
  - o Need to address public distrust of land use changes + pressures + poor consultation communication. Use of social media to "sell" the benefits and rationale behind national targets urgently required. Education + communication issues apparent
  - o Identifying PWS especially where residents do not want to respond to queries
  - o How LA's respond to concerns from PWS users regarding the potential impact or potential development/land use change. Uncertainties around roles and responsibilities for different organisations.
- Varied **regulation of PWS**.
  - o Legislation - single legislation to cover all PWS regulated and exempt and all human consumption
  - o Single or unified legislation

Other comments flagged wider concerns such us the impacts of land use change on rural communities and the need to reflect on water use rights. One comment flagged the need for national level mapping, and another the possibility to extend catchment protection zones. One participant reflected that difficult decision-making was needed at policy-making level.

Discussion following plenary biophysical and policy talks

The talks outlined the details provided in the information sheet which was circulated to participants in advance. In response to the biophysical talk, we received:

- A question asking for clarification on why wind farms could increase evapotranspiration. It was described that this relates to a modification in the vertical energy and moisture distribution.
- There was a comment in response to the wind farm map which showed current and proposed wind farms at different stages of development across Scotland. A desire was expressed to have a live version of such a map available in an accessible place.
- A comment about the accumulation of impacts of different land use activities at different times and/or different locations within a catchment. A desire for defining tipping points was expressed. The discussion that followed indicated the complexity around this issue and a need to be careful with such general approach, as any such tipping points would be different from site to site.

The presentation on the policy and practice review received the following comments:

- There is a lack of integration between EIAs that are prepared for different elements of a wind farm development (e.g., the wind farm itself, powerlines), and for wind farm development alongside forestry. The legislation does not require for EIAs for related projects to be linked or integrated, and this should be considered. The model that is followed for housing development was mentioned as a good example where this is done better.
- There is a need to ensure that the mitigation activities written into EIAs is acted upon. There is a need for transparency of information (and sharing information) in general.

BREAKOUT SESSIONS

Responses for each question asked of the participants are grouped by theme, with direct quotes from post-its illustrated in bold text.

Breakout session 1: Focused discussions on advancing policy and practice in relation to wind farm developments in PWS catchments.

Wind farms – Question 1: *Practice perspective: what practical activities (e.g., information needs, management approaches) would help in managing risks to PWS from wind farm development and continuing operations? Please indicate using your coloured dots those that you feel are critical.*

Priority aspects:

- Local Authorities, Scottish Government, and sectoral reps all called for **an integrated data platform which allows catchment scale evaluation of pressures** that might impact on water availability for PWS. This would include accurate and accessible **GIS maps of PWS sources, catchments, and supply infrastructure** (type, location of sources and properties), incorporating OS maps, and other relevant data layers. This would **enable LAs to deal with the large increase in wind farm applications and the scale of information requests**. It was commonly agreed that such a platform would be underpinned by **compulsory registration of PWS**.
- Scottish Government and LAs recognised that once registered, PWS users should be **supported to assess and manage risks to their supply. PWS details could be contained in title deeds**, and related **PWS guidance** could be a **component of home reports**.
- LA representatives and sectoral representatives asked that a **legal framework that prescribed minimum expected steps for developers** was required for the design, development, and construction phases of wind farms and associated infrastructure. Ideally, PWS should be a formally recognised design consideration and development proposals should include consistent use of appropriate buffer zones, as well as **detailed plans with mitigation measures** as a contingency if PWS are shown to be impacted by activities.
- There was a generally agreed need for **definitions of PWS related terms to be agreed across the sectors involved** to facilitate understanding.
- LA and governmental representatives asked for **joint site visits** by LAs, applicant representatives, landowners, and the use of aerial photographs prior to scoping being written up. This was considered important to allow **ground-truthing of locations and risk impact potential**, to **underpin development plans** and the **generation of comprehensive site maps**, and to **facilitate communication between stakeholders**.
- Site assessments need to be at the **appropriate scale**, consider **geology and replenishment mechanisms**, and **acknowledge uncertainties**.
- LA representatives asked for effective **before-during-after monitoring** to be implemented to help identify and manage (cumulative) impacts using agreed criterion and methodology for water catchment rather than developer decides.
- A caveat was noted: resourcing and proportionality needs consideration in relation to calls for comprehensive ground truthing and monitoring given the finite resources available.

Other issues raised in relation to practice included:

- Wind farm development plans to include related works (e.g., substations, offsite access roads, powerline wayleaves, etc).
- Improved consistency and oversight of EIAs and associated risk assessments, and guidance for LAs to do this.
- Improved consultation processes including use of non-specialist language, and information relating to construction materials (e.g., PFAS).
- Improved understanding of the impact of smaller wind farms would reduce uncertainties around risk assessments in such cases.

***Wind farms – Question 2**: Policy perspective: What improvements to policy, regulatory and related implementation measures are required for solutions to be enabled? Please indicate using your coloured dots those that you feel are critical.*

Priority aspects:

- LAs asked for policy **requiring registration of PWS**, and **identification of sources** to help underpin the information and mapping needs described above.
- LAs emphasised the need for updated **PWS legislation to cover both 'exempt' and 'regulated' supplies to provide protection for all users**. This is important for both quality and quantity for PWS.
- **Guidance for PWS owners on how they can exercise their rights** was considered important by sectoral representatives. This would be possible once a common register was established and possibly incorporated title deeds or contained within home/property reports provided at purchase.
- Scottish Government recognised the need for policy needs to support **clearer requirements for better consultation around permitted developments**, including **more notice for communities** and their involvement in providing information around associated PWS.
- Sector representatives and Scottish Government participants flagged the need for **clear policy guidance defining good practice, minimum reporting requirements, risk mitigation and regulations and enforcement tools** in relation to developments impacting PWS. Linked to this is the need to **raise awareness of impacts of wind farm developments on hydrology**.
- Sector representatives and Scottish Government recognised the need for **policy guidance** for when **trading-off benefits of national priorities for LUC with risks to PWS**.
- Participants from all sectors agreed that **LAs require supporting information, staffing resources** and annual workplans to allow better **oversight of development proposals**.
- Sectoral representatives asked that policy support **catchment specific decision-making, integrating flood, drought, and water quality within the risk assessment process**.

Other issues raised in relation to policy included:

- Legislation concerning development proposals needs to require applications to address all the components linked to the wind farm (e.g., export powerlines, site access, storage, and maintenance continuity).
- Could Rural Land-use Partnerships (RLUPS) help with catchment scale PWS protection?
- There was a question about who has regulatory oversight for renewables (is it the Energy Consent Unit in SG?)
- Guidance and understanding required in relation to defining permitted development areas.
- Legislation needs to clarify roles and responsibilities of the various stakeholders involved.
- Can PWS related policy be better linked or integrated with the NPF4?
- Considering if site impact boundaries need extending to account for downwind impacts (influence of turbulence on moisture stratification) due to prevailing winds.
- The need to provide appropriate level of training to individuals involved in planning, developing, and monitoring LUC.

***Wind farms – Question 3:** How might your organisation or sector help to action the above?*

Discussion of the potential adoption of roles that organisations could adopt specifically mentioned:

- DWQR could support improved PWS mapping if Local Authorities were able to collect more comprehensive information.
- Scottish Water noted that extensive peatland restoration (presumably in their catchments, but more broadly too), would have long term impacts or benefits on water quantity, quality, and flood mitigation.

Breakout session 2: Focused discussions on advancing practice and policy on forest management.

Following the same structure as the earlier discussions on wind farm development, the three breakout groups started discussing measures needed to advance the practice of forest development for protecting the water availability for PWS, and then, moved into the policy and regulatory changes needed. To finish, participants were asked to mark with their coloured dots the changes or improvements that they considered more critical.

In any case, it should be noted that policy and regulation discussions organically developed when discussing practice, and vice versa. However, in this report, for the aim of clarity, we have moved those discussions to the thematic heading that corresponds best.

Afforestation – Question 1: *Practice perspective: Information needs, risk assessment tools and management approaches that would help in managing risks to PWS from afforestation and continuing management operations.*

Priority aspects:

- **Enhanced land-use Scotland-wide integrated mapping** that integrates accurate information about PWS, soil and land-use was considered important by participants across all sectors at the workshop. This type of tool would be useful to assess cumulative impact on water availability at catchment level. It was pointed out that this tool should be online and accessible however, some concerns were noted regarding potential issues of national security and the need to prevent cyber-attacks.
- Specific information needs regarding enhancing the **identification of PWS** were noted as important by participants from both Local Authorities and sectoral organisations.
- Stakeholders from LAs and sectoral organisations also considered important to develop **enhanced communication and engagement** with and between stakeholders, including particularly the Environmental Health Officers in the LAs, and the use of consultations.
- Another measure considered critical across different types of participants was the need for **regular monitoring** of the impacts on PWS that include baselines (considered important by stakeholders in public bodies and sectoral organisations) and post-completion monitoring.
- The need for **on-site visits** that ground-truth assessments was noted as important by stakeholders from the national public bodies and local authorities, while acknowledging the challenges around resourcing these. These would **improve confidence** in decisions in relation to **risk management options**.

Other areas of improvement to practice that were discussed and noted are the need for enhancing:

- **Clarity regarding roles and responsibilities,** particularly regarding enforcement, coordination and implementation of measures (this was also noted in relation to policy needs, to facilitate this clarification).
- **Accessible and detailed guidance and capacity building** within the sector, from developers and consultants to forestry workers acting on the ground (e.g., educational programme, detailed guidance and clear information materials).
- Statutory risk assessments to **consider impacts of subsidiary work** on PWS.
- Develop a cross-stakeholder understanding of what **mitigation strategies** (e.g., buffer zone extent and location, species mixes, infrastructure corridors) are available to forest planners to minimise risks to PWS and their infrastructure.
- **Emergency and contingency planning**, to be clearer and detailed including the establishment of clear communication channels in case of contingency.

Finally, other practice aspects that were suggested as potentially beneficial are:

- Improving the existing PWS risk assessment tool used to capture water quality issues.
- Adopting improved project management processes.
- Developing catchment assessment tools.

Afforestation – Question 2*: Policy and regulation: Needed improvements to policy, regulatory and related implementation measures.*

Priority aspects:

- The suggestion for **Scottish Forestry to become a statutory consultee for Local Authority Forest and Woodland Strategies (under the Planning (Scotland) Act)** was considered important across the different stakeholders. Sectoral stakeholders also noted a need for specialist advice from other organisations (e.g., BGS).

- **Enhancing guidance and assistance to LA officers** (Environmental Health Officers in particular) to regulate correctly was also noted as critical by participants from national public bodies and LAs. This could also include enhancing the coordination of PWS at national level (e.g., via an independent or government level coordinator) and withing LAs via the Environmental Health Office.
- The need to **ringfence funding for PWS action in Local Authorities**, given their regulatory role for PWS, and the constrained situation in which Environmental Health Officers work in many local authorities. It was noted that the same approach might not be appropriate for all local authorities given the different scales, number of PWS issues, and resources available.
- **The need for SEPA to update the GBRs** (General Binding Rules) was considered important by stakeholders from sectoral organisations and the Local Authorities.
- **Going beyond guidance to enforce good practice** was considered important by participants from national public bodies and LAs. (note: Guidance is not legally binding so going 'beyond compliance' is not enforceable when there is no legal statute in law).
- At micro-level, the **upgrade of the PWS infrastructure** to increase their resilience was seen as important within the national public bodies, noting the need for the improvement of government grants.
- And at a larger scale, it was noted the **need for act on resource management policies at national level**, particularly under the NPF4, was also highlighted across the discussions and noted by important by sectoral stakeholders.

Other areas of improvement to policy that were discussed and noted are the need for enhancing:

- **Local planning sensitive to PWS**, with LAs accounting for PWS areas in their forest and woodland strategies and including adequate consultation processes.
- To require **assessments of water sufficiency**, with policy and regulations to specify this as a consideration in EIAs and risk assessments, as is already the case for water quality.
- **To change convictions under PWS regulations** (particularly with regards to removing level 4-5 fines).

And a general note was made about the need for policy and regulatory changes to be proportionate and open the possibility to explore other possibilities (e.g., relocation, alternative supplies) in cases when a specific project development is considered of national interest.

***Forestry – Question 3**: How might your organisation or sector help to action the above?*

The discussions highlighted a general need for clarifying roles and responsibilities. Roles and actions that were specifically mentioned included:

- SEPA was identified as responsible for updating GBRs. It was also discussed that SEPA should be given new additional powers to issue tree planting licences.
- Scottish Forestry to become statutory consultee in any Local Authority Forest and Woodland Strategy development.
- DWQR to improve the risk assessment tool for PWS to capture issues of water quantity, and to audit the actions of Local Authorities in relation to their regulatory responsibilities.
- Environmental Health Officers in Local Authorities to support strategic developments through guidance.
- Scottish Government to unify policy on Scotland’s natural resources, to develop legislation and regulation updates, and to provide 50% grants to upgrade PWS assets.
- It was suggested that British Geological Society (BGS, not present at the workshop) could offer free advice for PWS on boreholes.

Breakout session 3: “Pathways”

This session involved the same groupings as Breakout 2. It was often difficult to identify the actions required to enable subsequent activities given the interdependencies. However key policy refinements were often a prerequisite, and the need to collect and share spatial PWS information to underpin activities was considered important. While government bodies were often flagged as having the ability to drive change, responsibility for resulting actions falls variously on Local Authorities, developers, regulators, and PWS users themselves.

Primary considerations related to the need for:

- Scottish Government to drive changes (e.g., Water policy currently under consultation), including strategic level policy alignment in relation to LUC and hydrology, and addressing water availability issues.
- Standardise and raise awareness of guidance for PWS users and land-use sectors using common terminology, including perhaps replacing PWS with PWSS (Private Water Supply System).
- Development of policy, guidance, and regulations (penalty for non-compliance?) appropriate to registering and mapping PWS related information.
- Develop obligatory Key Performance Indicators for EIAs to address.
- Share existing forestry related good practice guidance for LUC developments in other sectors.
- Building standards need to be updated to incorporate water related issues.
- Consider need for hydrogen creation (nascent industry) as annex to wind farm related EIAs.

Subsequent actions and activities mentioned included:

- DWQR oversight and support for LAs to standardise PWS registration and their involvement in PWS user risk assessments.
- DWQR to support awareness raising and provision of guidance to all affected and registered PWS users prior to LUC (ongoing).
- Continuation and expansion of this forum (group of relevant stakeholders) to create an ongoing working group. This links with the need to improve cross-sectoral awareness and information sharing relating to terminology, resources, etc.
- Use data collected via monitoring and evaluation processes to improve good practice. For example, compare monitoring of groundwater recharge from forests at different growth-stages with adjacent land-uses to improve impact modelling and risk to PWS by type.
- Does SEPA need additional powers relating to (abstraction?) licencing?
- More involvement from Scottish Water (unclear)
- Resources to allow for timely and coordinated onsite visits involving Local Authorities, developers, PWS users and statutory agencies as appropriate.

Final Plenary Feedback

This session allowed groups to share their thoughts on recommendations for improvements in relation to afforestation planning, but many of the requirements were thought to apply across different types of land-use change, with PWS related needs being the common factor.

In terms of priorities and dependencies, the feedback flagged a desire for the day's conversations to continue to ensure that change happens, perhaps through the establishment of a stakeholder forum to include other relevant roles and expertise. This would allow the workshop participant's sharing and learning to be continued, and facilitate decision-making around roles and activities. Several new ideas and recommendations were raised, in addition to the findings reported above:

- Continued effort required to identify and assign roles and activities that stakeholders might lead on or assist.
- The overall process needs to engage with landowners and users (and their representatives).
- Important to consider the technical requirements for national level data storage.
- The impact on water availability of wider changes in (sustainable) land management needs to be considered, linked to effective land use models for Scotland.
- Continuation of discussions around land use trade-offs and thresholds.
- Consider how best to act in relation to PWS demand management.
- Increase overall resilience of PWS, including flooding and drought as well as LUC.
- All stakeholders to raise issues and engage via clear communication pathways.
- Continuation and development of stakeholder forum (building on this workshop) to facilitate action.

More broadly, final comments reflected a common desire for improved water resource planning (both supply and demand), raising the profile and prioritising PWS related policy, and for impacts on PWS to be a focus of land use planning processes.

Conclusion

The workshop brought together many (but not all) stakeholders appropriate to the issues discussed. Key challenges, themes, and ideas that were shared will be incorporated in the overall project report and help to frame and provide impetus to any recommendations made. Another more qualitative role that the workshop played was to encourage knowledge sharing and discussion between representatives from different organisations and sectors. Feedback suggests that this was for the most part successful and welcomed by the participants. Moreover, the need was expressed for this process to continue, and to involve input from additional stakeholders, if impacts of land use change on PWS are to be more effectively managed (alongside climate change and other factors).

Finally, the research team would like to express their thanks again to the participants for bringing their enthusiasm and willingness to engage with the topic, and each other, on the day.

Good practice examples as posted throughout the day on a board in the Sandeman room.

- LABSS – Local Authority Building Standards Scotland (LABSS) | LABSS | Building control "Each LA building control regional office has a National Specialist who shares or contributes to National Policy work and practice and advises and liaises with ScotGov/TRAMS"
- CONFOR/SCOTTISH Forestry Consultation Review to be published soon
- LENS – there are two scoping studies up and running with input from NatureScot, Scottish Enterprise, and Scottish Water:
    - o Speyside – the Spey Catchment Initiative has now been set up as a new SCIO to support a LENS project on Speyside with likely business demand from distilleries and their supply chain
    - o Loch Leven – the Forth Rivers Trust has just secured FIRNS funding to develop a LENs project focussed on improving water quality in our NNR at Loch Leven and the river Leven below the loch (note this is internal information at this stage, FIRNS projects will be announced publicly soon). Likely business demands include Scottish Water and Diageo
- Air pollution cumulative and potential impacts and predictions (APAS/JNCC). Message is to consider future needs when processing new applications. (possibly referring to this: UK Air Pollution Assessment Service (UK APAS) Q&A | JNCC – Adviser to Government on Nature Conservation)

Key feedback from evaluation forms completed in person at the end or returned by email.

Feedback on the workshop was captured using a short evaluation form distributed to participants at the end of the day (a total of 14 were returned). Overall feedback was encouraging, and the workshop was considered "very useful" by all respondents but one, who said it was useful. Eleven of the responses indicated that the quality of interactions in the day had been very good.

The aspects most valued by the participants as noted in the evaluation forms were:

- The workshop provided an opportunity to engage and network across sectors and beyond the usual suspects: "Good to engage with energy sector"; "Good groups, great interaction, good networking possibilities". It also provided a good opportunity to understand the views of different stakeholders in land use processes around PWS: "Good to understand different views"; "Bringing many different perspectives from a wide range of stakeholders"
- In this sense, some stakeholders noted their interest for this type of forum to continue beyond the project: "Keep it going please"; "It is very useful and supportive"; "Finding out that we are not alone"; "Excellent workshop – needs combined, and contacts need to keep in touch"
- The quality of the discussion and interactions: "Excellent open discussion – no egos at play"; "Good frank discussion"

A concern was raised (verbally) about the lack of representation from the wider forestry sector because of invitees being unable to attend (only one representative was present on the day).

Stakeholders present: either by name and role, role, or organisation as specified on consent forms

- **Stakeholders from Local Authorities:**
    - o Patricia Sheldon, Highland Council Senior Environmental Health Officer.
    - o Argyll and Bute Council Environmental Health Manager
    - o Scottish Borders Council Environmental Health Officer
    - o Constance Lobban, S. Ayrshire Council Environmental Health Enforcement Officer

- **Stakeholders from the Scottish Government and national public bodies:**
  - o Senior Policy Advisor, Water Policy Unit, Scottish Government
  - o John Gorman (SEPA's Forestry Lead Officer)
  - o Moira Malcolm, Drinking Water Specialist (Drinking Water Quality Regulator)
  - o Matt Bower, Operations Team Leader (Drinking Water Quality Regulator)
  - o Linsey Mason-Maclean, Land Use and Environment Policy Advisor, Scottish Forestry
  - o Rural and Environment Science and Analytical Services (RESAS) Science Advisor
  - o Sue Marrs, Freshwater and Air Pollution Policy at NatureScot
  - o Alan Aitchison, Scottish Water's Sustainable Land Management Team
- **Stakeholders from sectoral organisations and other researchers:**
  - o Iain Kirkpatrick, independent consultant
  - o Joanna Cassidy, ITP energised consultant
  - o Sarah Halliday, Reader in Environmental Sciences, UNESCO Centre for Water Law, Policy and Science, University of Dundee
  - o Two representatives of SP Energy Networks
- **Stakeholder responded to emailed workshop questions by 5th Feb.**
  - o Aberdeenshire Council (Scientific Officer)
- **Organisations invited but unable to attend on the day or respond to email questionnaire:**
  - o CONFOR
  - o Consumer Scotland
  - o Dumfries and Galloway Council
  - o Perth and Kinross Council
  - o Scottish Land and Estates
  - o SNIFFER (Adaptation Scotland)

Additional stakeholders suggested by participants in their evaluation forms

- CONFOR (invited but could not attend)
- Forestry and Land Scotland
- Forest Research
- Woodland Trust
- Tilhill (and other forestry sector actors)
- Consumer Scotland (Emma Ash) (invited but could not attend)
- Scottish Gov't policy officer for Energy (Energy Consents Unit)
- Scottish and Southern Energy
- Other DWQR officers (e.g., Rosemary Greenhill)
- Local Authority Planning officers
- Civil contractors (e.g., Farrans, Morrisons, Kelbrey)

Appendix 2 – Spatial patterns of physiographical characteristics in context of PWS

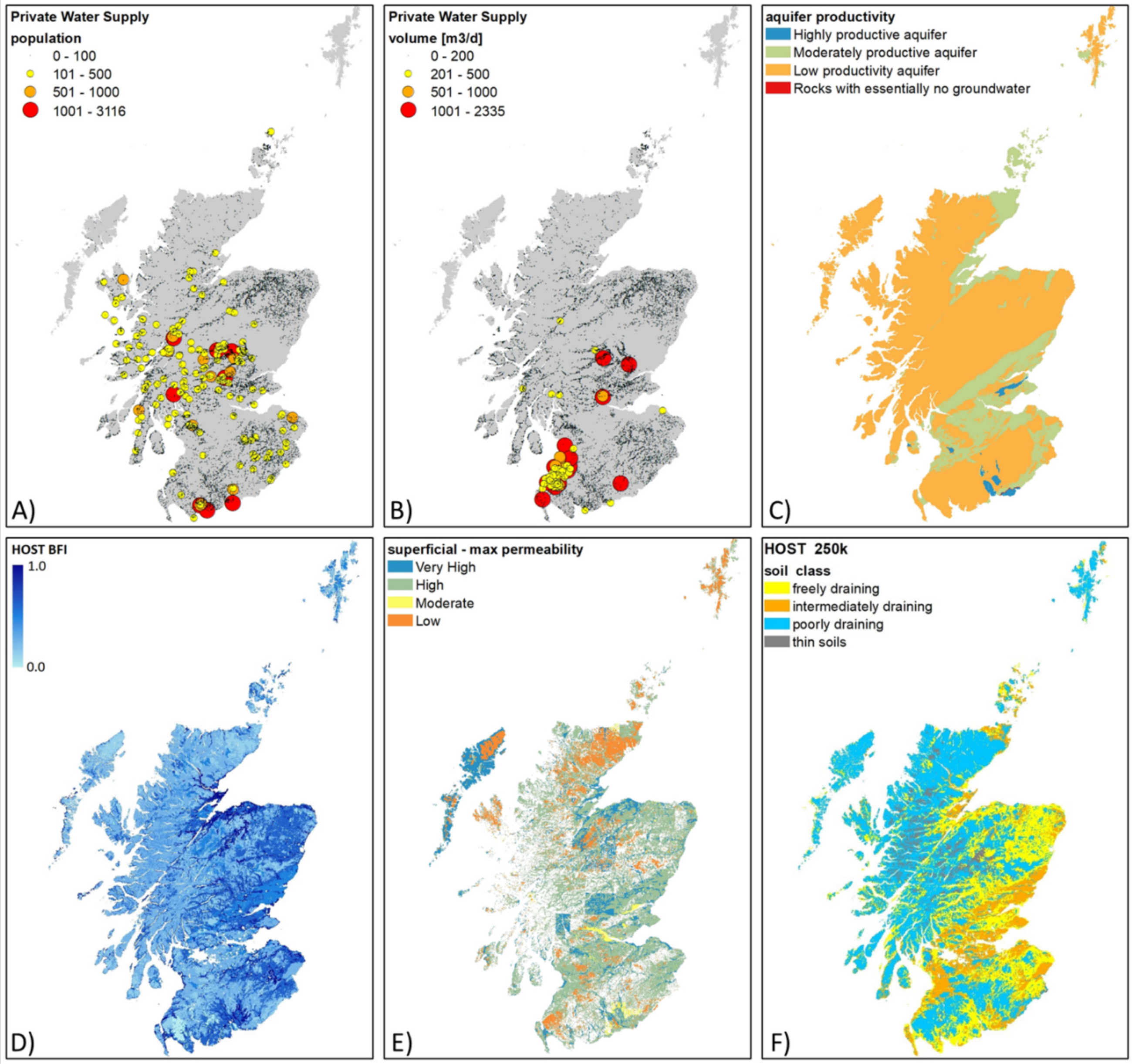

Figure A1: A) estimated population depending on individual private water supply sources and B) estimated volumes of water extracted for each source. source: (DWQR, 2022) with a note that data from several local authorities missing. C) Bedrock aquifer productivity (British Geological Survey, 2015), D) baseflow index (UK Centre for Ecology & Hydrology, 1995), E) maximum permeability of superficial deposits (British Geological Survey, 2021) and F) soil wetness and relative draining properties (UK Centre for Ecology & Hydrology, 1995) for Scotland.

Appendix 3 – Keywords for literature review on water availability

Table A1: Search terms used to identify relevant literature for this review		
Land use	**Land use change**	**Hydrology indicators for water availability**
Forestry	• Pasture to forest • Agriculture to forest • Grassland to forest • Afforestation	• Discharge • Low flows • Peak flows • Groundwater levels • Water table • Recharge • Soil water • Soil moisture • Infiltration • Interception • Evapotranspiration
Agroforestry	• Agroforestry • Silvopastoral • Silvoarable • Agro-silvo-pastoral • Silvopasture • Windbreaks • Riparian buffer • Alley cropping	• Discharge • Low flows • Peak flows • Groundwater levels • Water table • Recharge • Soil water • Soil moisture • Infiltration • Interception • Evapotranspiration
Wind farm development	• Wind farm • Wind farm and forest • Wind turbine	• Discharge • Low flows • Peak flows • Groundwater levels • Water table • Recharge • Soil water • Soil moisture • Infiltration • Interception • Evapotranspiration • Land surface temperature

Appendix 4 – Overview of literature on effects of land use change on water availability

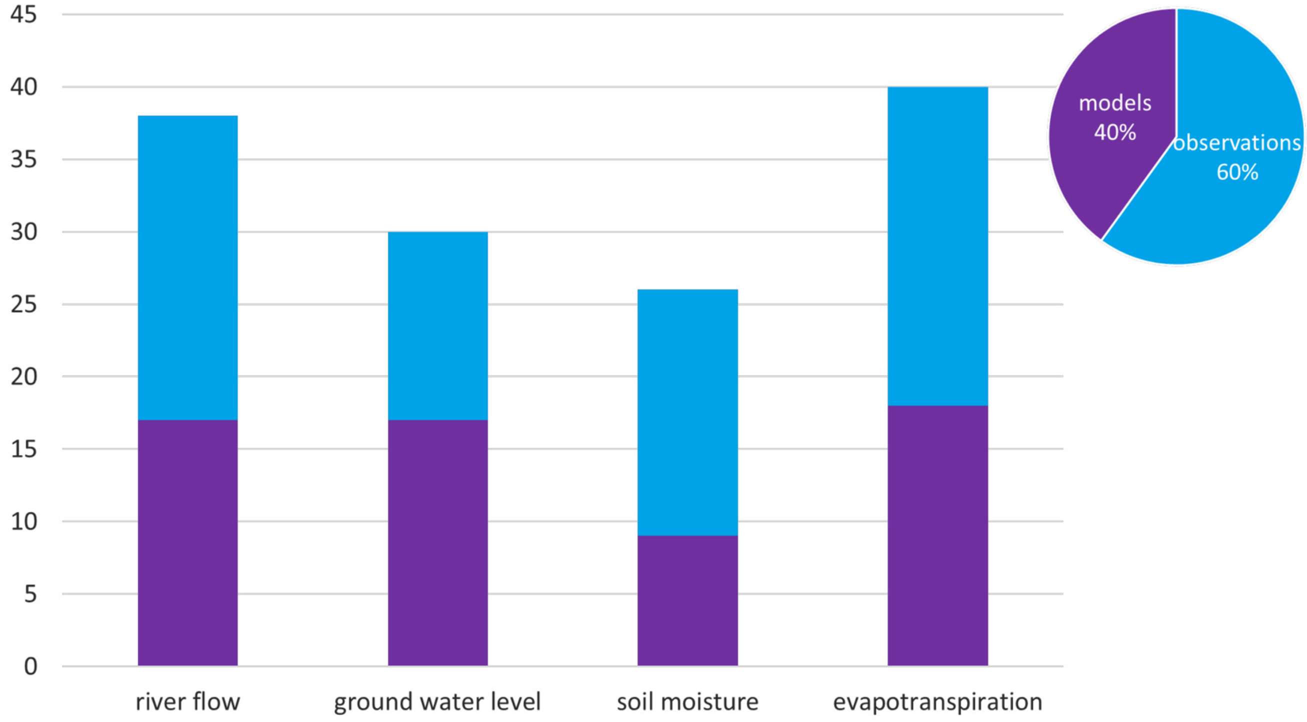

Figure A2: Overview of the type of available evidence (from observations or models) on the hydrological effects of afforestation.

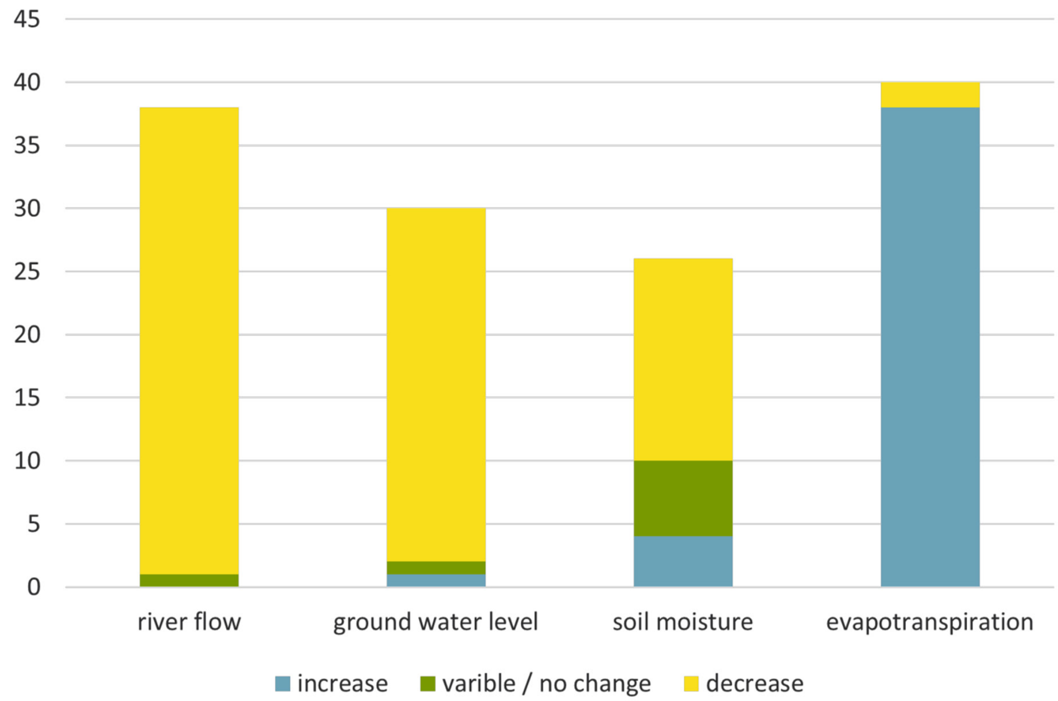

Figure A3: Overview of reported hydrological changes due to afforestation

Table A2: Overview of afforestation literature reported, change (↑increase, ↓decrease, ~variable or no change) and reported methodology

Study		Change (%)				Methodology				
Authors, Year	**Country**	**River discharge**	**GW table**	**Soil moisture**	**Evapotrans-piration**	**Catchment size [km²] (% afforestation)**	**Tree type**	**Bedrock**	**Soil**	**Data**
(Archer *et al.*, 2016)	United Kingdom (Inshriach Forest)		↑ (42%)	↑ (28.9%)		NA	coniferous + deciduous		humus podzols and humus-iron podzols	observed
(Archer, 2007)	United Kingdom (Plynlimon)	↓ (35.2%)				8.7 (48-67%)	coniferous	mudstones, grits, siltstones, slates	peat, podzol, alluvium, peat, gley	observed
(Bathurst *et al.*, 2018)	United Kingdom (Coalburn)	↓ (24%)				1.5 (90%)	coniferous		peat	observed
(Bellot *et al.*, 2001)	Spain (Ventós aquifer)	↓ (24.5%)	↓ (36.9%)	↓		6.1 (NA)	coniferous	marls, chalk	loam	modelled
(Boulton *et al.*, 1997)	New Zealand (Waipa River)	↓ (69.4%)				0.9; 2.0; 3.0 (NA)	coniferous	greywacke, argillite	yellow brown earth soils	modelled
(Buechel *et al.*, 2022)	UK	↓ (2.8%)				500.0 – 10000.0 (25%; 50%)	coniferous + deciduous			modelled
(Bultot *et al.*, 1990)	Belgium (Houille)	↓ (11.9%)			↑ (13.6%)	113.7 (up to 100%)	coniferous + deciduous		quartzo-schisto-phyllades	modelled
(Bulygina *et al.*, 2011)	United Kingdom (Plynlimon)	↓ (13%)				0.9; 3.1; 3.7; 8.7 (100%; 78%; 48%; 67%)	Coniferous		peat, podzols, alluvium, gley	modelled
(Calder *et al.*, 1997)	United Kingdom (Greenwood Community Forest)	↓ (51%)	↓ (62%)		↑ (17.6%)	416 (9% to 27%)	coniferous + deciduous		sand, clay, loam	modelled
(Calder *et al.*, 2002)	United Kingdom (Greenwood Community Forest)		↓ (14%)			NA (9% to 27%)	coniferous + deciduous	sandstone	sandy soils	modelled
(Calder *et al.*, 2003)	United Kingdom (Clipstone Forest)		↓ (75%)			NA	coniferous + deciduous	sandstone	sandy soils	modelled

Table A2: Overview of afforestation literature reported, change (↑increase, ↓decrease, ~variable or no change) and reported methodology

Study		Change (%)				Methodology				
Authors, Year	**Country**	**River discharge**	**GW table**	**Soil moisture**	**Evapotrans-piration**	**Catchment size [km²] (% afforestation)**	**Tree type**	**Bedrock**	**Soil**	**Data**
(Calder, 1993)	United Kingdom (Balquhidder)	↓				NA	coniferous + deciduous		peat soils	observed
(Calder, 2004)	United Kingdom (Greenwood Community Forest)	↓ (11%)	↓ (66%)			NA (9% to 27%)	coniferous + deciduous		sandy soils	modelled
(Cao *et al.*, 2009)	New Zealand (Motueka River)	↓ (19.5%)			↑ (9.2%)	1822.0 (25% to 50%)	coniferous			modelled
(Chandler *et al.*, 2018)	United Kingdom (Glensaugh)			↑ (97.4% kfs)		NA	coniferous + deciduous		leptic podzols / cambisols	observed
(Collins *et al.*, 2023)	United Kingdom (Thames)	↓ (24.7%)				1616.0 (23%)	coniferous + deciduous	impermeable	sand and gravel, clay-rich soils	modelled
(Dons, 1987)	New Zealand (Purukohukohu)	↓ (53.2%)	~		↑ (33%)	0.4 (<0.1%)	coniferous + deciduous	sediments, pyroclasts	developed from volcanic ash	observed
(Duncan, 1995)	New Zealand (Moutere Gravel hill)	↓ (90%)	↓ (44.3%)	↓ (51%)		0.03 to 0.08 (20% to 100%)	coniferous	Moutere gravel formation	strongly enleached	observed
(Fahey and Jackson, 1997)	New Zealand (Tadmor valley)	↓ (65%)				0.05 to 0.2 (6% to 100%)	coniferous	quartzo-feldspathic schist with colluvium	silt loams	observed
(Fahey and Watson, 1991)	New Zealand (Otago)		↓ (20%)		↑ (20%)	3.1 (67%)	coniferous	quartzo-feldspathic schist	silt loams and loess	observed
(Farley *et al.*, 2005)	global	↓ (44%)			↑	NA (up to 100%)	coniferous + deciduous			observed
(Greene, 1987)	United Kingdom (Strathclyde region)	↓ (66%)			↑	NA (10% to 100%)	coniferous + deciduous			observed
(Gribovszki *et al.*, 2008)	Hungary (Jászfelsőszentgyörgy)		↓	↓		6.0 (NA)	deciduous		sand, silt	observed

Table A2: Overview of afforestation literature reported, change (↑increase, ↓decrease, ~variable or no change) and reported methodology

Study		Change (%)				Methodology				
Authors, Year	**Country**	**River discharge**	**GW table**	**Soil moisture**	**Evapotrans-piration**	**Catchment size [km²] (% afforestation)**	**Tree type**	**Bedrock**	**Soil**	**Data**
(Gustard and Wesselink, 1993)	United Kingdom (Balquhidder)					6.9 (39%)	coniferous	mica-schist, dolerite	glacial till	observed
(Haria and Price, 2000)	United Kingdom (Allt a'Mharcaidh)			↓ (33.9%)	↑ (41%)	10.0 (NA)	coniferous		podzol, peaty podzol	modelled
(Heal *et al.*, 2004)	United Kingdom (Loch Bradan and Ballochbeatties)	~ (0%)			↑ (45%)	0.9 (45%)	coniferous + deciduous	hard metamor-phosed greywacke	peat, peaty gley, peaty podzols	observed
(Hudson *et al.*, 1997)	United Kingdom (Plynlimon)	↓ (61%)			↑ (28.7%)	8.7 (NA)	coniferous	slates, mudstones and sandstones	peat and gleyed mineral soils	observed
(Hudson, 1988)	United Kingdom (Plynlimon)			↓ (5%)		NA (68%)	coniferous		peat, podzols, alluvium, gley	observed
(Hughes *et al.*, 2020)	New Zealand (Waikato region)	↓ (50%)				2.7; 3.1 (up to 62%; 100%)	coniferous	greywacke and argillite	strongly weathered yellow brown earth soils	observed
(Iacob *et al.*, 2017)	United Kingdom (Tarland)	↓ (70%)			↑	98.0 (20% - 40%)	coniferous + deciduous	impermeable bedrock	cambisols, humus-iron podsols	modelled
(James *et al.*, 2003)	Canada (White Butte Recreation A)			~		NA (33%)	deciduous		sandy soils	observed
(Johnson, 1995)	United Kingdom (Balquhidder)	↓ (15.1%)			↑ (34%)	6.9 (0% to 100%)	coniferous		peat	modelled
(Khorchani *et al.*, 2021)	Spain (Arnás)	↓ (5.9%)		~	↑ (92.7%)	0.3 (33% to 94%)	coniferous + deciduous	sandstone, marl	poor eroded soils	modelled
(Khorchani *et al.*, 2022)	Spain (Arnás)	↓ (24%)			↑ (21.4%)	0.3 (33% to 94%)	coniferous + deciduous	sandstone, marl	poor eroded soils	modelled

Table A2: Overview of afforestation literature reported, change (↑increase, ↓decrease, ~variable or no change) and reported methodology

Study		Change (%)				Methodology				
Authors, Year	**Country**	**River discharge**	**GW table**	**Soil moisture**	**Evapotrans-piration**	**Catchment size [km²] (% afforestation)**	**Tree type**	**Bedrock**	**Soil**	**Data**
(Kirby, 1991)	United Kingdom (Plynlimon)	↓ (13%)			↑ (32%)	8.7 (70%)	coniferous	fractured bedrock	palaeozoic grits, mudstones and shales	observed
(Kleine *et al.*, 2020)	Germany (Demnitzer Millcreek)	↓	↓	↓	↑	66.0 (NA)	deciduous		peat, sandy gleysols, peaty histosols	observed
(Kleine *et al.*, 2021)	Germany (Demnitzer Millcreek)		↓ (30.7%)	~	↑ (3.7%)	66.0 (NA)	coniferous + deciduous		sandy soils	observed
(Leterme and Mallants, 2011)	Belgium (Nete)		↓ (41%)			1673.0 (21%)	coniferous + deciduous		podzol	modelled
(Lewis *et al.*, 2013)	Ireland (Glencar)	↓ (20%)	↓		↑	121.0 (30%)	coniferous		peat	modelled
(Madani *et al.*, 2018)	United Kingdom (Plynlimon)	↓ (4.6%)			↑ (2.2%)	NA (70%)	coniferous	mudstones, grits, siltstones, slates	peat, podzols alluvium, gley	observed
(Mansour and Hughes, 2014)	United Kingdom (Thames, Dee, Ely-Ouse, Hampshire Avon, Stour, Tees, Trent and Derwent)		↓			NA (50% arable to forest)	coniferous + deciduous	chalk, limestone		modelled
(Marc and Robinson, 2007)	United Kingdom (Plynlimon)	↓ (5.9%)			↑ (16%)	NA (70%)	coniferous	slate, mudstone, sandstone	regolith, glacial deposits, peat	observed
(Monger *et al.*, 2022)	United Kingdom (Haweswater reservoir)	↓ 60%)		↑ (48.5%)		<0.2 (0% to 100%))	deciduous		upland organo-mineral soils	observed
(Mongil-Manso *et al.*, 2022)	Spain (Tajo River basin)			↓ (40%)		NA	coniferous + deciduous	adamellite, leuco-granite, pegmatite	humic and gleic cambisols	observed
(Móricz *et al.*, 2016)	Hungary (Jászfelsőszentgyörgy)		↓		↑ (20%)	NA	deciduous		fluvial sediments	observed

Table A2: Overview of afforestation literature reported, change (↑increase, ↓decrease, ~variable or no change) and reported methodology

Study		Change (%)				Methodology				
Authors, Year	**Country**	**River discharge**	**GW table**	**Soil moisture**	**Evapotrans-piration**	**Catchment size [km^2] (% afforestation)**	**Tree type**	**Bedrock**	**Soil**	**Data**
(Murphy *et al.*, 2021)	United Kingdom (Dartmoor National Park)			↓ (2.6%)		900 (12%)	deciduous		gley soil, brown earth	observed
(Neal *et al.*, 1993)	United Kingdom (Blackwood, Hampshire)	↓			↑	NA	deciduous	chalk	organic rich	observed
(Paço *et al.*, 2009)	Portugal (Herdade da Alfarrobeira				↑	NA (21%)	deciduous	granite	cambisol	observed
(Parkin *et al.*, 2003)	United Kingdom (Nottinghamshire)		↓			NA	coniferous + deciduous	sandstone	sandy podzols	modelled
(Peskett *et al.*, 2021)	United Kingdom (Eddleston)		↓	↓ (21.9%)		67 (NA)	coniferous + deciduous	sandstone greywackes	brown soils	observed
(Peskett *et al.*, 2023)	United Kingdom (Eddleston)		↓ (58.7%)	↓		67 (0.5% to 94.3%)	coniferous + deciduous		gley soils, peats	modelled
(Price *et al.*, 1995)	United Kingdom (Balquhidder)			↓ (7.5%)	↑ (x2.39)	2.1; 2.6; 2.7; 5.7; 30.3; 31.0; 37.5; (0%; 55%; 75%; 15%; 4%; 75%; 21%;)	coniferous			modelled
(Quilbé *et al.*, 2008)	Canada (Quebec)		↓			6682 (63%)	coniferous + deciduous		loam, clay loam, loamy sand	modelled
(Renger *et al.*, 1986)	Germany (Hannover)		↓		↑	NA	coniferous			modelled
(Revell *et al.*, 2022)	United Kingdom (Warwickshire)			~		2.2 (NA)	deciduous		sandy clay loam, sandy silt loam, sandy loam, clay	observed

Table A2: Overview of afforestation literature reported, change (↑increase, ↓decrease, ~variable or no change) and reported methodology

Study		Change (%)				Methodology				
Authors, Year	Country	River discharge	GW table	Soil moisture	Evapotrans-piration	Catchment size [km²] (% afforestation)	Tree type	Bedrock	Soil	Data
(Roberts *et al.*, 2005)	United Kingdom (Blackwood, Hampshire)			~ (0%)	↑	NA	deciduous	chalk	silty clay	observed
(Roberts and Rosier, 2005a)	United Kingdom (Blackwood, Hampshire)				↓ (3%)	NA	deciduous	chalk	silty clay	observed
(Roberts and Rosier, 2005b)	United Kingdom (Blackwood, Hampshire)				↑	NA	deciduous	chalk	silty clay	observed
(Robinson *et al.*, 1991)	Germany (Southern Chiemseemoors)	↓ (40%)	↓	↓	↑ (46.7%)	0.6 (0.1%)	coniferous + deciduous		peat	observed
(Robinson *et al.*, 1998)	United Kingdom (Coalburn)	↓ (17.5%)			↑ (36.8%)	1.5 (90%)	Coniferous	mudstones and shales	peat, podsol	observed
(Robinson, 1986)	United Kingdom (Coalburn)	↓ (20%)		~		1.5 (90%)	coniferous		peat	observed
(Robinson, 1998)	United Kingdom (Coalburn)	↓ (17.5%)			↑ (36.8%)	1.5 (90%)	coniferous	mudstones and shales	peat, podsol	observed
(Rodríguez-Suárez *et al.*, 2011)	Spain (Mabegondo)	↓ (47.5%)	↓ (10.8%)			0.1 (85%)	deciduous	metamorphic schist	loams / silt loams	observed
(Rodriguez Suarez *et al.*, 2014)	Spain (Mabegondo)	↓ (22%)			↑ (6.5%)	4.0; 10.7 (80%; 85%)	deciduous		Loam, silt loam	modelled
(Rosenqvist *et al.*, 2010)	Denmark/Sweden (Vestskoven and Tönnersjöheden)		↓ (32%)	↓	↑ (35.7%)	NA	coniferous + deciduous		sandy loam, sandy glacio-fluvial	modelled
(Salazar *et al.*, 2013)	Denmark (Vestskoven)		↓	↓	↑	NA	coniferous + deciduous		sandy loam, arenosols, podzols	modelled

Table A2: Overview of afforestation literature reported, change (↑increase, ↓decrease, ~variable or no change) and reported methodology

Study		Change (%)				Methodology				
Authors, Year	**Country**	**River discharge**	**GW table**	**Soil moisture**	**Evapotrans-piration**	**Catchment size [km²] (% afforestation)**	**Tree type**	**Bedrock**	**Soil**	**Data**
(Sonnenborg *et al.*, 2017)	Denmark/Sweden (Skjern and Lejre)	↓ (47%)	↓ (34%)		↑ (26.7%)	1098 (17.4%)	coniferous + deciduous		sandy	modelled
(Van Der Salm *et al.*, 2006)	Netherlands (NE)		↓ (79.4%)	↓	↑	NA	coniferous + deciduous		loamy sandy soils	modelled
(Wattenbach *et al.*, 2007)	Germany (Federal State of Brandenburg)		↓ (3%)		↑ (25.1%)	29479 (100%)	coniferous + deciduous			modelled
(Wolf *et al.*, 2013)	Switzerland (Chamau, Oensingen1, Früebüel and Laegeren, Davos)			↑	↓	0.1 – 0.2 (varies)	coniferous + deciduous			observed
(Yang *et al.*, 2019)	Canada (Lethbridge, Alberta)		↓	↓	↑ (52.8%)	NA	deciduous		glacial till	observed
(Zha *et al.*, 2010)	Canada (Lethbridge, Alberta)				↑ (2.5%)	NA	coniferous + deciduous		clay-rich loamy soil	observed
(Zhang and Hiscock, 2010)	United Kingdom (Sherwood)		↓ (45%)			NA (20%)	deciduous	sandstone	sandy soils	observed

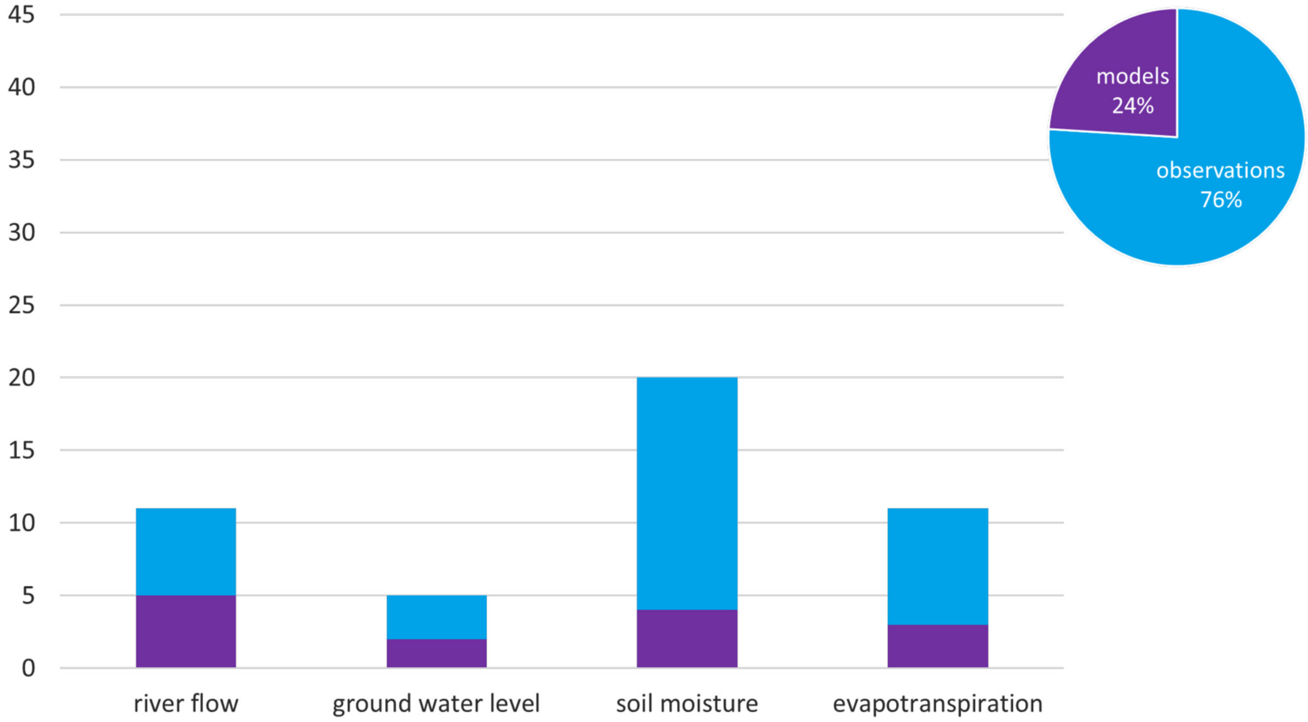

Figure A4: Overview of the type of available evidence (from observations or models) on the hydrological effects of agroforestry.

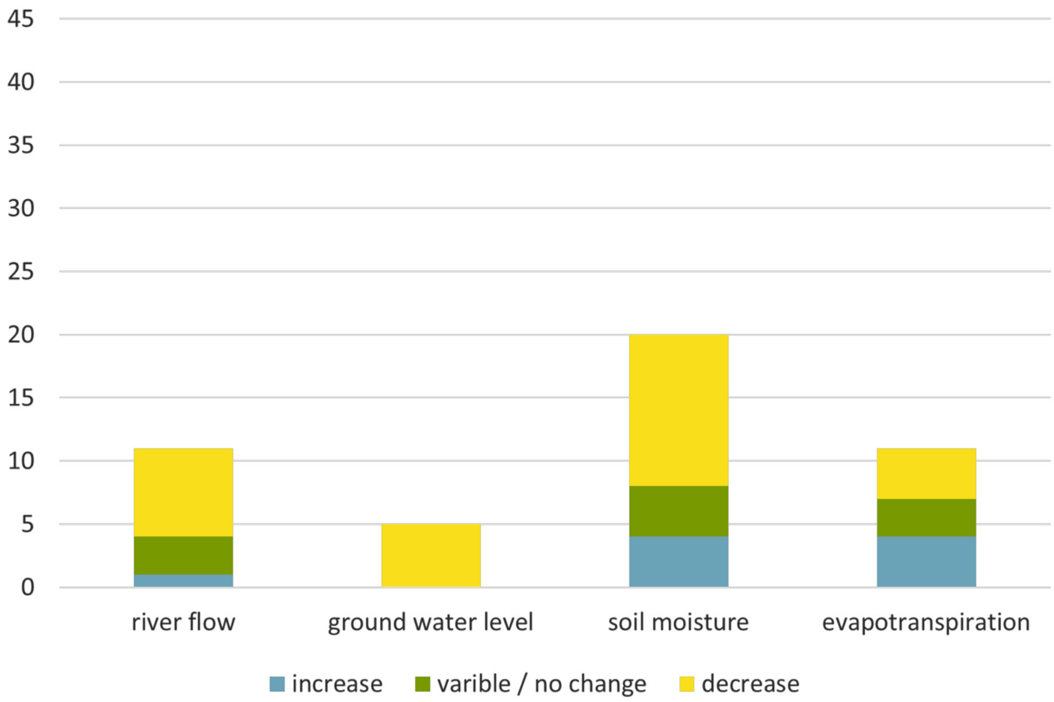

Figure A5: Overview of the reported changes due to agroforestry.

Table A3: Overview of agroforestry literature reported, change (↑increase, ↓decrease, ~variable or no change) and reported methodology

Study		Change (%)				Methodology				
Authors, Year	**Country**	**River discharge**	**GW table**	**Soil moisture**	**Evapotrans-piration**	**Catchment size [km²] (% afforestation)**	**Tree type**	**Bedrock**	**Soil**	**Data**
(Bharati *et al.*, 2002)	USA (Bear Creek, Story County, Iowa)		↓	↓		NA	deciduous		fine-loamy, mixed, superactive, mesic Cumulic Endoaquoll	Observed
(Chase *et al.*, 2016)	Canada (New Brunswick)	~		↓		NA				Observed
(Coble *et al.*, 2020)	USA (University of New Hampshire Organic Dairy Research Farm)			↓	↓	NA (-50%)	coniferous & deciduous			Observed
(Coussement *et al.*, 2018)	Belgium (Ypres, West Flanders)			↓		< 0.1 (NA)	deciduous		Luvisol	Observed
(Fernández *et al.*, 2002)	Argentina (Estancia Lemú Cuyén)		↓ (-51%)	↓ (-22.2)	↑ (13.2%)	0.1 (NA)	coniferous			Observed
(Inurreta-Aguirre *et al.*, 2022)	France (Restinclières Agroforestry Platform (RAP)")			↑ (250%)	↓	NA	deciduous		deep calcareous silty clay	Observed
(Kanzler *et al.*, 2019)	Germany (Neu Sacro, Brandenburg)				↓ (-32%)	0.7 (NA)	deciduous		Gleyic Fluvisol	Observed
(Kumar, 2009)	USA (HARC near New Franklin, Missouri)			~		<0.1 (NA)	deciduous		silt loam	Observed
(Kumar *et al.*, 2012)	USA (HARC near New Franklin, Missouri)			↑ (30%)		<0.1 (NA)	deciduous		silt loam	Observed

Table A3: Overview of agroforestry literature reported, change (↑increase, ↓decrease, ~variable or no change) and reported methodology

Study		Change (%)				Methodology				
Authors, Year	**Country**	**River discharge**	**GW table**	**Soil moisture**	**Evapotrans-piration**	**Catchment size [km^2] (% afforestation)**	**Tree type**	**Bedrock**	**Soil**	**Data**
(Lawson *et al.*, 2019)		↓				NA	coniferous & deciduous			Modelled
(Mackay-Smith *et al.*, 2022)	New Zealand (Wairarapa)	X		↓		<0.1 (0.2%)	deciduous	greywacke and argillite	silty loam and silty clay loam	Observed
(Markwitz *et al.*, 2020)	Germany (Dornburg, Forst, Mariensee, Reiffen-hausen, and Wend-hausen)				~ (+31% to -16%)	< 0.1; <0.1; 0.2; 0.4; 0.5 (72%;6%; 11.5%; 12%; 8%)	deciduous			Observed
(Matocha *et al.*, 2012)		↓		X		NA	deciduous			Modelled
(Perry *et al.*, 2000)	USA (Minnesota)	↓		↓		NA	deciduous			Modelled
(Pollock *et al.*, 2009)	New Zealand (near Lincoln on the Canterbury plains)		↓ (-3.6%)	↓ (-9.1%)	↓	NA	deciduous		silt loam over gravels	Observed
(Rodríguez Pleguezuelo *et al.*, 2019)	Spain (Lanjaron)	~				4 (80%)	deciduous	Cordilleras Béticas	colluvium and residuum	Observed
(Schnabel and Parra, 2018)	Spain (Parapuños)	~		~	~	10 (NA)	deciduous		low organic matter content, Leptosols and Cambisols	Observed
(Seobi *et al.*, 2005)	USA (Greenley Memorial Research Center near Novelty)			↑ (3.6%)		<0.1 (NA)	deciduous		Putnam soil (fine, smectitic, mesic Vertic Albaqualf)	Observed
(Sharrow, 2007)	USA (Corvallis, Oregon)			~		NA	coniferous			Observed

Table A3: Overview of agroforestry literature reported, change (↑increase, ↓decrease, ~variable or no change) and reported methodology

Study		Change (%)				Methodology				
Authors, Year	**Country**	**River discharge**	**GW table**	**Soil moisture**	**Evapotrans-piration**	**Catchment size [km^2] (% afforestation)**	**Tree type**	**Bedrock**	**Soil**	**Data**
(Svoma *et al.*, 2016)	USA (Greenley Memorial Research Center near Novelty, Missouri)			~ (1.7% to -2.1%)	~	> 0.1 (NA)	deciduous			Observed
(Udawatta *et al.*, 2010)	USA (HARC, New Franklin, Missouri)	↓ (-70%)		↓		NA	deciduous		silt loam	Observed
(Udawatta *et al.*, 2011)	USA (Central Mississippi Valley and Central Claypan)	↓ (-15%)		↓		NA	deciduous		smectite clay-rich vs loess-derived deep Menfro soils	Observed
(Wang *et al.*, 2011)	China (Ecological Experimental Station of Red Soil)	↓		↓ (-46)	↓	NA	deciduous	Cretaceous sandstone	surficial clayey, sandy or their mixture deposits, ferruginized caprock and mottled zone	Modelled
(Zhao, 2012)	China (Red Soil Ecologi-cal Experi-mental Research Station)	↓ (-60)	↓ (-29)	↓ (-45)	↑ (11%)	NA	deciduous		soil is 450 cm deep, low in pH and nutrients and water retention capacity	Modelled

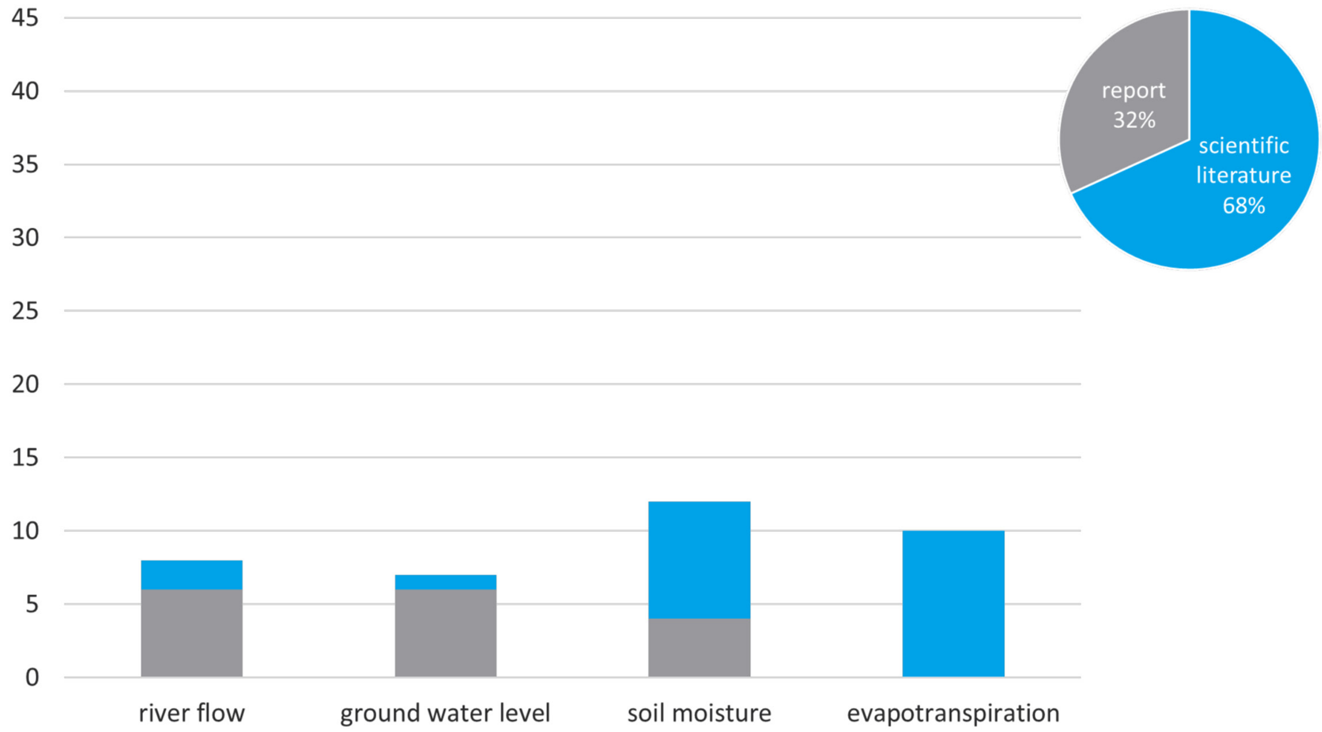

Figure A6: Overview of the type of available evidence (from scientific literature or grey literature reports) on the hydrological effects of wind farms.”

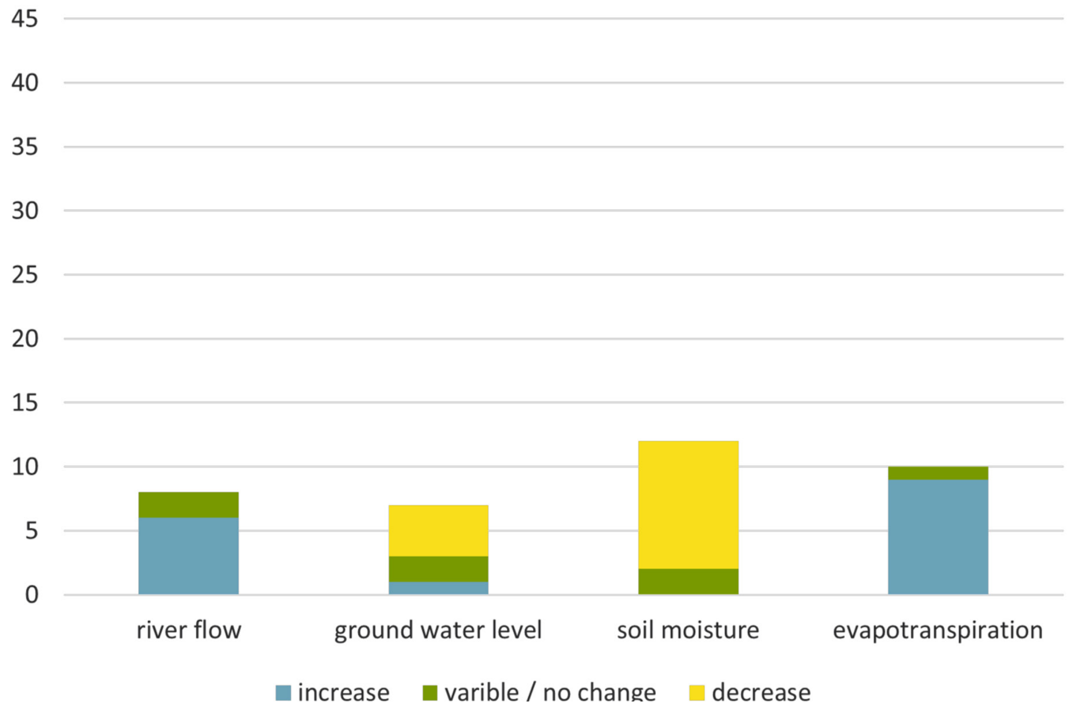

Figure A7: Overview of reported hydrological changes due to wind farms.

Table A4: Overview of wind farm literature reported, change (↑increase, ↓decrease, ~variable or no change) and reported methodology. Grey literature is highlighted in grey

Study		Change (%)				Methodology			
Authors, Year	Country (site name)	River discharge	GW table	Soil moisture	Evapotrans-piration	Study area [km²]* (%wind farm)	Nr of turbines	Bedrock	Soil
(Armstrong *et al.*, 2016)	United Kingdom			~ (0%)	↑ (3%)	18.6	54		peat
(EDF Renewables, 2022)	United Kingdom (Llaithddu)	~	↑			NA	17		peat
(Fred. Olsen Renewables, 2023)	United Kingdom (Balnespick)	↑	↓			NA	9		peat, podzols, peaty gleyed podzols
(Gomes *et al.*, 2019)	Brazil (Amarelas)		↓ (10%)			10.4	50		
(Hassanpour Adeh, 2018)	USA (Fowler Ridge)				↑ (15%)	NA	300		
(Headley, 2020)	United Kingdom (Tom na Clach)			↓		NA	13		peat
(Heal *et al.*, 2020)	United Kingdom (Whitelee)	↑			↑	0.1 - 12	215		glacial and recent drift deposits, peat
(Henschen *et al.*, 2011)	USA (Indiana)				↑ (52%)	NA	303		
(ITP Energised, 2022)	United Kingdom (Torphi-chen)	↑	~			NA	19		peat, till, glaciofluvial deposits
(Liu *et al.*, 2022)	China (Northern China)			↓	↑		7077		sand
(Liu *et al.*, 2023)	USA & China				↑	NA	25139; 24513		
(LUC, 2018)	United Kingdom (Muaithea-bhal)	↑		↓			45		carbon rich soils
(Millidine *et al.*, 2015)	United Kingdom (Allt a' Gheallaidh and Tulchan)	↑		↓		<0.1	28	Quartzite, feldspar, siliceous psammite	peat, peaty and humus-iron podzols
(Multiconsult, 2020)	Poland (Kuslin)		↓	↓		NA	12		
(Natural Power, 2023)	United Kingdom (Caithness)	~	~			NA	7		peat

* Most studies don't report on the area affected, so that scale is best represented by the number of turbines (see next column)

Table A4: Overview of wind farm literature reported, change (↑increase, ↓decrease, ~variable or no change) and reported methodology. Grey literature is highlighted in grey

Study		Change (%)				Methodology			
Authors, Year	**Country (site name)**	**River discharge**	**GW table**	**Soil moisture**	**Evapotrans-piration**	**Study area [km²]* (%wind farm)**	**Nr of turbines**	**Bedrock**	**Soil**
(NIEA, 2015)	United Kingdom	↑	↓	↓		NA	NA		
(Qin *et al.*, 2022)	USA & China			↓		NA	25139; 24513		
(Roy *et al.*, 2004)	USA (Oklahoma)			↓ (4%)	↑ (6.8%)	10000	10000		
(Slawsky *et al.*, 2015)	USA (Illinois)			↓	↑	NA	140		
(Wang *et al.*, 2022)	China (Inner Mongolia))			↓ (4.4%)	↑	NA	1096		chestnut soil, sandy soil, light chernozem
(Zhou et al., 2012)	USA (Texas)			~	~	NA	NA		

* Most studies don't report on the area affected, so that scale is best represented by the number of turbines (see next column)

Appendix 5 – Summary of the grey literature documents on international PWS practice and policy reviewed in the project

Grey literature includes legislation, policy frameworks, strategies, plans, programmes, project descriptions, consultations and policy and technical reports, and guidance and documentation associated to the development of administrative and regulatory processes such as EIAs. Table A.5 contains a summary of key documents reviewed in each of the countries included in the international insights (Appendix 6), and for Scotland and Northern Ireland.

In addition, anecdotal documentation has been reviewed to gain evidence insights from Canada (guidance on the development of wind farms: New Brunswick Department of Environment and Local Government, 2019) and Portugal (report on management of eucalyptus plantations for water supplies: Quintela *et. al,* 2021).

Table A.6.contains a list of international research projects that explore the management of land use or land use change, in particular afforestation and agroforestry, in relation to drinking water supplies, which documentation has been reviewed to identify the state-of-the art regarding the advancement of practice and policy recommendations. Some ongoing projects that are expected to deliver significant contributions for the topic of this report are described in section 4.1 of the main report.

Table A5: Summary of documents reviewed by country on measures regarding wind farm development	
Country	**Type of documents and cases reviewed and references**
Austria	Guidelines for conservation and protection of water supplies (Guideline ÖVGW W 72). Austrian Foret Report (Federal Ministry of Agriculture, Forestry, Regions and Water Management BMLFUW, 2023). Case-study reports on adaptive forest management in a number of Interreg funded projects (Boljat 2018; Čenčur Curk *et al.,* 2019; Courseau and Bojanowski, 2022; Katzensteiner *et al.,* 2014; Lukač Reberski, 2018) and associated literature (Koeck *et al.,* 2018).
Ireland	Ireland's Forest Strategy (Department of Agriculture, Food and the Marine, 2023) and River Basin Management Plan (Government of Ireland, 2021). Standars for felling and reforestation (Department of Agriculture, Food and the Marine, 2019). Specific planning regulations (Donegal County Council, 2022). Environmental Protection Agency Research Reports (Bresnihan *et al.,* 2021; EPA, 2021; Rolston *et al.,* 2017). The Water Forum Reports (O'Loughlin and Mozafari 2023; The Water Forum, 2021). Publications of the National Federation of Group Water Schemes (NFGWS, 2019, 2020). Documentation of the Interreg VA Project "Source to Tap" (Gallagher, 2018; McIntosh *et al.,* 2022)
New Zealand	Freshwater Package. Amendments to the national environmental standards for water supplies (Ministry for the Environment 2022; 2023a). Reports of the Minister for the Environment (Ministry for the Environment and Stats 2023). Guidance for freshwater farm plans (Ministry for the Environment 2023b). Standards and good practice for plantation forestry (Eastland Wood Council 2022; Ministry for the Environment and Ministry of Primary Industries, 2017). Guidance on the assessments of wind farms (Hobbs, 2022; New Zealand Wind Energy, 2023).
Norway	Report on water supply systems (Steinberg *et al.,* 2020). Description of projects on the topic of afforestation and water supplies at the Norwegian Institute of Bioeconomy Research (NIBIO) and the Norwegian Institute for Water Research (NIVA) (e.g., Skarbøvik, n.d.).
Spain	General (wide country) situation reports (Schmidt *et. al.* 2022) and regulations (MITERD 2020). Cases from the Northern regions: environmental impact stateaments from Galicia (MITERD, 2023: Badulaque, Galicia) and regulations in the Vasque Country (Vasque Government, 2021). Documentation of the projectS Life Rural Supplies (Life Rural Supplies 2015, 2018) and the Life URBASO (lifeurbason.com).
Scotland	General (wide country) regulations (SEPA, 2017a) and good practice and recommendations for wind farm construction (NatureScot, 2019; Scottish Renewables, 2019, 2015) and decommissioning (Welstead *et al.,* 2013). Responses to the Scottish Government Consultation on the Onshore Wind Policy Statement 2022. Cases exposed in the blog Winds of Justice (2019). Specific planning guidance considerations in several Local Authorities (Angus Council, 2017; East Ayrshire Council, 2017; Scottish Border Council, 2018; West Lothian Council, 2015). Also guidance offered by Scottish Water (n.d.). Adittionally, a number of scoping reports and specific report on EIAs of wind farm projects that refer to water supplies were reviewed: Ackron, Creag A' Bhaird, An Suidhe, Crossaig, Cloich Forest, Upper Sonachan, Brown Muir, Cloiche, Sneddon Law, Burnfoot Hill, Greenscares Plantation, Longcroft, Shepherds' Rig.
Northern Ireland	Guidance to developing EIA and planning (DAERA, 2019; NIEA, 2015; NIEA, 2009). Documentation of the Interreg VA Project "Source to Tap" (Gallagher, 2018; McIntosh *et al.,* 2022).

Table A6. Scoping list of recent international research projects exploring land-use impacts and management regarding drinking water supplies.			
Acronym	**Full tittle/topic**	**Funding**	**Timeline**
BIOCONSENT	Decision-making Support for Forest Biodiversity Conservation and Restoration Policy and Management in Europe: Trade-offs and Synergies at the Forest-Biodiversity-Climate-Water Nexus	Biodiversa+	2022-2025
BIOWATER	Integrating land and water management for a sustainable Nordic bioeconomy	Nordic Programme of Bioeconomy, NordForsk	2017-2022
CPES	Channel Payments for Ecosystem Services	Interreg France (Channel) England	2017-2020
FAIRWAY	Farm System Management and Governance for Good Water Quality and Drinking Water Supplies	Horizon 2020	2017-2021
FoWAP	Forests for drinking water protection	EUSDR CENTRAL EUROPE Programme	2012-2014
HOBO	Forest Management in Climate Change – Safeguarding the Soil Functions of Forest Ecosystems through Site-appropriate Timber Harvesting	Austrian forest Fund	2022-2025
INNOFOREST	Smart information, governance and business innovations for sustainable supply and payment mechanisms for forest ecosystem services	Horizon 2020	2017-2020
OPTAIN	Optimal strategies to retain and re-use water and nutrients in small agricultural catchments across different soil-climatic regions in Europe	Horizon 2020	2020-2025
OptFor-EU	OPTimising FORest management decisions for a low-carbon, climate resilient future in Europe	Horizon Europe	2023-2027
Package of Norwegian research (all in Norwegian)	• A limited literature review on forestry and water [a] • Assessing impacts on water from fertilizing forests[a] • Assessing impacts of forestry on the eutrophication of the Oslo Fjord (ongoing)[ba] • Assessing environmental impacts of different logging strategies (on-going)[b]	a. Directorates of environment and/or agriculture b. County municipality/ River Basin District of Viken	2021-present
PESFOR-W	Payments for Ecoysstem Services Forests for Water	COST Action	2016-2020
PROLINE-CE	Efficient Practices of Land Use Management Integrating Water Resources Protection and Non-structural Flood Mitigation Experiences	Interreg Central Europe	2017-2019
PROWATER	Managing landscapes for resilient water resources	Interreg 2 Seas	2017-2022
REFORMWATER	Reducing the Effects of Forest Management to inland Waters	JPI-Water, 2019-2022	2019-2022
SHARP	Sustainable Hydro Assessment and Groundwater Recharge Projects	Interreg IVC 2007-2013	2010-2012
SINCERE	Spurring INnovations for forest eCosystem sERvices in Europe (SINCERE)	Horizon 2020	2018-2022
SOS-Water	Water Resources System Safe Operating Space in a Changing Climate and Society	Horizon Europe	2022-2026
Source to tap	Cross-border partnership project focusing on the Erne and Derg catchments which span the Ireland-Northern Ireland border. The project aims to develop sustainable, catchment-scale solutions for the protection of rivers and lakes which are the main sources of our shared drinking water.	Interreg VA Programme	2017-2022
STARS4WATER	Supporting Stakeholders for Adaptive, Resilient and Sustainable Water Management	Horizon Europe	2022-2026
SURFER	Surface waters: The overlooked factor in the forestry climate mitigation debate	Research Council of Norway	2017-2020
TEACHER-CE	Joint efforts to increase water management adaptation to climate changes in central Europe	Interreg Central Europe	2020-2022

Table A6. Scoping list of recent international research projects exploring land-use impacts and management regarding drinking water supplies.			
Acronym	**Full tittle/topic**	**Funding**	**Timeline**
URBASO	Forest based solutions for surface drinking water protection, biodiversity, bioeconomy and climate resilience	LIFE20	2021-2025
WAMBAF	Water Management in Baltic Forests	EU Interreg BalticSea Region Programme	2016-2019
WATERAGRI	Water retention and nutrient recycling in soils and streams for improved agricultural production	Horizon 2020	2020-2024
WaterProtect	Innovative management for drinking water resources protection	Horizon 2020	2017-2020

Appendix 6 – International insights on policy and practice

Policy and practice insights – Austria

In Austria, around 10% of population is self-supplied by the equivalent to PWS via springs or wells, and the Federal Ministry, the provinces and municipalities share responsibility for environmental regulation and the protection of water resources (Deane and Mac Domhaill, 2021).

Relevant for the protection of water supplies is the Guideline ÖVGW W 72 "Water protection and conservation areas" (2004) aimed to guarantee the quality and quantity of groundwater for drinking water supply, serving as a support for the designation of protection zones. It establishes three zones for the protection against pollutants and also disturbances of water quantity: i) capture zone, ii) inner protection zone with 60-day-residence-time of water, and iii) outer protection zone, 360-days), with different land use and management restrictions. It has been highlighted that the constant monitoring of the areas by the people responsible of the water supplies is critical, due to developers not always respecting the guidelines, sometimes due to lack of knowledge about them (Katzensteiner *et al.,* 2014).

Forestry is an important land use in Austria, and the role of good forest management in protecting water supplies is nationally recognised. The national strategy recognises the function of forest in cleaning drinking water (Federal Ministry of Agriculture, Forestry, Regions and Water Management BMLFUW, 2023) but it does not mention water availability at all.

There have been several projects looking into forest programmes for water protection. One of such initiatives, for example has been developed through several projects (CC WATERS, PROLINE, TEACHER-CE), based on the development of the knowledge management strategies combining a Forest Hydrotope Model, a spatially explicit survey-based model, along a catalogue of Best Practices for water protected areas that results in tailored guidance for safeguarding water supplies (Koeck *et. al.* 2018).

Policy and practice insights – Ireland

In Ireland there are over 1,750 small rural water supplies registered with local authorities and over 400 group water schemes (serving just under 200,000 people) set up by a local community that manages the abstraction, treatment and distribution of treated water. In addition, there are approximately 180,000 private wells, that are not regulated under the Drinking Water Regulations and are not discussed in this report. Collectively, one fifth of the people of Ireland get their water from these private supplies" (EPA, 2021).

The National Federation of Group Water Schemes (NFGWS), which represents and works with the community-owned group supplies, published a handbook of source protection and mitigation actions for farming (NFGWS, 2020) that includes action on woodlands and agroforestry. However, these considerations are only regarding water quality, and not impacts on quantity. The NFGWS also works with local authorities and individual group water schemes to identify and address ongoing water quality issues and risks" (EPA, 2021).

Ireland's Forest Strategy 2023–2030 contains a section dedicated to the interactions of forests and water, but it is exclusively considering the interactions regarding water quality of the supplies.

Agroforestry and planting with native woodlands is considered a management option that contributes directly to water quality benefits from a perspective of integrated land management, however there is no mention to water quantity (The Water Forum, 2021).

However, Forestry 2030 is anticipated to have indirect impacts on water balance/yield (Rolston *et. al.* 2017) and it is recognised that "it is critical that water quantity is included in conversations about a sustainable economy and future climate change, due to the significance of a resilient water supply to support both population growth and economic sustainability." And so it goes on making a call for integrated catchment management and resource planning (O'Loughlin and Mozafari, 2023).

The Department of Agriculture, Food and the Marine published standards for felling and reforestation (2019) that include specific guidelines required from all felling (thinning, clear-felling) and reforestation projects, undertaken under a felling licence issued under the Forestry Regulations 2017, and include specific requirements and measures regarding the harvest plan and pre-, during and post-operation, including templates for harvest plan, contingency plan for forestry operations and monitoring records.

The Ireland-Northern Ireland cross-border Interreg Project "Source to Tap" looked into watershed management for water supplies around several topics, one of which was forestry (Gallagher, 2018; McIntosh *et al.,* 2022). The focus of the project was quality protection, but some of their insights are valuable for considering the supplies from a quantity perspective as well. Information is accessible via https://www.sourcetotap.eu/water-professionals-land-managers/forests-for-water/.

Policy and practice insights – New Zealand

Quality and quantity concerns of supplies are considered in New Zealand as risks to supply sufficient safe drinking water for rural communities, particularly the marae (Ministry for the Environment and Stats, 2023).

New Zealand has been updating its policy and regulatory framework for the protection and management of environmental resources, including freshwater, natural resources, and environmental standards. In 2022, the New Zealand Government consulted on proposed amendments to the National environmental standards for sources of human drinking water (NES-DW) to improve the protection of human drinking water sources, and the Ministry for the Environment would have been since then revising the proposal based on feedback received during consultation. One of the proposals was to extend the protections of the NES-DW to smaller registered drinking water supplies (supplies serving 500 people or less), but following on consultation the Ministry would have decided not to action this (Ministry for the Environment, 2023a). In the consultation concerns were risen questioning the impact that that the amendments would have on small water suppliers, for not being proportional (benefits outweighing the cost) and need to consider simpler alternative solutions for small supplies (Ministry for the Environment, 2022).

Considerations for forestry and agroforestry

In New Zealand in general there are no issues with forestry as a land use in relation to water yield under existing rainfall patterns. However, some councils had concerns on the potential impacts of afforestation reducing water quantity in surface water or groundwater supplies, and so had policies and rules pertaining to afforestation and reforestation in place, particularly given increased uncertainty and unpredictability in future rainfall patterns (Meason *et al.,* 2019).

In 2020 came in to force a new package of Freshwater policies and regulations. A key part of this package are Freshwater farm plans, intended to support farm planning regarding water. Freshwater farm plans need to contain maps that show private drinking water supply points (Ministry for the Environment, 2023b). The Freshwater Farm Plans regulations requires "regional councils to collate existing information about the catchment context, challenges, and values relevant to its region, including on the following categories:

- Landforms, soil data, climate data, freshwater data, freshwater bodies, contaminants, sites that are significant to the community, and significant species or ecosystems
- Cultural matters of importance to tangata whenua (people of the land), including the traditional names of freshwater bodies in the local area; and significant sites.
- Any objectives, policies, and rules relevant to the management of freshwater or freshwater ecosystems in policy statements or the regional plan
- Any relevant freshwater matters in planning documents that are recognised by iwi authorities and lodged with the regional council, the National Policy Statement for Freshwater Management and any action plans made by the regional council (Ministry for the Environment, 2023c).

Policy and practice insights – Norway

Norway started in 2017 the registration of PWS (small water supply systems supplying 50 people or less) with a mechanism based on self-reporting. Still, figures for PWS in Norway are seen insufficient (4,741 registered at the end of 2019) (Steinberg *et al.,* 2020). There is a lack of studies on land-use impacts on small supply systems.

Speaking of water supplies in general, the focus of concern is impacts of forestry activities on the quality of supplies, mainly linked to the momentum of the bioeconomy, even if following the Programme for the Endorsement of Forest Certification) Still, experts consulted affirmed this is still a field in development with a number of recent and ongoing studies financed by the environmental and agricultural authorities (e.g., Futter *et al.,* 2019; Kaste *et al.,* 2021; Skarbøvik *et al.,* 2023; Sundnes *et al.,* 2020). One of the issues highlighted is that there is no data available, so there is the need to implement monitoring stations.

Policy and practice insights – Spain

Independent and small water supplies in Northern regions in Spain experience pressures and challenges similar to PWS in Scotland, including pressures from afforestation and wind farm development. The detailed identification of water supply sources with updated information available cross stakeholders and the need to enhance administrative coordination and governance arrangements are highlighted as two critical aspects to advance on the protection of small water supplies.

Spain is a country with much higher levels of water stress that Scotland. Northern regions in the country (e.g., Galicia, Asturias, Cantabria and Vasque Country) have a wetter climate than the rest of the country and also include a high proportion of small PWS water supplies (Naves and Varela-Alvarez, 2021).

Recently, concerns about the potential impact of wind farm developments in small PWS catchments has mobilized community and environmental groups against the development of specific projects in Galicia and Cantabria. This reached the international media (e.g., news piece in Le Monde "En Galice, des écologistes protestent contre «l'invasion éolienne»" (Morel, 2022)) and in some cases the development was halted. In these cases, the impacts on water supplies was included among a larger list of impacts that led to the objection (see e.g., Gobierno de Cantabria, 2023 – Bustafrades wind farm project).

Afforestation has also been identified as an important pressure to small water supplies due to the reduction of recharge and increased tree water use (Life Rural Supplies, 2015; Schmidt *et al.,* 2022), supplemented by the extension of wildfire risks during droughts (Life Rural Supplies, 2018).

In a recent study of small PWS, Schmidt *et al.,* (2022) identified a series of issues in the protection of supplies and offered insights on guidance and solutions:

- In many cases the supply sources, and particularly groundwater intakes, are not adequately identified in the hydrological planning processes and so are not considered as part of delimiting protection perimeters. To solve this, the authors of the study pointed out the need to improve available knowledge and coordination between administrations, including the users' participation regarding the governance of water for humans. Although focusing on water quality issues, the authors pointed out the need for a complete identification of all collection points and points of use, as the essential first step for any adequate planning and for the definition of perimeters of protection and application of the corresponding preventive measures.
- Need to improve coordination between administrations (in particular local authorities, basin management organisations, and health departments) due to inconsistencies among the information managed by different institutions. Ideally all the administrations involved could cross-reference the available data, to achieve a robust and reliable common information system.
- Protection perimeters are typically established by catchment management authorities for supplies that serve more than 10 m^3 per day or that supply more than 50 people (the equivalent to regulated PWS in Scotland). Among the criteria needed to be taken into account for the delimitation of the protected areas, for groundwater supplies, it was indicated that if there are several nearby catchments, these could be grouped into the same protected area, which can cover the entire groundwater mass (Order ARM/2656/2008, of September 10). Protection zones might differentiate between zones of immediate (1 day of travel time or 25m), nearby (50 days travel time) and far away (10 years travel time) protection.
- There is no equivalent to the "the polluter pays" principle -what they call "the damager pays"- from the water quantity perspective, particularly when referring to groundwater supply users. The authors of the report suggested the development of appropriate fiscal instruments to implement such principle to the sector involved (in the case of their report, agricultural sector).

Schmidt *et al.,* (2022) noted the need for regulating procedures that allow domestic supplies to be safeguarded in all cases against other uses (e.g., that the surface or underground sources that sustain the supplies are not overexploited and that, if resources are insufficient resources for all uses, are other uses rather than drinking water the ones facing restrictions). However, such procedures are not in place yet. Measures pointed out by the authors as desirable in that line are greater control of water withdrawals, constitution of a community of users and the establishment and compliance of an action program that regulates the extraction regime to achieve a rational exploitation of resources, and the reduction of extractive pressures in water masses with pressures associated with the amount of water, through hydrological planning and its measurement programs.

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