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REVIEW ARTICLE

A review on modeling nutrient dynamics and loadings in forest-dominated watersheds under cold climate conditions

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Abstract

This review summarized the past and current studies on forest nutrient export and existing watershed water quality models that are capable of predicting nutrient loadings from forest-dominated watersheds. Emphasis was given to the watershed models used under cold climate conditions and their capacities and limitations in assessing the impacts of forest best management practices (BMPs) and climate change scenarios on nutrient loadings at a watershed scale. The nutrient export rates in forest-dominated watersheds were found to vary significantly controlled by local climate and landscape conditions. Some watershed water quality models can estimate nutrient loadings from forests either with a simplified forest growth function or without a forest growth component. No existing watershed water quality models have explicit representation forest BMP functions. Combining or coupling with a forest growth model is required for a realistic simulation of nutrient dynamics and assessing the impact of forest BMPs in a forest-dominated watershed. The review also considered the suitability of models for exploring the potential effects of climate change on hydrologic and nutrient processes relevant to forest management. Discussions on the challenges and limitations of forested watershed water quality models and recommendations for future development were made following the review. The findings of this study can provide valuable references for water quality modeling studies in forest-dominated watersheds under cold climate conditions.

Keywords Watershed modeling. Forest. Nutrient loadings. BMPs. Climate change

Introduction

Forests can act as both source and sink of nutrients and influence the overall nutrient balance in a watershed (Osman 2013). The rate or coefficient of nutrient export from forests can be defined as the amount of nutrients per area, such as nitrogen and phosphorus in both dissolved and particulate forms, transported from forested areas to adjacent water bodies or downstream ecosystems through surface runoff, subsurface flow, groundwater movement, and streamflow. This export rate is a crucial factor in understanding the role of forests in nutrient cycling and their impact on water quality and the ecosystem within the watershed. To minimize nutrient losses from forests and maintain the watershed aquatic systems, forest BMPs have become a major component of forest management (Sun and Vose 2016). Therefore, understanding the process of nutrient export from forests and the effectiveness of forest BMPs on nutrient reduction is therefore essential for integrated watershed management and sustainable development.

Nutrient export rates in a forested watershed can vary spatially and temporally and are affected by a combination of natural and human-induced factors. The spatial distribution of nutrient loss from a forested watershed is mainly controlled by topography, soil characteristics, bedrock geology, vegetation type and diversity, and climate patterns (Band et al. 2001). Nutrient loss from a forested watershed is also affected by natural disturbances such as wildfires, storms, pest infestations, disease outbreaks, and recovery processes including revegetation and soil stabilization. In addition, human activities such as deforestation, agriculture, grazing, urbanization, pollution, and forest management practices

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including logging, thinning, fertilization, and reforestation can significantly alter nutrient export dynamics (Beckers et al. 2009). Due to the variation in precipitation, temperature, plant growth, and biological activity within a year, nutrient exports and subsequent loadings in rivers and lakes would vary significantly in different seasons. The interaction of all these influencing factors makes the forested watershed a very complex system in terms of hydrobiological and water quality processes.

To estimate nutrient exports and loadings in a forested watershed, researchers and watershed managers usually conduct studies through field experiments, monitoring data collection and analysis, or watershed-scale water quality models. In 2016, Environment and Climate Change Canada (ECCC) initiated the Lake of the Woods (LoW) Science Initiative focusing on the most pressing challenges affecting water quality and aquatic ecosystem health in the basin. LOW is a large, multi-basin transboundary waterbody between Canada and the US that has been exhibiting harmful algal blooms and a deterioration of water quality with nutrient loading from the watershed as one of the main causes (Greenwood and Eimers 2023). The watershed covers approximately an area of 69,250 km^2 dominated by forest (55%), wetlands (23%), and open water (18%), while agricultural land is about 2.2% of the watershed area. The LoW watershed has a continental climate with warm summers and cold winters, with average annual precipitation about 744 mm, and snow on the ground generally between November and April (Fong et al. 2023). A combined water quality sampling and watershed modeling has been conducted under ECCC's LoW science initiative with an objective to evaluate the impacts of BMPs and climate change scenarios on lake ecosystem and water quality, and to provide sound scientific policy recommendations for managing nutrient loading and reducing the frequency and severity of harmful algal blooms (HABs) in the lake.

This paper provides a review of the capability of process-based water quality models in simulating nutrient export from forest-dominated watersheds with an emphasis on cold climate conditions based on available information documented in the literature. We reviewed (i) nutrient exports from forested watersheds based on monitoring studies, (ii) watershed models for simulating nutrient loadings, and (iii) their applications in assessing the impact of BMP and climate change scenarios in forested watersheds. The review is followed by a discussion on challenges and limitations of forested watershed models and recommendations for future development. The findings of this review can be used to improve the next phase LoW watershed modeling and provide valuable references for water quality modeling studies in forest-dominated watersheds under cold climate conditions.

Nutrient export from forested watersheds based on monitoring data analysis

Analyzing nutrient export from forested watersheds based on monitoring data involves collecting, processing, and interpreting observed data to understand nutrient dynamics, sources, pathways, and their impacts on downstream water quality. These data provide insights into hydrologic processes and water quality dynamics at different spatial and temporal scales, and other factors influencing watershed nutrient cycling and export to streams and rivers. The results of observation data analysis also form a fundamental basis for model calibration, validation, and uncertainty analysis, and therefore, are crucial for watershed water quality model development and evaluation of BMPs and climate change scenarios.

Numerous field experiments and watershed studies have been carried out to quantify the rates of nutrient export from forest areas over the past decades across the world. Reckhow et al. (1980) conducted an extensive literature survey of nutrient export coefficients from different land uses, and found the annual total phosphorus (TP) export rate from forest land ranged from 0.019 to 0.83 kg/ha with a mean of 0.24 kg/ha, while the annual total nitrogen (TN) ranged from 1.38 to 6.26 kg/ha with a mean of 2.86 kg/ha. Loehr et al. (1989) reported the range of forest annual TN and TP nutrient export coefficients of 1.0-6.3 and 0.007–0.88 kg/ha, respectively, at various locations in the US and Europe. Dodd et al. (1992) used annual forest TP and TN export coefficients of 0.13 (0.09–0.21) and 2.33 (0.69–3.8) kg/ha with a confidence level of 75%. Similar ranges were also found by Raty et al. (2020) based on observations in a 1.02 km^2 forested catchment in east-central Finland. These ranges of nutrient export rates from forest land use are much lower and relatively narrow compared to agricultural land use as reported by Reckhow et al. (1980). Hydroclimatic factors, such as precipitation, surface and subsurface runoff, and landscape factors, such as soil and forest productivity, appear to be the major factors determining nutrient export variability at a field scale.

At a watershed scale, in addition to the above-influencing factors, nutrient exports at the forest-dominated watershed outlet are further controlled by forest location and distribution area within the watershed, as well as contributions from other land uses such as agriculture, urban, and wetlands. Scott et al. (2000) carried out an extensive study in Nova Scotia to determine phosphorous export coefficients with various combinations of geology, soil type, and land use and suggested that the annual TP export coefficient was about 0.0069 kg/ha for forested watersheds with igneous bedrock, 0.0083 kg/ha for forested watersheds with igneous bedrock and > 15% wetlands, 0.0088 kg/ha for forested watersheds with sedimentary bedrock, and 0.0115 kg/ha for forested watersheds with sedimentary bedrock and > 5% wetlands. De Melo et al. (2022) concluded that average annual TN and TP export rates were 1.47 and 0.12 kg/ha based on a survey of 18 rivers dominated by peatlands, coniferous forests, and lakes in the Eastern James Bay region, QC, Canada. Finer et al. (2021) carried out a nutrient export study of 61 managed catchments and 28 natural catchments in Finland and found that average annual TN and TP export rates were 1.85 and 0.084 kg/ha for managed forested watersheds, and 1.29 and 0.041 kg/ha for natural forested watersheds. A study by Hargan et al. (2011) showed that the average annual TP export rate of the Rainy River, the major water source to the Lake of the Woods forming part of the Canada–USA border separating northwestern Ontario and northern Minnesota, was 0.006 kg/ha. Table 1 lists observed average annual runoff and nutrient loadings from forest-dominated watersheds calculated with various interpolation methods at the monitoring stations. Four watersheds (the watershed in northern Portugal, Pingqiao River watershed in China, Beaver Lake watershed USA, Upper Pearl River watershed USA) in Table 1 had warm humid subtropical climate conditions which were used for comparison with other watersheds under cold climate conditions.

Despite the short monitoring periods in some studies in Table 1, the TN and TP export rates in a forest-dominated

Table 1 Observed average annual runoff and nutrient loadings from forest-dominated watersheds

Location	Watershed description	Runoff (mm/yr)	TN (kg/ha)	TP (kg/ha)	Source
18 rivers in the Eastern James Bay region, QC, Canada	Total area 358,914 (44–209,453) km^2 covered by peatlands, coniferous forests, and lakes, with average annual temperatures −3 °C.	591 (426-1,075)	1.47 (1.02–2.73)	0.12 (0.054–0.43)	De Melo et al. (2022)
3 watersheds in the Penobscot River Basin, ME, USA	Watershed area 20,109/8,824/15,076 km^2, Forest 78.1%, 82.2%, 76.9%, agriculture 10.9%, 4.8%, 7.4%, wetland 5.2%, 4.3%, 6.1%.	-	1.4, 2.7, 1.9	0.005, 0.055, 0.015	Cronan (2012)
4 tributaries in the Beaver Lake watershed, AR, USA	Total watershed area 4,275 (42.2–1064) km^2, annual precipitation 1,001 mm/yr, pasture 33.3% (16-55%), forest 63.5% (42-82%).	-	0.31 (0.24–2.19)	0.018 (0.009–0.189)	Haggard et al. (2003)
A forested catchment in east-central Finland	Catchment area 1.02 km^2, annual precipitation 765 (646–847) mm, average annual temperature 4.0 (2.3–4.8) °C over the monitoring period, forest 100%.	126 (93–164)	1.6 (1.0-2.5)	0.4 (0.3–0.7)	Raty et al. (2020)
Church branch, St. Martin River basin, MD, USA	Watershed area 12.84 km^2, annual precipitation 1,041 mm/yr, agriculture 40%, urban 13%, feeding operation 0.14%, forest 47%.	-	6.78	0.33	Beckert et al. (2011)
Four watersheds in northern Portugal	Total area 573 (58, 215, 132, 168) km^2, annual precipitation 1,882 (3123, 1954, 1453, 999) mm/yr, forest 84.5% (94%, 75%, 88%, 81%).	-	-	1.5, 0.5, 0.2,0.4	Santos et al. (2015)
Lena station, Upper Pearl River, MS, USA	Watershed area 5,131 km^2, annual precipitation 1,348 mm/yr, forest 72%, grassland 20%, urban 6%, others 4%.	253	1.11	0.65	Jayakody et al. (2014)
Mica Creek, 7 experimental watersheds, ID, USA	Total area 27.0 km^2, annual precipitation 1,450 mm/yr, dominated by naturally regenerated and replanted mixed conifers.	640 (474–818)	0.88 (0.22–3.39)	0.12 (0.09–0.15)	Deval et al. (2021)
Pingqiao River watershed in the Taihu Basin, China	Watershed area 220.3 km^2, annual precipitation 1,129 mm/yr, agriculture 31.3%, urban 5.3%, water 1.4%, forest 62%.	-	20.9	0.35	Xue et al. (2019)
Rainy River at Manitou Rapids, ON, Canada	Watershed area 50,200 km^2, annual precipitation 744 mm/yr, agriculture 2.3%, wetland 33.3%, open water 16%, forest 46.8%.	232	-	0.006	Hargan et al. (2011)
Sixty-one managed catchments in Finland	Average catchment area 5.0 (0.04–53.2) km^2, annual precipitation 561 mm/yr, agriculture 0.5%, lakes 0.6%, forest 98.9%	305 (193–503)	1.85 (0.16–7.69)	0.084 (0.006–0.424)	Finer et al. (2021)
Twenty-eight natural catchments in Finland	Average catchment area 403 (6 – 4,209) ha, annual precipitation 564 mm, agriculture 0.0%, lakes 0.0%, forest 100% (peatland 44%).	357 (244–485)	1.29 (0.37–4.01)	0.041 (0.006–0.209)	Finer et al. (2021)
Tumen River watershed in Northeast China	Watershed area 33,168 km^2, annual precipitation 400–600 mm/yr, forest 71% dominated by deciduous broad-leaved trees.	-	7.89	0.37	Ouyang et al. (2022)
Winnipeg River at Pointe du Bois, MB, Canada	Watershed area 126,000 km^2, annual precipitation 780 mm/yr, agriculture 1%, grassland < 1%, open water 17%, wetland 7%, forest 73%.	250	0.133	0.006	Board (2006)

watershed showed a wide range of variation compared to the values obtained from field studies. TN loadings ranged from 0.133 kg/ha (Winnipeg River, Canada) to 7.89 kg/ha (Tumen River, China), and TP loadings ranged from 0.006 kg/ha (Winnipeg River, Canada) to 0.43 kg/ha (Eastern James Bay region, Canada). Compared to watersheds characterized by warm humid subtropical climate conditions, the TN and TP export rates were much lower mainly because of the difference in climate and forest productivity (Table 1). Haggard et al. (2003) reported that nutrient export amount (kg/yr) increased with watershed size, but nutrient export rate (kg/ha) decreased with watershed size based on a study in the Ozark Plateau, USA. Hence, the watershed models need to represent the major influencing factors that control nutrient loadings in a specific forest-dominated watershed and account the loadings in model simulation and assessment of various management scenarios.

Watershed models for simulating nutrient loadings in forest-dominated watersheds

Watershed models are valuable tools that have been extensively used in scientific research and water resources engineering applications to resolve current-day hydrologic and environmental problems. In comparison to statistical and machine learning models, process-based watershed models incorporate physical principles in terms of empirical relationships and/or physical mathematical formulations, and scientific knowledge to describe, analyze, predict, and understand hydrologic processes and their interactions within a complex watershed system. Therefore, they are commonly used to simulate pollutant loadings, evaluate management practices, and assess the impact of climate change on nutrient reductions at a watershed scale (Beckers et al. 2009). Non-point source nutrient loading models have a long history of development and have been applied extensively in watershed management and decision-making. However, most of these models were developed with an emphasis on agricultural non-point source pollution, and there is limited knowledge on nutrient processes and dynamics within a forested watershed under cold climate conditions, where snow and frozen soil are more important. A summary of watershed hydrologic models that include some representation of nutrient dynamics in and loadings from forest-dominated watersheds is provided in Table 2.

All these watershed models have high complexities ranging from a full to semi-distributed structure that disaggregates watersheds into multiple computation units to represent the spatial variability of watershed characteristics, model parameters, and weather inputs. General inputs to these models include geospatial data (topography, soil, land cover), climate data (precipitation, temperature, solar radiation, wind speed, and air humidity), and land management model data (reservoirs, lakes, wetlands, point sources, water uses, irrigation, and surface/subsurface drainage). Some models, e.g. HSPF and SWAT, need more land management data including crop management, grazing management, and livestock management for a more precise simulation of non-point source pollution from agricultural fields. Outputs of these models include time series of runoff, sediment, and water quality variables at reach outlets and their spatial distribution over the watershed at subbasin or computation unit level. All these models have snow cover and snowmelt processes, but only SWAT and HYPE incorporate frozen soil processes in the nutrient export simulation. However, none of these models contain a detailed description of forest growth and management, therefore, coupling the model with a specific forest model, such as the Forest Vegetation Simulator (FVS) (Crookston and Dixon 2005), is required for a detailed study of forest dynamics and associated ecosystem service in addition to estimate of nutrient loadings from the forested watershed.

Nutrient transport via groundwater flow is an important pathway in forest-dominated watersheds because of higher groundwater recharge compared to non-forested areas. Models including HGS, MIKE-SHE, MODHMS, and WaSiM-ETH use rigorous physically-based equations and numerical solutions to describe groundwater movement and water quality dynamics within the aquifer and therefore can be used to study nutrient processes in the groundwater flow. However, high-quality data of soil, geology, mineral resources, and field sampling are required to limit the uncertainty of modeling results. Other models either do not have process-based groundwater components (e.g. HYPE and WARMF) or use simplified approaches (e.g. HSPF, MESH, SWAT, and SWMM) to simulate the movement of water and nutrient into and out of the groundwater storage. These simplified models require fewer inputs but cannot capture the complexities of groundwater quality dynamics within a watershed. For forest-dominated watersheds under cold climate conditions, processes including canopy snow interception, snowdrift, and redistribution, snowmelt and sublimation, frozen soil, permafrost, and glacier melt, as well as lakes, wetlands, and infrastructure (e.g. road construction) are critical in controlling the processes of runoff and nutrient export. However, none of the above listed models has a full set of these functions. Coupling these controls with a detailed hydrologic model, such as the cold regions hydrologic model (CRHM) (Marsh et al. 2020) is required for a plausible simulation of spatial and temporal dynamics of nutrient export in a complex forest-dominated watershed.

Among the ten watershed models listed in Table 2, the SWAT model has the advantages of applicability and operability to a wide range of climate and landscape conditions

Table 2 Watershed models that can be used for simulating nutrient loadings in forest-dominated watersheds

Model	Description	Source
HSPF[1]	Small to large watershed scale, semi-distributed, with forest harvesting, lake, groundwater, and snow processes but not for forest growth, wetland, frozen soil, and road construction, sub-daily time step, high complexity.	Duda et al. (2012)
HGS[2]	Small to large watershed scale, distributed, with lake, wetland, groundwater, and snow processes but not for forest growth, forest harvesting, and frozen soil, 1-D simulation for road construction, flexible time step, high complexity.	Brunner and Simmons (2012)
HYPE[3]	Small to large watershed scale, distributed, with snow, frozen soil, and forest harvesting processes but not for forest growth, groundwater, wetland, lake, and road construction, flexible time step, high complexity.	Lindstrom et al. (2010)
MESH[4]	Small to large watershed scale, distributed, with snow, groundwater, and lake processes but not for forest growth, forest harvesting, frozen soil, wetland, and road construction, flexible time step, high complexity.	Pietroniro et al. (2007)
MIKE-SHE[5]	Small to large watershed scale, distributed, with lake, wetland, snow, groundwater, and forest harvesting processes but not for forest growth, frozen soil, and road construction, flexible time step, high complexity.	Jaber and Shukla (2012)
MODHMS[6]	Small to large watershed scale, distributed, with forest harvesting, lake, and wetland processes but not for forest growth, frozen soil, and road construction, physical equations for groundwater, flexible time step, high complexity.	Panday and Huyakorn (2004)
SWAT[7]	Small to large watershed scale, semi-distributed, with forest harvesting, forest growth, snow, frozen soil, groundwater, and wetland processes but not for lake and road construction, daily time step, high complexity.	Douglas-Mankin et al. (2010)
SWMM[8]	Urban landscape, small to large watershed scale, semi-distributed, with snow, groundwater, lake, wetland, and road construction processes but not for frozen soil, forest growth, and forest harvesting, dynamic time step, high complexity.	Rossman (2010)
WARMF[9]	Small to large watershed scale, semi-distributed, with snow and forest harvesting processes but not for forest growth, frozen soil, groundwater, lake, wetland, and road construction, daily or sub-daily time step, high complexity.	Chen et al. (2000)
WaSiM-ETH[10]	Small to large watershed scale, distributed, with snow, groundwater, forest harvesting, and lake processes but not for forest growth, frozen soil, wetland, and road construction, sub-daily time step, high complexity.	Schulla and Jasper (2007)

[1]Hydrologic Simulation Program Fortran developed by USGS and USEPA, [2]HydroGeoSphere developed by Aquanty Inc. Canada, [3]Hydrologic Predictions for the Environment developed by Swedish Meteorological and Hydrologic Institute. [4]Modélisation Environnementale communautaire - Surface Hydrology developed by ECCC, [5]European Hydrologic System Model developed by Danish Hydraulic Institute, [6]MODFLOW-based Hydrologic Modeling System developed by HydroGeologic Inc. USA, [7]Soil and Water Assessment Tool developed by USDA-ARS, [8]Storm Water Management Model developed by USEPA, [9]Watershed Analysis Risk Management Framework developed by Electric Power Research Institute, USA, [10]Water balance Simulation Model developed by Federal Institute of Technology Zurich, Switzerland

and allowing a hydrologic analysis of watersheds to be conducted through a long-term predictive simulation, and therefore, has been applied more frequently in recent-year studies on nutrient dynamics and loading in forest-dominated watersheds under cold climate conditions. In SWAT, a watershed is divided into multiple subbasins, which are further subdivided into hydrologic response units (HRUs) with homogeneous land use, soil, and a slope range. The model runs at a daily time step and is composed of a single vegetation layer and multiple soil layers, together with a conceptual shallow and deep groundwater reservoir. Surface runoff in SWAT is simulated using the SCS Curve Number or Green-Ampt methods, while snowmelt is calculated using a temperature degree-day approach within an elevation band. The SWAT model simulates plant growth by the method of leaf area index and converting light interception to biomass under optimal water and nutrient supply conditions. The growth of different plant species is simulated based on a set of plant growth parameters defined for each type of plant. In addition, the SWAT model contains components of lakes, reservoirs, wetlands, and a set of agricultural management practices allowing the simulation of flow, sediment, and nutrient cycling within a complex hydrologic system. To adapt the SWAT model for forest simulation, Lai et al. (2020) developed a forest growth module featuring variable density and mixed vegetation types to address the drawbacks of the SWAT model in estimating the accumulated biomass, based on the average forest vegetation density and single plant growth pattern. Kiniry et al. (2008) adapted the SWAT model to the boreal forest environment by incorporating a process-oriented plant growth module for simulating the growth of crops, grasses, and forests.

A list of SWAT model applications for nutrient export modeling in forest-dominated watersheds is provided in Table 3. Watershed sizes ranged from 145 km^2 to 168,400 km^2 with forest area coverage from 44.5 to 83.4%. Nutrient exports including total suspended solids (TSS), TN, nitrate (NO_3), TP, dissolved nitrogen (DN), or total dissolved phosphorus (TDP) were reported at the watershed outlet or from forest areas within the watershed. The studies indicated that

Table 3 Selected SWAT applications for nutrient export modeling in forest-dominated watersheds

Location	Watershed description	Results (average annual)	Source
Athabasca River below Fort McMurray, AB, Canada	Watershed area 160,000 km^2, average precipitation 510 mm/yr, forest > 80% of the watershed area.	TN 0.94 kg/ha and TP 0.17 kg/ha from forest areas. TN 1.35 kg/ha and TP 1.74 kg/ha from range areas.	Shrestha and Wang (2020)
Chungju Dam watershed, South Korea	Watershed area 6,661 km^2, average precipitation 1,359 mm/yr agriculture 2.8%, wetland 8.8%, forest 83.4%.	TSS 0.72/0.54 t/ha, TN 0.70/0.75 kg/ha, TP 0.85/0.70 kg/ha from 2 main tributaries.	Park et al. (2010)
Delaware River watershed, NY-NJ-PA-DE, USA	Watershed area 36,570 km^2, dominated by deciduous forest.	Runoff 657 mm/yr, TSS 0.56 (0.26–1.35) t/ha, TN 2.75 (2.26–3.43) kg/ha, TP 0.24 (0.16–0.34) kg/ha.	Hanson et al. (2017)
Grand watershed Near Painesville, OH, USA	Watershed area 1,896 km^2, average precipitation 1,093 mm/yr, agriculture 27%, hay 10%, urban 10%, forest 52%.	Runoff 409 mm/yr, TSS 0.527 t/ha, TN 6.46 kg/ha, NO_3 3.68 kg/ha, TP 0.38 kg/ha, TDP 0.048 kg/ha.	Bosch et al. (2014)
Lake of the Woods watershed, Canada-USA	Watershed area 69,250 km^2, average precipitation 713 mm/yr, agriculture 2.4%, wetland 30.4%, water 21.3%, forest 44.5%.	Runoff 209 mm/yr, TSS 0.035 t/ha, DN 0.78 kg/ha, TN 1.13 kg/ha, TDP 0.03 kg/ha, TP 0.06 kg/ha.	Fong et al. (2022)
Lake Yenicaga watershed, Black Sea Basin, Turkey	Watershed area 145 km^2, average precipitation 677 mm/yr, agriculture 42%, forest 56%.	TDP 0.4 kg/ha, TP 1.1 kg/ha, NO_3 2.0 kg/ha	Gungor et al. (2016)
Lancang River Basin in southwestern China	Basin area 168,400 km^2, average precipitation 438–1921 mm/yr from north to south. Grassland 44%, forest 47%.	TN 46.8 kg/ha, TP 0.43 kg/ha	Hao et al. (2022)
Le 'an River Watershed, Jiangxi, China	Watershed area 8,376 km^2, average precipitation 1,772 mm/yr, agriculture 24.9%, urban 3.2%, forest 70.6%.	TN 1.57 (0.002–6.37) kg/ha, TP 0.26 (0.002–1.26) kg/ha	Li et al. (2023)
Muskingum River watershed, OH, USA	Watershed area 20,855 km^2, agriculture 22%, pasture and hay 18%, urban 12%, wetland and water 3%, forest 45%.	TSS 0.02–1.23 t/ha, TN 0.82–17 kg/ha, TP 0.03–2.6 kg/ha.	Khanal et al. (2018)
Saugahatchee Creek watershed, AL, USA	Watershed area 570 km^2, average precipitation 1,336 mm/yr, agriculture 11.7%, urban 8.4%, grass 11.7, forest 67.8%.	TSS 0.94 t/ha, TN 2.1 (0.57–5.31) kg/ha, TP 0.19 (0.02–0.87) kg/ha.	Niraula et al. (2013)
St. Croix River watershed, WI-MN, USA	Watershed area 20,000 km^2, average precipitation 808 mm/yr, agriculture 9.6%, wetland 17.9%, forest 46.6%.	Runoff 253 mm/yr, TSS 0.054 t/ha, TN 0.75 kg/ha, TP 0.13 kg/ha from forest areas.	Yang et al. (2018)
Meijiang River Basin, Jiangxi, China	Watershed area 3,304 km^2, average precipitation 1,706 mm/yr, forest 70%.	Runoff 256 mm/yr, TN 1.13 kg/ha, TP 0.11 kg/ha.	Lai et al. (2020)
Upper Pearl River watershed, MS, USA	Watershed area 7,588 km^2, average precipitation 1,348 mm/yr, forest 72%, grassland 20%, urban 6%, others 4%.	Runoff 245 mm/yr, TSS 0.03 (0.01–0.06) t/ha, TN 0.58 (0.30–1.06) kg/ha, TP 0.37 (0.14–0.64) kg/ha.	Parajuli et al. (2010)
Vansjo-Hobolv watershed in south-eastern Norway	Watershed area 690 km^2, average precipitation 810 mm/yr, agriculture 16%, open water 7%, forest 77%.	TN 0.45 kg/ha, TP 0.008 kg/ha from forest areas.	Panagopoulos et al. (2011)

nutrient export rates at the watershed outlet were mainly affected by forest fractions with higher values for watersheds with lower forest fraction because more nutrients were produced from non-forest areas. In addition, nutrient export rates from forest areas within the watershed are affected by multiple factors such as climate, hydrology, and forest growth characteristics. Thus, the major influencing factors on forest growth and forest hydrology must be accounted for in the model for a proper simulation of nutrient dynamics and nutrient export in forest-dominated watersheds.

Model applications for accessing the impact of forest BMPs on reduction of nutrient loadings

Forest BMPs are designed for sustainable forest management, environmental protection, and ecosystem health maintenance. One main objective of forest BMPs is to minimize the negative impacts of forest activities on water quality in receiving water bodies. These activities involve actions and practices associated with forest management, conservation, and utilization. For example, varying degrees of impact on sediment and nutrient export can be produced from harvesting (e.g., selective-cutting, clear-cutting, shelterwood-cutting, and location within a watershed), logging (e.g., cable yarding, ground skidding, and location of landing site), road (e.g., construction and maintenance), and forest regeneration (e.g., natural and artificial). To address these issues, an integrated watershed management approach consisting of the implementation of BMPs and land conservation strategies is essential for the reduction of nutrient pollution and the protection of water quality. A detailed description of forest BMPs designed for water quality improvement was provided by Shah et al. (2022). A review of the effectiveness of forestry BMPs in the United States was provided by Cristan et al. (2016) based on field measurements. Table 4 gives a list of typical forest BMPs proposed for the LoW

Table 4 Forest BMPs proposed for the LoW watershed water quality modeling and assessment

Practice	Description
Road planning, design, and location	Avoid erosion from poorly designed skid and haul roads. Locate roads away from poorly drained sites and soils. Maintain protective buffers between roads and streams. locate roads on contours with water bars. Reduce rutting and skid trail disturbance. Implement bank protection measures at stream crossings.
Landing planning, design, and location	locate landings on gentle slopes with drainage or well-drained soils, and away from streams. Install diversion ditches on the uphill side of landings.
Fertilization	Minimize fertilizer application. Do not apply fertilizer during wet weather. Do not apply fertilizer within defined exclusion zones or buffer areas.
Timber harvest planning and design	Conduct selective cutting instead of clear-cutting. Design roads and select cutting areas before harvesting. Develop ground stabilization measures during harvesting. Regenerate plant cover after harvesting. Avoid wet season logging.
Protection of wetlands, streams, and lakes	Maintain buffer strips around wetlands, streams, and lakes, and avoid crossing on non-forested wetlands.
Site stabilization and revegetation	Grade roads and side ditches to ensure proper drainage. Seed and mulch disturbed areas to stabilize soils.

watershed water quality modeling and assessment by Liu and Yang (2020).

Watershed models for forest BMPs planning and assessment aim to provide forest managers, landowners, and other stakeholders with actionable guidelines to minimize negative environmental impact and protect natural resources (Beckers et al. 2009). To assess the impact of forest BMPs, the hydrologic and water quality processes of these forest BMPs must be accounted for in the watershed water quality model. In addition, questions such as whether the spatial layout of BMP areas in the watershed needs to be represented, whether the model outputs include required parameters, whether the modeling time step meets the objectives, whether the simulation capacity of forest growth, snowmelt, and frozen soil processes is required, and whether all required climate and management input data are available, need to be answered to select a suitable model for forest BMPs simulation and assessment. Except for HGS and SWMM, other models listed in Table 2 do not simulate explicitly the road hydrology and water quality processes. Moreover, none of these models can simulate explicitly the forest activities, such as clear-cutting vs. selective-cutting, cable-logging vs. ground-logging, landing design and location, and natural vs. artificial reforestation. Assumptions or simplifications of processes are required when applying these models for forest BMPs assessment.

In comparison to the numerous BMP modeling studies in agricultural watersheds, very few studies have been conducted to assess the impact of forest BMPs on water quality in a forested watershed, particularly under cold climate conditions. Peraza-Castro et al. (2018) applied the SWAT model to assess the impact of forest clear-cutting on discharge, suspended particulate matter (SPM), and particulate organic carbon (POC) load from the upper part (31.6 km^2) of the Oka River watershed in Northern Spain. Results showed that the practice of clear-cutting could increase discharge, SPM, and POC load by 3–15%, 19–106%, and 9–47% respectively compared to the baseline scenario. Khanal and Parajuli (2013) applied the SWAT model to evaluate the impacts of forest clear-cutting on water and sediment yields in the upper Pearl River Watershed (7,885 km^2) of Mississippi, USA. Results showed that potential changes in water and sediment yields were between 17 and 96% and 33–250%, respectively, with an increase in clear-cutting area from 10 to 75% compared to the base scenario. Nolan et al. (2015) evaluated stream crossing BMPs of forest roads and skid trails on erosion in the southern Piedmont region of Virginia, USA, using the Universal Soil Loss Equation modified for forestland (USLE-Forest), and concluded that BMP upgrades had the potential to reduce erosion rates to similar levels found in undisturbed forests. However, these forest BMP modeling studies focused on the environmental benefits of erosion and sediment control in forest areas, while the reduction of nutrient export from forest BMPs was not included in the modeling assessment.

Model applications for accessing the impact of climate change on forest nutrient dynamics

Climate change has been identified as one of the greatest threats to water resources and ecosystem management (Keller et al., 2023). In addition to changes in annual precipitation and air temperature, climate change also affects their intra- and interannual variations and could lead to more intense and frequent extreme weather events. In the cold-climate environment, these changes will affect the processes of snow accumulation, snowmelt rate and timing, lead to changes in the runoff intensity, evapotranspiration (ET), groundwater recharge, and increases the risk of flooding and soil erosion. With respect to forest growth and nutrient dynamics, changes in precipitation and temperature can affect soil moisture, nutrient leaching, and plant uptake, influencing nutrient mineralization and microbial activity. In addition, climate change has a potential to alter the distribution and abundance of tree species and may cause in northwards shifts of some species, which will have implications on nutrient demand and cycling. Therefore, incorporating climate change projections in the watershed water quality model is crucial for understanding the range of possible future impacts on forest nutrient dynamics. Furthermore, projecting the response of the forest ecosystem to climate change is important for developing management strategies for a sustainable development of forest-dominated watersheds.

Given the dynamics of nutrients are controlled by various factors, including climate, topography, soil properties, forest growth, and human activities, modeling nutrient export and loading in a forest-dominated watershed under climate change conditions involves an assessment of interactions climate with the landscape processes and the effects on hydrologic processes and nutrient cycling. Therefore, the selected watershed models must account for these key influencing factors in the process simulation. Of the ten watershed water quality models listed in Table 2, only the SWAT model has a simple plant growth component integrated with the key hydrologic and water quality processes, and therefore, provides a basis for assessing the impact of climate change on forest nutrient dynamics and export. Other models, when applied to assess climate change scenarios in a forested watershed, need to couple or combine a forest growth model for a reasonable process simulation.

Compared to studies of climate change's impact on nutrient export from agricultural watersheds, the number of studies on forest nutrient dynamics and water quality in the context of climate change has been very limited. The SWAT modeling study of Peraza-Castro et al. (2018) in the upper part of the Oka River watershed in Northern Spain showed climate change induced decrease in discharge, SPM, and POC loads in response to precipitation decrease and ET increase. Park et al. (2010) assessed future climate change impacts on nutrient loadings in a forest-dominated watershed in South Korea by integrating future vegetation canopy in the SWAT model. Results indicated a significant increase in annual TN load and a decrease in annual TP load in the 2080s, which were attributed respectively to the increase of subsurface lateral flows and the groundwater recharges by the future rainfall increase and decrease of sediment load during wet periods because the increase in leaf area index (LAI). Similar results were obtained by Shrestha and Wang (2020), who applied the SWAT model in the Athabasca River basin in Alberta, Canada, in terms of a significant increase in TN and a decrease in TP from the forest under the projection of wetter and warmer future climate. Jayakody et al. (2014) applied the SWAT model in the forest-dominated Upper Pearl River watershed, USA, and projected increases in TSS, TN, and TP loadings up to 26.3%, 7.3%, and 14.3% respectively under future climate conditions. Hao et al. (2022) applied the SWAT model in the forest-dominated Lancang River Basin in China and projected that the annual DN and TDP export from the watershed could increase by 38.63% and 44.38%, while the annual export of PP and PN can be up to 1.5-fold under the condition of changes in future temperature and precipitation. Bosch et al. (2014) applied the SWAT model in the forest-dominated Grand watershed in the US and projected a slight increase in TP and TN yield (4% and 6% on average) under the moderate climate change scenario, and an increase of 6% and 16% in TP and TN under the pronounced climate change scenario. All these studies reported an increase in TN loadings in a forest-dominated watershed under future climate change conditions, but TP may increase or decrease depending on the difference in future precipitation and temperature patterns, as well as the watershed and forest characteristics. However, uncertainties existed in these modeling results due to the challenges simulating the complex watershed system under future climate conditions. Future climate projections are also associated with uncertainties due to GCM structure and internal variability, and greenhouse gas concentration and emissions pathways, downscaling method, and hydrologic and water quality model structure and parameters (e.g. Hattermann et al. 2017; Shrestha et al. 2014).

Discussion

Like any modeling approach, watershed water quality models have certain limitations and uncertainties when applied to simulate nutrient dynamics and estimate pollutant loadings in a forest-dominated watershed. Firstly, reliable and high-resolution data on land use, soil properties, climate, water quality, and forest management practices may not be available in remote areas leading to challenges in capturing spatial and temporal variations of hydrologic processes for model validation, leading to uncertainties in the model outputs. Secondly, watershed models often simplify complex hydrologic and water quality processes, and most of these models (Table 2) do not incorporate dynamic forest growth and biological interactions in soil and water bodies, which introduces uncertainties to the assessment results and limits their predictability in response to land management practices and climate change. Thirdly, the simulation of a complex watershed hydrobiological system needs high model flexibility to represent various topographic, soil, land use, and land management characteristics, resulting in highly complex model structure and overparameterization. Most model parameters have a wide range of acceptable values leading to uncertainties in the model calibration (Beven 2006) and resulting in limited model scalability and transferability to other watersheds with different climate or landscape conditions. In addition, the efficiency of forest BMPs varies both spatially and temporally. Challenges exist in watershed water quality models on how to represent various forest BMPs and their effectiveness, how to scale up findings from a well-calibrated watershed model, and how to transfer findings to other watersheds. Being aware of these limitations and uncertainties is important for watershed managers in interpreting the modeling results, especially for forest BMPs planning and assessment in a changing climate.

In cold climate regions, a significant portion of runoff comes from snowmelt during spring, while the amount of snow accumulation, spatial distribution, and timing and rate of snowmelt play a crucial role in water availability and quality. Compared to models applied in watersheds with a snow-free climate condition, the cold region watershed models must include a variety of process representations such as snowfall, snow accumulation, redistribution, sublimation, snowmelt, and soil freezing-thawing cycle (Christopher et al., 2020). These processes have a significant effect on water quality in forested watersheds, for example, the majority of sediment and nutrient loadings occur during snowmelt season, plant growth and nutrient cycling are altered due to frozen conditions, and the numerous lakes and wetlands which are typical in the northern landscape, e.g. the LoW watershed, play a critical role in contaminant cycling and transport within the watershed. Therefore, the model selected for water quality studies in a forest-dominated watershed needs to integrate all these relevant processes in the simulation, in particular, for the impact assessment of forest BMPs and future climate change on water quality. In recent years studies, scientists have recognized that some agricultural BMPs that leave more residues on the ground, such as cover crops, conservation tillage, and vegetative filter strips have a mixed effect on nutrient loadings under cold climate conditions (e.g. Tiessen et al. 2010 and Habibiandehkordi et al. 2019). These BMPs would reduce TDP loading for summer storm events but may increase TDP loading during spring snowmelt events due to surface accumulation of phosphorus and its released from plant residues under a cold climate. These findings would have implications for relevant forest BMPs in the cold climate region. How to incorporate this unique process in the watershed water quality models poses a big challenge for assessing forest BMPs and climate change scenarios.

To simulate nutrient dynamics and assess the impact of BMPs and climate change on nutrient loadings in a forest-dominated watershed, fully-distributed and processes-based watershed models are more suitable compared to empirical and statistical models because of their process representation for addressing the complex hydrologic and water quality systems. However, tradeoffs exist between model complexity and model functionality causing difficulties in data preparation and model calibration. Some watershed models, such as SWAT, HSPF, and SWMM contain internal components for automated sensitivity, calibration, and uncertainty analysis. However, these tools cannot eliminate the inherent issue of parameter equivalence, and therefore, further manual calibration or external procedures such as the Monte Carlo simulation and the generalized likelihood uncertainty estimation are required to assess the reliability of watershed sub-process simulation based on site-specific minoring data (Piccioni et al. 2022). As such, the development of modeling approaches that better recognize and minimize trade-offs between functionality and complexity is needed so that high-complexity models listed in Table 2 can be applied in forest-dominated watersheds operationally and reliably with an efficient model parameterization, calibration, and validation.

Future developments of watershed water quality models need advancements in modeling techniques aimed at addressing practical challenges discussed above that includes simulation nutrient dynamics and quantification of nutrient loadings for assessment of BMPs and climate change impacts in forest-dominated watersheds. These include: (1) continuous climate, flow, water quality, and plant growth data at field to watershed scales need to be collected, especially at BMPs implementation sites and paired experimental watersheds. These datasets are essential for reliable use of processes-based models and improve our scientific understanding of water quality processes and pollutant loadings from different sources; (2) the existing watershed water quality models need to be improved for a detailed forest land characterization within a watershed, including snow, frozen soil, plant growth, erosion and nutrient dynamics, and biogeochemical processes under cold climate conditions, and interactions with land surface and in soils and water bodies. Model enhancement to better incorporate the hydrologic and water quality processes is also desired for assessing the impacts of climate change; (3) as discussed in this review, no existing watershed water quality models in Table 2 have an explicit component in simulating forest BMPs causing difficulties in simulating their hydrologic and water quality processes. New forest BMP modules embedded or coupled with the existing watershed models need to be developed for the assessment of their impacts on water quality; and (4) the HRU-based watershed models, such as SWAT and HSPF which are popular tools for the simulation of nonpoint source pollution, group the same land use, soil, and slope range into one computation unit within a subbasin, which causes difficulties in applying the model for site-specific BMPs simulation. New location-based models that incorporate a full set of BMP information and allow prediction and assessment at various spatial and temporal scales need to be developed. In addition to the above-mentioned developments, an ensemble modeling approach for cross-comparison of models in relatively data-rich forest-dominated watersheds is required to identify the model's suitability and reliability by testing different models against a stand-level measurement dataset.

Conclusions

We reviewed past and current advances on forest nutrient export and capabilities of existing watershed water quality models in predicting nutrient loadings from forest-dominated watersheds in this paper. Emphases were given to the watershed models to be used under cold climate conditions, and their capacities and limitations in assessing the impacts of forest BMPs and climate change scenarios on nutrient loadings at a watershed scale. Results summarized in Table 1 indicated that nutrient export rates in forest-dominated watersheds vary significantly which were controlled by local climate, soil, plant growth, land cover, and land management practices. Some existing watershed water quality models (Table 2) can estimate nutrient loadings from forests either with a simplified forest growth function (SWAT) or without a forest growth component. Combining or coupling with a forest growth model is required for a reliable simulation of nutrient dynamics and loadings in a forest-dominated watershed. No existing watershed water quality models have explicit forest BMP functions. Assumptions or process simplifications are required when applying existing models to assess the impact of forest BMPs. Compared to other models, the SWAT model incorporates management factors for describing hydrologic and water quality processes and has been used widely in estimating sediment and nutrient exports and assessing the impact of climate change scenarios on nutrient export in forest-dominated watersheds under cold climate conditions.

Compared to field measurement and statistical data analysis, watershed water quality models have advantages such as providing flexible spatial and temporal scales, integration of various climate, topographic, soil, land use, and hydrologic processes into one system, scenario analysis, and risk assessment. However, watershed water quality models also suffer from limitations and uncertainties when applied in a forest-dominated watershed for simulating nutrient dynamics and assessing the impact of forest BMPs and climate change on water quality. These may include (1) models needs field data of climate, flow, water quality, and forest management practices which are normally rare in remote areas, (2) models may not always reliably predict real-world outcomes due to simplifications and assumptions made during the modeling process, (3) the challenge and uncertainty in describing complex phenomena with mathematical equations may lead to misunderstandings or misinterpretations of the modeling results, and (4) a calibrated model and BMP assessment results may be limited to specific local climate and landscape conditions, making it difficult to scale up and transfer to other watersheds. Overall, while watershed water quality models offer valuable insights and predictions, it is important to understand their limitations and uncertainties for proper watershed water quality process simulation and environment impact assessment in a forest-dominated watershed.

Future development of watershed water quality models for forest nutrient management involves the enhancement of scientific understanding of nutrient dynamics and processes influencing nutrient export. These include (1) field data collection, (2) improvement of existing models, (3) forest BMPs representation, and (4) development of new models for site-specific forest BMPs characterization and assessment. Scientific research and innovation in these areas will contribute to the development of more robust and effective watershed water quality models, supporting forest BMPs management and environmental sustainability.

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Declarations

Conflict of interest We have no conflicts of interest to disclose.

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