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Executive Summary

Forestry operations potentially exert various influences on water quality, with impacts varying depending on soil properties, slope, local climate, seasonal variations, and distance from operations to water. Management practices such as tree species selection, harvesting and thinning can be improved to mitigate risks, ranging from short-term fluctuations to long-term trends. These operational practices coupled with interventions, such as the incorporation of buffer zones for woodland establishment, highlight the importance of effective environmental management. With regards to forestry operational and compliance purposes the current process is deemed sufficient for identifying site level high risk area to inform mitigation. However, understanding the cumulative impacts and attributing them to specific landscape characteristics pose significant challenges, reinforcing the intricate nature of impact assessments. While existing models serve as valuable tools to guide assessment of forestry impacts, many lack comprehensive integration with water quality considerations and forestry activities as the inputs. The Scottish Environment Protection Agency (SEPA) believes there is a critical need for a model that should include the development of harvest timing and location-specific mitigation strategies (e.g., road networks, presence, and characteristics of buffer zones), particularly concerning activities near watercourses and steep areas. The project found that a quantitative model is not currently available. Although such quantitative model is likely to be complex and have high uncertainty, such tools would also help SEPA identify where environmental impacts were most likely and hence where mitigation was most needed. This highlights the necessity for enhanced strategic planning to address environmental risks effectively. Our data show a notable gap in modelling efforts needed to effectively couple water quality dynamics with forestry operations, emphasising the imperative for further research and innovation in this area.

Purpose of research

1. To evaluate current evidence on the impacts of commercial forestry activities on water quality and identify high risk parameters and conditions where commercial forestry activities could adversely impact water quality.
2. What are the modelling needs of stakeholders to assess the impact of forestry on water quality in Scotland?
3. What relevant literature exists regarding the hydrological modelling tools utilised to assess forestry operations?
4. Are available hydrological models suitable, based on water quality and key criteria such as development purpose, model design and structure, processes, accessibility, usage, support data?

Background

Forestry operations can pose risks to water quality from traffic, ground disturbance, brash decomposition and inputs like chemicals and fertiliser if managed ineffectively. Concerns about the impact of commercial forest operations on water quality at various scales of catchment areas have been highlighted, requiring a shift towards more sustainable practices under the challenges of climate change. Despite efforts to minimise environmental impact, the risks of operational errors and non-compliance remains an issue, necessitating their identification and monitoring. Furthermore, restrictions placed on harvesting can lead to narrower harvesting windows and therefore harvesting can occur during periods of higher potential risk. Diffuse pollution, primarily from nutrients, sediments and dissolved organic carbon, poses a significant risk to vulnerable ecosystems. Hydrological models can estimate environmental impacts, but results have been inconsistent due to a lack of appropriate models and data to evaluate forestry activities for planning. Improving modelling approaches is therefore crucial for understanding and predicting risks to water quality so that management plans and mitigation strategies can be improved.

Method

Directed by stakeholder engagement with forest industry professionals, government professionals, regulatory bodies and researchers, a comprehensive literature review was conducted to evaluate the suitability of existing models in predicting forestry activities and their impacts on water quality. The qualitative review focused on examining the input parameters of these models, their ability to incorporate both forestry activities and forest hydrology, as well as their capability to simulate factors such as dissolved organic carbon, carbon, and sediment load. Valuable information on perceived impacts on water quality from forestry was collected from regular stakeholder meetings and workshops. The literature search extended to models used for other land-based activities, such as agriculture, providing a direction of future forestry-focused models.

Key findings

1. Model review

- Reports from stakeholders and practitioners identify significant localised impacts on water quality from forestry activities, but on a larger catchment scale, there is a lack on evidence of significant impacts in published literature.
- From a review of over 1,700 papers, 41 potential models that could be applied to assess water quality impacts from forestry were identified.
- None of the models produced outputs that coupled forestry activities as inputs with key water quality output parameters dissolved organic carbon (DOC), sediment, and carbon.
- Only 4 models are available that consider both forest operations and forest hydrology impacts, but these lacked water quality outputs.
- Existing models do not integrate small-scale point-source impacts more likely found in forestry to assess larger-scale risks.
- Based on existing models, the potential exists to develop a forestry water quality model for Scotland, but data requirements vs. availability presents a challenge, as well as uncertainties on applicability of models across locations.

2. Stakeholder Workshop – key points

- Pathways (drains, watercourses) as well as receptors (private wells) are important for forestry water quality impacts.
- Forest Research have concentration and nutrient flux data, which could help model development.
- Trade-offs in environmental benefits are important to assess, especially if positive mitigation strategies for one aim have a negative impact on another.
- Soil disturbance and runoff from harvesting were viewed as major sources of diffuse pollution, and although some evidence of the risks exists, further understanding of impacts is required.
- A GIS approach focused on soils, topography and drainage would be accessible and could link to environmental impact assessments. Ideally these data would be used in a high-level qualitative risk model to highlight where the potential for pollution is greatest and therefore additional care/more thorough environmental impact assessments and compliance audits are needed.
- Forest Research have long-term water quality datasets, e.g., on the effects of conifer afforestation on water quality, the effects of forest harvesting on water quality and the effects of fertilisation on water quality. They also have data on methods to mitigate the effects of forest operations on water quality, nevertheless these although long-term, are limited in terms of encompassing a wide range of physical and climatic conditions. Therefore, although very valuable, it is still deficient in allowing effective assessment of impacts on water quality under a range of conditions (soil types, elevations/slope, weather conditions and forest harvesting approaches).

Recommendations

1. The deficit in available models tailored for assessing the impacts of commercial forestry on water quality, limits the capacity to mitigate risk.
2. Decision-making processes concerning forestry practices and land use planning should be driven by an understanding of the vital role of factors like soil type, slope, connectivity and precipitation in determining forest water quality. Current UKFS Guidelines and associated Guidance have been developed by considering such factors.
3. Prioritising key activities such as watershed forest management, forest road networks, and harvest operations in future modelling efforts is crucial.
4. Supporting the integration of both forestry activities and forest hydrology as inputs in modelling endeavours will lead to a better understanding of forest water quality dynamics and support informed decision-making.

5. Understanding of forest water quality dynamics and support informed decision-making by practitioners in Scotland. As a first step, a qualitative risk-based model should be developed using a GIS approach focused on soils, topography and drainage that would allow for the identification of high-risk areas and scenarios. Subsequently, a quantitative model, supported by long-term data, is ultimately needed in assessing these impacts and risks adequately.
6. To develop a high-level model to qualitatively identify areas of high risk, it is possible that sufficient data and expert knowledge already exists. It is recommended that such a model is developed to provide a workable tool for stakeholders until a more robust quantitative model can be developed.

1 Introduction

1.1 Background and scope

Concern over the impact of commercial forest operations on water quality is a recurrent issue in the management of water catchments in Scotland. In recent decades, there has been a significant shift in forest management practices towards minimising environmental impacts. These are overseen by the UK Woodland Assurance Standard and The UK Forestry Standard (UKWAS and UKFS, 2023), an independent certification standard for verifying sustainable forest management in Britain. While detailed practical field guides based on UKWAS and UKFS are available to support foresters in planning forest operations in relation to water discharge levels and quality and assess and identify high-risk areas (e.g., Nisbet, 2019), the risk of operational errors/non-compliance remains and therefore it is important to identify when these instances occur. The potential risks of diffuse pollution from forestry are primarily associated with nutrient input like phosphorus to vulnerable upland lochs, either from the use of fertilisers during tree planting or disruption of soils when planting or felling trees. There can also be effects of forest operations on water quality from practices such as cultivation, drainage, and road construction (e.g., Shah *et. al.*, 2022).

Water quality impacts from forestry operations could have major off-site impacts if non-compliant practices occur. Forests serve as critical components of global hydrological, nutrient, and carbon cycles, exerting a significant influence on water dynamics and playing essential roles in runoff generation, groundwater recharge, and the transport of water to riverine and lake systems (Schäfer *et. al.,* 2023). Furthermore, they dominate carbon exchange between the atmosphere and terrestrial biosphere, accounting for about 80% of the global aboveground biomass and offering vital opportunities for carbon sequestration and storage in standing biomass and wood products (Shah *et. al.,* 2019). With these, forests exert a significant influence on aquatic ecosystems by delivering water, sediments, nutrients, and carbon. Consequently, alterations to forest ecosystems, such as felling/restocking, wildfires, and pest infestations, can profoundly impact water quality and aquatic carbon fluxes. By extension, dissolved organic carbon (DOC) transport is particularly significant, affecting terrestrial carbon loss related to global warming and the treatment of drinking water quality (Zhang *et. al.,* 2017). Concern has escalated due to reported increases in DOC concentrations in both forested and non-forested environments (e.g., Foster *et. al.,* 2024; Shah *et. al.,* 2019). Additionally, soil and surface water acidification remain relevant issues, especially in forested regions with sensitive geology and high deposition of sulphur and nitrogen and other pollutants. For instance, the mobilization and methylation of mercury post-forest harvest pose further concerns due to its toxicity and potential effects on freshwater ecology (Bishop *et. al.,* 2020). Given the sensitivity of many species, such as fish and freshwater invertebrates, to changes in water quality, there is increasing examination of forest management practices and their impacts on aquatic environments (Park *et. al.,* 2008). Therefore, the forestry industry's impact on water quality is a critical concern due to the diverse array of species inhabiting both natural and plantation forests.

Nevertheless, many of the negative effects associated with forest harvesting can be significantly reduced by low impact harvesting systems that are now widely applied in commercial forestry practice (e.g., Killmann *et. al.,* 2002) commercial forestry practice (e.g., Killmann *et. al.,* 2002), although potentially less so in Scotland due to the higher costs associated with these harvesting approaches. As a result, there is a need to evaluate, monitor and predict the changes in forest water quality due to commercial forestry practices. This study highlighted and attempted to describe the current evidence with regards to forestry impacts on water quality and examined the modelling research needs to support environmental decision-making of management practices to improve water quality of forests particularly regarding forestry activities. This was achieved by examining currently available models and considering the necessary inputs for forest water quality and related watershed programmes.

1.2 Project objectives

The aim of this study was to gather evidence on potential impacts of commercial forestry operations on water quality and to assess suitability of available hydrological and hydrochemical models in determining the impact of commercial forestry operations on the quantity and quality of water. A key feature of this study was identifying deficiencies in the spatial discretisation, assumptions, accuracy, and data needs of current models. This allowed an objective assessment of the ability to predict risks associated with commercial forestry operation in relation to threats from other land uses. While general concepts and a wide range of results were used, the emphasis was on commercially managed forests within the UK, as well as temperate and boreal zones of Continental and Northern Europe. Furthermore, the project aimed to identify pollutants of concern, risk factors and vulnerable habitats which future policies can focus on. Areas of data weakness were also identified. With these, the following questions were considered:

1. What current evidence exists on the impacts of commercial forestry activities on water quality?
2. What are the modelling needs of stakeholders to assess the impact of commercial forestry operations on water quality in Scotland?
3. What relevant literature exists regarding the hydrological modelling tools utilised to assess commercial forestry operations?
4. Are available hydrological models suitable, based on water quality and key criteria such as development purpose, model design and structure, processes, accessibility, usage, support, data?

2 Current evidence of impacts of commercial forestry activities on water quality

Generalising impacts on different aspects of water quality from commercial forestry operations can be extremely challenging due to the large number of site-specific parameters and characteristics (for example, soil type, slope, connectivity, precipitation levels following the activity etc.), that may interact and have a profound influence on the results (Shah *et al.,* 2022. Issues in relation to impacted water quality (mostly sedimentation, see for example Safeeq *et al.,* 2020) from logging and forest road construction sites indicate that there can be an issue with these activities impacting local receiving waterbody water quality (see workshop participant comments in section 5). In literature, there is evidence for example, of significant increases in nutrients in receiving waterbodies following tree felling, with these changes not detectable on a bigger scale (Neal *et al.*, 2004a, Palvianen *et al.,* 2014, Deval *et al.,* 2021). There is also strong evidence that nutrient increases in receiving waterbodies post tree felling are strongly linked to rainfall and water flow (Harr and and

Fredriksen, 1988). Overall, from the evidence available from primary literature, the impacts of forest management activities on water quality tend to range from no impact to moderate levels (Table 1).

Table 1. Summary of evidence of potential impacts of forestry activities on aspects of water quality. Cells are colour-coded based on the assessment of the impacts within each study; "White" no available literature/evidence of impact, "Green": no impact; "Yellow": low/medium impact; "Red": high impact. This categorical assessment is based on the consensus derived from the evidence available from primary literature.

Parameters	Main activity - Logging	Main activity – tree planting	Main activity – road construction	Receptors (streams, rivers, lochs, and wetlands)
Hydrology	(Thomas and Megahan, 1998; Neal *et. al.*, 2004b; Robinson and Dupeyrat, 2005; Tezlaf *et. al.*, 2007)	(Ponette-Gonzalez *et. al.*, 2015; Filoso *et. al.*, 2017)	(Thomas and Megahan, 1998)	Streams, Groundwater
DOC	(Tezlaf *et. al.*, 2007)	(Shah *et. al.*, 2021)		Streams
Phosphorous	(Binkly and Brown, 1993; Nisbet, 2001)	(Binkley *et. al.*, 1999; Shah and Nisbet, 2019)		Stream
Nitrates	(Binkly and Brown 1993; Neal *et. al.*, 2004)	(Shah *et. al.*, 2021)		Streams
pH	(Shah *et. al.*, 2021) (Nisbet, 2014)	(Nisbet, 2001) (Nisbet, 2014)	(Nisbet and Evans, 2014)	Streams
Sediment	(Bathust and Iroume, 2014)		(Binkly and Brown, 1993; Bathust and Iroume, 2014); (Kastridis, 2020)	Streams

3 Existing models relating to water quality

Models are used in applications around various forest watershed management issues including water supply, water quality, carbon sequestration and biodiversity. The term "model" describes the set of equations or algorithms that are used to simulate a physical system. To address a specific technical problem, an analyst may choose to apply an existing model, apply multiple models alone or in combination, modify an existing model, or develop a site-specific model. Each application of a model must be designed to meet the analytical needs of the specific system. Therefore, models serve to address inquiries, aid in decision-making processes, and evaluate options; they function as a tool for comprehending and illustrating the dynamics of physical systems, including in applications encompassing watersheds and bodies of water such as lakes, rivers, estuaries, and coastal regions (e.g., Zhang *et. al.,* 2017; Sun *et. al.,* 2024).

Developing models that accurately depict watersheds and waterbodies poses a significant challenge, requiring analysts to meticulously determine how to depict the system with adequate precision to inspire confidence in the outcomes. Practical and technical limitations necessitate that the system's representation aligns with available data, time, resources, and scientific comprehension. Each modelling endeavour must confront this challenge, striving to strike a balance between the requirements of the specific study and the requisite level of accuracy and dependability (Sun *et. al.,* 2023). Despite models being utilised successfully in environmental and water quality management since the 1970s, new complexities have arisen due to the diverse array of pollutants, sources, and conditions of receiving waters requiring assessment. Watershed and forest management planning increasingly rely on modelling to establish restoration objectives and to identify the necessary reductions in pollutant loads (e.g., Schäfer *et. al.,* 2023).

Most models focus on specific land-water features; some are dominantly receiving water models, while others are primarily oriented to calculating watershed loading. Two broad classes of models are 'watershed' and 'receiving water' models. Both receiving water and watershed models can incorporate the ability to simulate management techniques. Watershed models tend to operate at large-scale, exploring how inputs and hydrological processes within a watershed affect the cycling and transport of water, nutrients, and pollutants within a geographically bounded system. The receiving water group of models emphasises description of hydrology and water quality of water conveyance systems, including rivers, canals, reservoirs, lakes, and estuaries. Some include bi-directional flow, pumps, and operations in freshwater systems. Others include evaluation of tidal systems and the influences of wind, waves, and tides on mixing. Water quality simulation mainly involves representation of sediment and pollutant transport and transformation. Some models include ecological processes, such as vegetative growth, aquatic organisms, and aquatic productivity. Not all receiving water models address water quality. Sometimes, water quality functions are provided by linking hydrological and water quality models. On the other hand, the watershed group of models emphasises description of watershed hydrology and water quality, including runoff, erosion, and wash-off of sediment and pollutants. Some models include surface-groundwater interactions and simplified groundwater transport. Some also include internally linked river transport and water quality processes and reservoirs (Zhang *et. al.,* 2017; Sun *et. al.,* 2024).

Therefore, to comprehensively assess the hydrological impacts of forestry activities, a model is needed that can address changes in hydrology resulting from forestry operations, offering insights into potential alterations in water flow patterns with sub-catchment scale features. The model needs to be designed to evaluate the specific impacts on sensitive habitats and private water supplies, particularly focusing on sediment and nutrient dynamics. Combining these modelling needs is challenging. The overview of modelling approaches reveals a notable gap in the connection between water quality and forest management, with few existing models addressing this nexus. Despite the broad-scale nature of current modelling efforts, there is a deficiency in linking them to specific management practices to provide utility in helping with planning. Our comprehensive qualitative assessment was undertaken according to forest water quality-related research generated with VOSviewer and based on 1,700 publications. Details are shown in Figure 1. Our research was conducted based on model inputs, forestry impacts and forest hydrology, and whether models can assimilate both forestry activities and forest hydrology, structure, and have capabilities to simulate dissolved organic carbon, carbon, and sediment load. The models investigated are listed in Table 2.

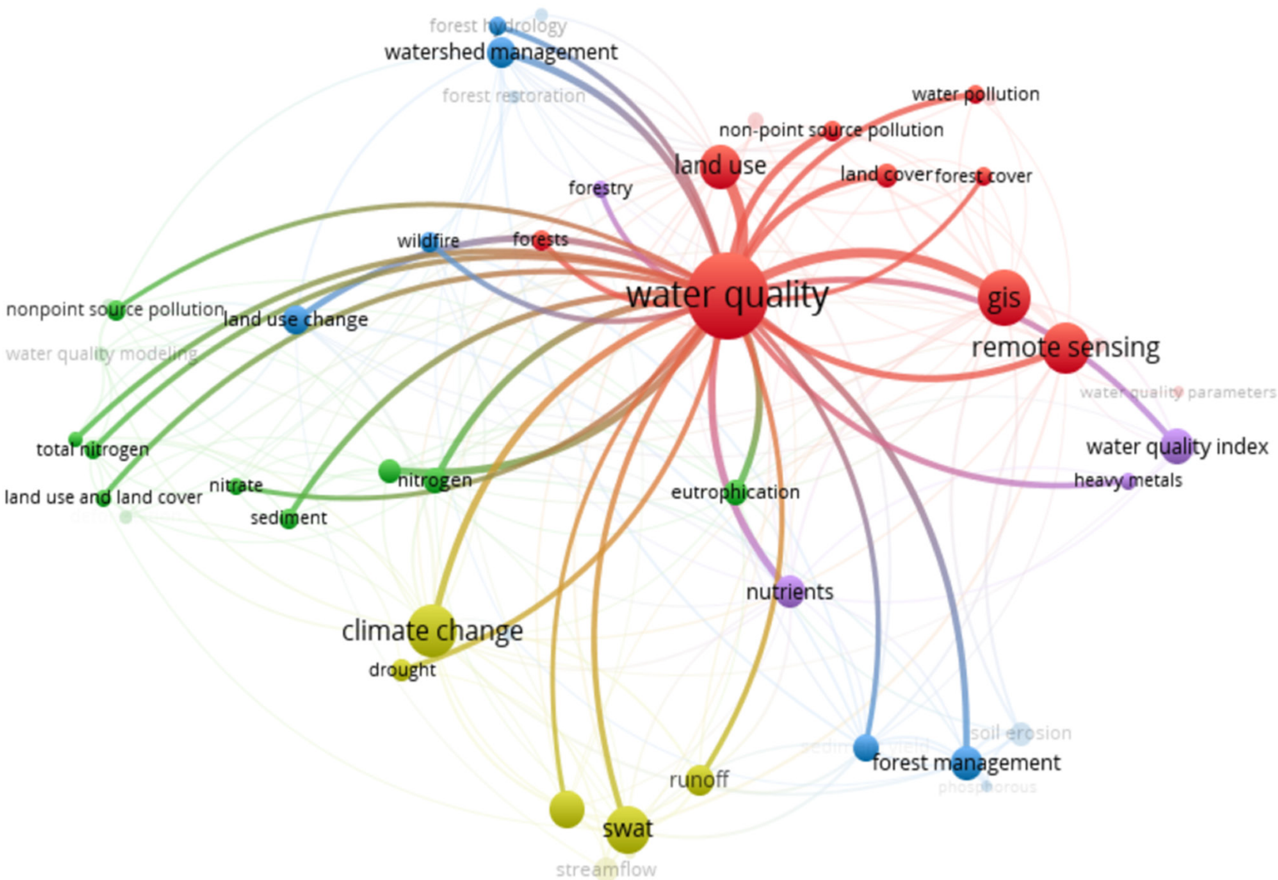

Figure 1. Intersectoral gap in Forest water quality-related research generated with VOSviewer and based on 1700 publications using the keywords *"forest water quality, modelling forest water quality, forest water quality and GIS/SAGIS, Forest based hydrological model, Forest management and water quality".* Each circle corresponds to a keyword found in the articles and is linked by a line if it co-occurs frequently in articles. The size of the circles corresponds to the number of occurrences of a keyword.

4 Model Evaluation

In assessing the models (Table 2), our initial focus was on several key aspects. Firstly, we identified the most important water quality parameters related to forest environments including DOC, sediment, and carbon. Secondly, we evaluated the models' capacity to generate predictions based on various management practices, including factors with forest hydrology impacts (e.g., land use, soil properties, etc.) and forest operations (e.g., planting and logging, etc.). The latter was mainly examined to understand the data requirements to represent the main factors as the inputs. Finally, we assessed each model's potential for up-scaling to assess impacts at the catchment/watershed scales, ensuring their applicability for comprehensive environmental assessments across larger geographical areas.

Our extensive qualitative review reveals that most models (e.g., WEPP-WQ, FS-WEPP, etc.) applied in forest areas consider biophysical factors such as soil, slope, and land cover/use, indicating the potential for monitoring forestry impacts on water quality. While water quality parameters such as dissolved organic carbon (DOC), carbon, and sediment are explored, only a minority of models incorporate all these concerning forestry activities and planning (Table 2). These models (e.g., SWAT, WASP, ANSWERS, HSPF, etc.) exhibit varying data demands, with some requiring heavy datasets while others operate with lighter requirements. For instance, models considering detailed drainage systems necessitate extensive data inputs compared with those focusing on broader landscape features. Despite this, only a limited model incorporates forestry activities as input parameters, including road networks, thinning, planting, and harvest (i.e., WFMIS, Table 2). This information is delineated in Table 1 of the assessment. In summary, none of the models sufficiently integrate forestry and water quality impacts, nor can they accurately identify localised impacts and scale up to assess catchment-level water quality impacts. Additionally, data availability is limited, particularly for more complex models in Scotland because all decision-making processes of the forestry operations are conducted based on regional risk assessments and guidelines proposed.

Only one simple model (i.e., WFMIS) brought together forestry operations and water quality, but it is no longer available for download and technically does not provide any information about sediment load, carbon, and DOC, and thus forest hydrology impacts. This model is a decision support tool (i.e., a GIS-based framework for forest management by providing systematic approaches and resources to aid decision-making processes), where users could input information about forestry operations and the landscape. Other models, like SWAT and its derivatives, work well with large-scale datasets (spatially and temporally) like soil maps and topography that are available for Scotland. However, these fail to incorporate point-source impacts that could affect forestry operations, especially from localised compaction and shear damage of soils by harvesting equipment.

Potential exists to include climate change predictions in some models (e.g., SWAT, FORHYCS, RHESSys, MC2, Budyko), so that future forestry impacts could be predicted. But again, these would not include localised impacts, especially in instances of non-compliance.

Table 2. The water quality models and the details of qualitative assessment.

	Models	Full model name	Forestry inputs	Forestry impacts	Forest hydrology	Both forestry and forest hydrology	Structure/ spatial discretisation	DOC (dissolved organic carbon)	Carbon	Phosphorous	Sediment
1	SWAT	Soil and Water Assessment Tool	No	Yes	Yes	No	Watershed	Yes	Yes	Yes	Yes
2	HEC-HMS	Hydrologic Engineering Center Hydrologic Modelling System	No	Yes	Yes	No	Watershed	No	No	Yes	Yes
3	MIKE SHE	Systeme Hydrologique Europeen	No	Yes	Yes	No	Watershed	Yes	Yes	Yes	Yes
4	RHESSys	Regional Hydro-Ecological Simulation System	No	Yes	Yes	No	Watershed	Yes	Yes	No	Yes
5	WEPP	Water Erosion Prediction Project	No	Yes	Yes	No	Watershed	Yes	Yes	Yes	Yes
6	WaSiM-ETH	Water Flow and Balance Simulation Model-ETH	No	Yes	Yes	No	Watershed	No	No	No	No
7	DRAINMOD-FOREST	Drain Modification- Forest	No	No	Yes	No	Watershed	Yes	Yes	Yes	Yes
8	AQUATOX	Aquatic ecosystem- Toxic organics	No	Yes	Yes	No	Watershed	No	Yes	Yes	Yes
9	HSPF	Hydrological Simulation Program – Fortran	No	Yes	Yes	No	Watershed	Yes	Yes	Yes	Yes
10	WFMIS	Watershed Forest Management Information System	Yes	Yes	No	No	Watershed	No	No	No	No
11	SEEA-EA	System of Environmental Economic Accounting-Ecosystem Accounting	No	Yes	No	No	Watershed	No	No	No	No
12	FORHYCS	FORests and HYdrology under Climate Change in Switzerland	No	Yes	Yes	No	Watershed	No	No	No	No
13	SPARROW	SPAtially Referenced Regression On Watershed attributes	No	Yes	Yes	No	Watershed	Yes	Yes	Yes	Yes
14	STEPLgrid	Spreadsheet Tool for Estimating Pollutant Load	No	Yes	Yes	No	Watershed	No	No	No	Yes
15	SIBERIA LEM	SEBIRIA landscape evolution models	No	Yes	Yes	No	Watershed	No	No	No	Yes
16	SWAT-WASP	SWAT-Water Quality Analysis Simulation Program	No	Yes	Yes	No	Watershed	Yes	Yes	Yes	Yes
17	WASP	Water Quality Analysis Simulation Program	No	Yes	No	No	Watershed	Yes	No	Yes	No
18	ANSWERS	Areal Nonpoint Source Watershed Environment Response Simulation	No	Yes	No	No	Watershed	No	No	Yes	Yes
19	SCS-CN	Soil Conservation Service- curve number	No	Yes	No	No	Watershed	No	No	No	Yes
20	VIC	Variable infiltration capacity	No	Yes	No	No	Watershed	No	No	No	No
21	SWMM	Storm Water Management Model	No	Yes	No	No	Watershed	No	No	Yes	No
22	DHSVM	Distributed Hydrology Soil Vegetation Model	No	Yes	No	No	Watershed	No	No	Yes	Yes
23	APEX	Agricultural Policy Environmental eXtender	No	Yes	No	No	Watershed	No	No	Yes	Yes
24	IBIS	Integrated Biosphere Simulator	No	Yes	Yes	No	Watershed	No	YES	Yes	Yes
25	WEPP-WQ	Water Erosion Prediction Project-Water Quality	No	Yes	Yes	Yes	Watershed	No	No	Yes	Yes

Table 2. The water quality models and the details of qualitative assessment.

	Models	Full model name	Forestry inputs	Forestry impacts	Forest hydrology	Both forestry and forest hydrology	Structure/ spatial discretisation	DOC (dissolved organic carbon)	Carbon	Phosphorous	Sediment
26	FS-WEPP	Forest service Interfaces for the Water Erosion Prediction Project model	No	Yes	Yes	Yes	Watershed	No	No	Yes	Yes
27	PLOAD-SEDD	Pollutant loading estimator sediment delivery distributed	No	No	Yes	No	Basin	No	No	Yes	Yes
28	EFDC+	Environmental Fluid Dynamics Code water quality model	No	No	No	No	Varies	Yes	Yes	Yes	Yes
29	BASINS	Better Assessment Science Integrating point and nonpoint sources	No	Yes	Yes	No	Basin	No	No	Yes	No
30	HYLUC	Hydrological Land Use Change model	No	No	Yes	No	watershed	No	No	No	No
31	BROOK90	BROOK90	No	No	Yes	No	watershed	No	No	Yes	No
32	i-Tree Hydro	i-Tree Hydrology	No	No	Yes	No	watershed	No	No	Yes	No
33	HYDRUS	HYDRaulic and Unsaturation Transport in Soils (1-D soil hydrological model)	No	Yes	No	No	Stand based	No	No	No	No
34	PROSPER	Probability of Streamflow Permanence Model	No	No	Yes	No	Stand based	No	No	No	No
35	KOMATSU	KOMATSU-Evapotranspiration	No	No	Yes	No	Stand based	No	No	No	No
36	Forest-DNDC	Forest-DeNitrification-DeComposition	No	Yes	No	No	watershed	No	Yes	No	No
37	3-PG Hydro	Physiological Principles in Predicting Growth	No	Yes	Yes	No	Stand based	No	Yes	No	No
38	MC2	MAPSS-CENTURY	No	No	Yes	No	Watershed	No	Yes	No	No
39	WaSSI	Water Supply Stress Index (WaSSI) model	No	Yes	Yes	No	Watershed	No	Yes	No	Yes
40	InVEST	Integrated Valuation of Ecosystem Services	No	Yes	No	No	Watershed	No	Yes	Yes	Yes
41	WaterWorld	WaterWorld	No	Yes	No	No	watershed	No	No	No	No
42	WYRC	Water Yield Response Curve	No	Yes	Yes	No	Watershed	No	No	No	No
43	Budyko	Budyko framework	No	No	Yes	No	Regional	No	No	No	No
44	MDMC	modified double mass curve	No	Yes	Yes	Yes	Basin	No	No	No	No
45	EMDS	Ecosystem Management Decision Support System	No	Yes	Yes	Yes	Watershed	Yes	Yes	No	Yes
46	SWAT+	Soil and Water Assessment Tool	No	Yes	Yes	No	Watershed	Yes	Yes	Yes	Yes

5 Workshop Summary

This section summarises evidence collected at two workshops and direct communication with stakeholders from the forestry industry, SEPA, NatureScot and Forest Research. The first workshop involved a roundtable discussion to discuss modelling needs related to forestry and water quality. The second workshop explored modelling requirements, including a briefing to stakeholders of our comprehensive review of forestry and water quality models that are available globally.

In the context of forestry operations in the first workshop, perceived impacts encompassed a range of parameters including tree species choice and their interaction with seasonality, the intensity and frequency of rainfall, and distinguishing short-term pulses from long-term fluxes. Cumulative effects were noted, albeit challenging to isolate or link to specific landscape features. Notably, it was discussed that even low-level water events can have significant impacts if resulting from isolated incidents. Drones are also employed to construct models facilitating drainage identification and management. Useful outputs involved the development of models to guide operations, particularly at the site level, and to address concerns like cumulative impacts and legacy drain compliance. Considering regulatory and policy needs, it appears that simpler models might also offer sufficient output levels. Among the existing models, SWAT emerges as the primary basis with more than 5000 associated publications and used in 90 countries (e.g., Karki *et. al.,* 2023), while SAGIS is used by SEPA.

Previous practices involved the use of models in Scotland, such as those used or developed by Forest Research (Nisbet, 2001; Nisbet *et. al.,* 2002; Nisbet *et. al.,* 2014). It was emphasised that existing models primarily focus on hydrology and lack integration with water quality considerations, despite the need for such integration to guide operations effectively. Broader discussions extended to considering climate change impacts, assessing drains at the beginning of operations, and adjusting timber harvesting timing based on vulnerability and market conditions. Data availability remained a concern, with limited upper catchment data from SEPA and a reliance on monitoring sites. Collaboration with Scottish Water was proposed to access relevant datasets, with a focus on site-specific information to address legacy impacts and compliance issues.

Our second workshop focused on the significant factors and potential risks associated with various forestry operations and suitability of models for water quality. Operational considerations, such as minimising impacts through strategic planning, were highlighted. Diffuse pollution, particularly runoff from harvesting sites, emerged as a primary challenge, compounded by the diverse nature of forestry operations ranging from windthrow management to clear-cutting. The discussion underscored the importance of site-specific factors like soil properties, drainage systems, and proximity to water bodies in assessing and mitigating environmental risks. It was noted that plans for woodland creation must incorporate buffer zones to safeguard water courses, necessitating careful timing of operations to minimise adverse effects. It was suggested that 20m buffer zones prevents all contaminants from entering watercourses, although 10m buffers are typically applied to smaller streams. An important consideration with regards to buffer zones is the potential additional phosphorous input as a result of the one needles dropped by the trees within the buffer throughout the life of the plantation.

The discussion was extended to recent forestry efforts and those focused on implementing best practices, persistent challenges, especially concerning phosphate pollution and sediment delivery following harvesting. Peat sites emerged as particularly vulnerable, warranting sustained monitoring efforts to assess long-term impacts accurately. Operational practices, however, were not uniformly aligned with recommended guidelines, highlighting compliance issues such as trench mounding and inadequate buffer zones. A number of on-site reports collected from workshop participants, do indicate significant impacts on water quality on receiving water-bodies following harvesting and/or forest road construction, as a result of non-compliance. The forestry best practice guidance, as presented within the UKFS guidance publications, are very comprehensive and cover all commercial and non-commercial forestry, as well as providing guidance on forestry in some types of sensitive areas (e.g., acid sensitive water catchments). Compliance with UKFS guidance publications means not only to the overarching UKFS guidance but to all of its subsidiary practice and technical guides, which includes those on the water environment and acid sensitive catchments. During the workshop a discussion was held between SEPA and FR regarding current UKFS guidelines especially in the context of sensitive catchments. It should be noted that revisions to the UKFS guidance were published in October 2024.

The workshop also addressed the complex interplay between forestry operations and ecological conservation, debating trade-offs between bird and fish protection and advocating for science-driven decision-making in machine choice and operational timing. Freshwater pearl mussels were identified as a potential issue due to their sensitivity to low water quality. Often, limitations with regards to bird protection, result in a potentially narrower window for harvesting, which may lead to harvesting under conditions that are less than ideal (e.g., during times of heavy rainfall). As forestry practices evolve, including the rise of agroforestry, the need for robust models to guide sustainable management has become increasingly apparent. In conclusion, compliance remains a big issue (e.g., in Argyll where SEPA has spent several weeks inspecting a variety of forestry sites). Therefore, to ensure all forestry practices meet environmental standards and minimise the impact of poor practices on water quality and aquatic ecology, ongoing efforts to refine modelling techniques and incorporate empirical data are essential. It should be noted that Forest Research expressed during the workshop that it does not think a water quality model is needed or useful, partly because considerable empirical data is available on the effects of forestry on water quality, but also due to the compounded uncertainties associated with a water quality model. Note that the project team response is outlined in Section 7 Conclusions.

Work continues to improve industry awareness and improve guidance. The stakeholders are committed to continuing compliance assessment work with forestry, and this will take some time. Compliance was also raised in the recent Royal Society of Edinburgh paper (The Royal Society of Edinburgh, 2024) as a key issue. However, the reliability of guidance and its focused delivery would be improved substantially by models combining forestry operations with impacts on water quality. This would allow relevant agencies to identify sensitive areas and thus reduce potential environmental issues.

6 Recommendations

The information provided emphasises the critical importance of improving forest management practices to protect water quality effectively. Various lessons were learnt:

1. There is a current deficit in available models tailored for assessing the impacts of commercial forestry on water quality, highlighting the urgent need for investment in developing a more robust and reliable model.
2. Understanding the vital role of factors like soil type, slope, and precipitation in determining forest water quality is imperative to effectively implement decision-making processes concerning forestry practices and land use planning.
3. An integrated approach to water protection planning in forest environments is needed, considering both post-impact hydrology and predictive forestry activities, to ensure comprehensive protection of water resources. Moreover, prioritising the inclusion of key activities such as watershed forest management, forest road networks, and harvest operations in future modelling efforts is crucial, given their significant impact on water quality.
4. Stakeholders should support the integration of both forestry activities and forest hydrology as inputs in modelling endeavours to achieve a better understanding of forest water quality dynamics and support informed decision-making. As a first step, a qualitative risk-based model should be developed, that would allow for the identification of high-risk areas and scenarios. Ideally these data would be used in a high-level qualitative risk model to highlight where the potential for pollution is greatest and therefore additional care/more thorough environmental impact assessments and compliance audits are needed.
5. A better understanding of forest water quality dynamics will support informed decision-making. As a first step, a qualitative risk-based model should be developed using a GIS approach focused on soils, topography and drainage that would allow for allow for the identification of high-risk areas and scenarios. Subsequently, a quantitative model, supported by long-term data, is ultimately needed in assessing these impacts and risks adequately.
6. To develop a high-level model to qualitatively identify areas of high risk, it is possible that sufficient data and expert knowledge already exists.

7 Conclusions

In conclusion, although the relative impacts of commercial forest activities to water are relatively small (compared to other land-uses), localised impacts on water quality can be significant and the existing literature highlights a critical gap in the connection between water quality and forest management, especially with regards to interactions between multiple environmental parameters and forestry activities.

With regards to forestry operational and compliance purposes the current process is deemed sufficient for identifying site level high risk area to inform mitigation. It should be noted that Forest Research expressed during the workshop that it does not think a water quality model is needed or useful, partly because considerable empirical data is available on the effects of forestry on water quality, but also due to the compounded uncertainties associated with a water quality model.

Nevertheless, SEPA feels there is a need for a modelling approach that allows SEPA to assess the contribution of forestry to wider scale water quality. The project team have restated that during the initial project proposal SEPA set out why a model would be useful: to include in source apportionment models which currently do not include forestry inputs, and to help identify potential areas at greatest risk from forestry to target audits. The project found that a quantitative model is not currently available and although pottentially challenging to develop due to uncertainties, it should still be considered if uncertainties can be overcome. A qualitative risk model however could probably be developed more readily based on site specific risk factors and could help SEPA target audits.

While current models consider biophysical factors, only a few incorporate forestry activities, such as road networks and harvesting, as parameters. The workshops identified potential issues of localised impacts on water quality in cases of noncompliance highlighted the complexity of forestry operations' impacts on water dynamics and the environment, emphasising the importance of site-specific factors and strategic planning to mitigate risks. Despite ongoing efforts to implement best practices, challenges persist, particularly regarding phosphate pollution and sediment delivery.

To ensure the long-term sustainability of forestry ecosystems and ecosystems, especially in sensitive catchments, SEPA require ongoing refinement of modelling techniques and incorporation of empirical data are imperative. It is thus crucial to initially develop a qualitative risk assessment model based on existing understanding of important risk factors that would allow for the identification of high-risk areas and scenarios. Ultimately, the goal would be to obtain and utilise long-term data, that would allow for a quantitative model that would be coupled with SAGIS, to verify forestry as a significant pressure and that will allocate SEPA compliance resources efficiently, guide industry best practices, support woodland creation targets, and implement SEPA's management plan commitments. This comprehensive approach will ultimately enable effective decision-making and the establishment of robust management strategies for forested landscapes.

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