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Forest hydrology modeling tools for watershed management: A review

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ABSTRACT

Demands for water services from forested watersheds have dramatically increased since the 1950s and the trend continues as global environmental change intensifies in the 21st century. The goal of this study is to provide an overview of existing hydrological modeling tools that can be used in watershed management in a forest environment, offer guidance of model uses, and identify knowledge gaps in model development and applications. We classify 47 selected hydrological models according to their development purposes, theories, functionalities, and potentials to be applied in Decision Support Systems (DSS) for addressing five emerging watershed management challenges. We found that generic field, forest stand, and watershed-scale hydrological models developed in the 1980s–1990s are readily available for being incorporated into DSS for projecting hydrological responses to climate and land cover changes and address other watershed management problems. However, these models rarely explicitly link forest structure and species-level information to hydrological processes and functions, thus have limited utilities to answer specific forest management questions. Since early 2000s, hydrological models have incorporated energy, vegetation, terrain, and ecohydrological processes to begin to answer questions at hillslope to regional scales. However, routine uses of advanced modeling tools in forest watershed decision making remain challenging. Future model development should integrate multiple stressors and fine scale ecosystem and surface processes (e.g., vegetation dynamics, energy partitioning, and biogeochemical cycling), and balance model complexity, applicability, and access. Effective forest watershed DSS should have the ability to forecast short and long-term consequences of forest management decisions that often involve high risk and uncertainty under environmental change. In addition, DSS should integrate both physical and social aspects of watershed sciences that value indigenous culture and values.

1. Introduction

Sound forest watershed management is rooted in forest hydrological science that was largely developed in the 1960s to address emerging issues from soil erosion to acid rain (Brooks et al., 2003; Black, 2005; Vose et al., 2016; Amatya et al., 2016; Jones et al., 2020). The advancement of forest hydrology has provided much-needed guidance on sustainable watershed management in a world that is increasingly more complex (Vose et al., 2011,2016). Our understandings of the role of forests in regulating hydrological processes, river flows, and water resources at multiple scales are converging (Zhang and Wei, 2021). The role of forestation as a Nature Based Solution (NbS) to address climate change and sustainable development is increasingly recognized (Creed and van Noordwijk, 2018; Lü et al., 2012; Sun and Vose, 2016; Springgay, 2019). Emerging forest hydrological questions, such as how to balance forest carbon sequestration, water supply, forest health, and biodiversity (Jackson et al., 2005; Grant et al., 2013; Liu et al., 2021b; Bruijnzeel, 2004; Huang et al., 2022) are often at the center of the controversy of natural resource management and sustainability science discussions (Bryan et al., 2018; Feng et al., 2016; Li et al., 2021). Global

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forests (1/3 of Earth's land area) provide over 70% of freshwater supply (MEA, 2005), but managing forest-water relations can be complex. Managing forests for water supply has a human dimension (Sun et al., 2020) and different emphasis on the positive and negative roles of forests in water security exists among different economic sectors, affecting decision making on forestry policies (Baulenas, 2021; Skulska et al., 2020). Cross-sectoral policy integration of forest and water management has been called upon in many European countries. For example, in Spain, some policy trajectories showed overplanting in the 1980s increased natural forest covers resulting in decreased streamflow (Fernández et al., 2006; Buendia et al., 2016; Khorchani et al., 2021), while the effects of unmanaged afforestation in headwaters on groundwater recharge are inconclusive (Juez et al., 2021; Vadell et al., 2016). Negative long-term effects of afforestation on surface water occurred in Mediterranean forests and effective forest management is needed to sustain groundwater recharge and realize the intended hydrological services percolation (González-Sanchis et al 2015; García-Prats et al., 2018). Indeed, challenges remain in managing forests for water globally (FAO, IUFRO, USDA, 2021) and advanced tools are needed to assist forest watershed management under multiple stresses on water resources (Sun et al., 2008).

Modern watershed management decision-making is often constrained by multiple objectives (Vose et al., 2016). For example, to maximize the ecosystem services of water supply and carbon sequestration of forests, forest planner and watershed managers need to assess the tradeoffs of water use by trees for achieving objectives of sequestering atmospheric CO_2 and provide water supply to downstream water users. Such optimizations require advanced ecohydrological modeling tools to describe the interactions of ecosystem services. To properly address these type of questions, advanced, sophisticated, and practical science-based Decision Support System (DSS) are often needed. DSS collects rich spatial information and has the capacity to easily communicate modeled scenarios in a central place with decision makers provides a powerful means in modern water resource management (Andreu et al., 1996). Science-based decisions reduce risk of negative consequences of management actions (Yousefpour et al., 2012). Hydrological models are the essential component of forest and water management DSS (Chapman et al., 2018) that have synthetical, analytical, and prediction capability and help better evaluate and optimize various complex management options at various scales for multiple purposes. Forest hydrology models can not only provide better understandings of hydrological processes at a forest stand or catchment scale, but also can be integrated with DSS to quantify hydrological responses to future forest management, such as silvicultural practices under a changing climate change (Golden et al., 2015).

However, implementing the modeling tools remains challenging given the complex natural and socio-economic issues involved in forest management (Sun and Vose, 2016) that must meet multiple demands under a changing environment. For example, successful reforestation is not simply planting trees (Holl and Brancalion, 2020) and ecohydrological principles must followed (Cao et al., 2011): 'planting right trees for the right places for the right purpose' (Creed and van Noordwijk, 2018); what are the innovative forest management practices to increase forest resilience to climate change (i.e. drought) while maintaining ecosystem services of forests (Grant et al., 2013; Vose et al., 2018). A recent *meta*-analysis from 75 studies on the effects of 128 afforestation actions suggests that Spanish afforestation policy improved timber provision and carbon sequestration but did not enhance regulation services (biodiversity, soil, water) when compared to natural lands (Pérez-Silos et al., 2021).

2. Objectives

The overall goal of this study is to synthesize existing literature on the hydrological modeling tools used by forest researchers and land managers to address contemporary watershed management and emerging environmental issues. Specifically, we attempt to (1) identify five broad emerging watershed management questions, (2) review pros and cons of existing hydrological modeling tools that may help answer these five questions, (3) provide guidance to model users for selecting the most appropriate tools to effectively achieve desired goals through presenting application examples, and (4) identify knowledge gaps and future research needs in forest hydrological modeling and DSS development.

3. Identifying emerging management problems and model review methods

Based on the recent IUFRO report (Creed and van Noordwijk, 2018) and our expert knowledge related to forest watershed management issues (Sun et al., 2011; Sun and Vose, 2016; Sun et al., 2020), we identified the following five key emerging management problem areas for which modeling tools can help to tackle.

We discussed modeling applications around following five broad forest watershed management issues that are interconnected and are not exclusive among them:

1. Ecosystem Service tradeoffs and synergies (e.g., water supply, water quality, carbon sequestration, biodiversity, water quality, human livelihood).
2. Watershed restoration for landscape resilience to disturbances (e.g., tree planting, prescribed burning, species conversion, thinning).
3. Urban forestry and green infrastructure towards resilient cities (e.g., storm flow abatement, mitigating 'Urban Heat Island' and 'Urban Dry Island').
4. Climate change mitigation and adaptation (e.g., hurricanes, sea-level rise, mega wildland fires).
5. Assessment of Cumulative Watershed Effects (CWEs) and threshold determination from forest disturbances (e.g., forest harvesting/reforestation planning, watershed restoration, and climate change adaptation).

Focusing on the five problem areas, we critically examined current modeling tools by comparing model design, structure, and processes. Results are summarized to give users an overall picture of model utilities and application potentials in watershed management decision making. We used Web of Sciences, Google Scholar, Endnote, tools to search for relevant key publications during the past 40 years. We limited our review on models that are applicable to forest conditions at different scales from forest stands to globe. Keywords include "Forest Hydrology Models", "Distributed Hydrological Models", and "Forest Watershed Decision Support Systems". Based on these broad criteria, a total of 47 modeling tools (Fig. 1) were examined and a subset of these models (Supplementary Table S1) that are more relevant to forest management were selected for in depth analysis.

We discussed uncertainty of modeling outcomes resulted from model deficiencies, inherent challenges for climate change projections, and the effects of management interventions. Finally, we proposed the most promising modeling approach toward developing better DSS for forest watershed management.

4. Results

A Web of Science search using "forest" AND "hydrology" AND "models" resulted in 5204 records and citation of 183, 000 for the period from 1971 to 2021. The number of publications increased from about 100 per year in 2005 to 440 records in 2021, suggesting dramatic rise of modeling research and application. Most of the publications are from the U.S. (42%), China (12%), and Canada (11%). Selected models were grouped by development timeline to show the progress of hydrological modeling science and technology since the 1960s (Fig. 1). It is obvious that the number of models has increased rapidly since the 2000s,

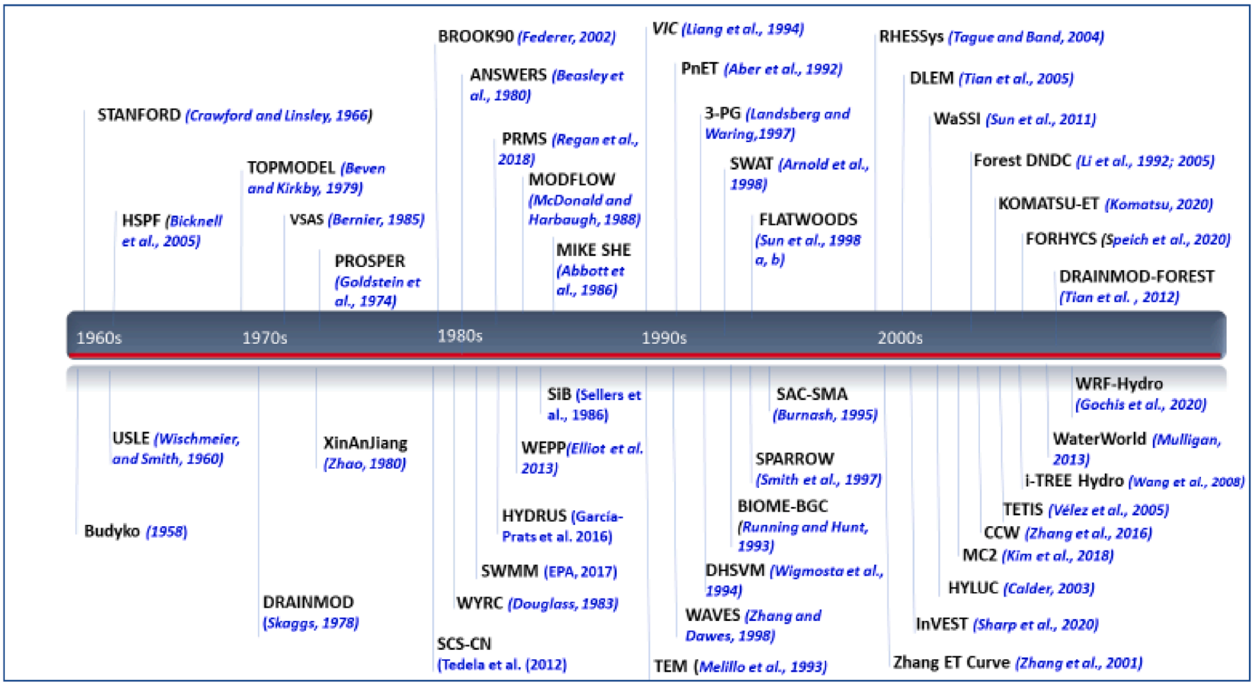

Fig. 1. Timeline of 47 selected models related to forest hydrology that may be used in Decision Support Systems for watershed management. Most recent citations are used for model variants. (See above-mentioned references for further information.)

consistent with the publication search results from Web of Science. The number of citations based on the search in Web of Science with the model title as key word for a few popular models was presented in Fig. S1.

Hydrological models are becoming more complex (e.g., explicitly considering the spatial heterogeneity, biogeochemical cycles) and more integrated (e.g., vegetation, soil, topography, atmosphere) during the past two decades. During the past 10 years, the rapid advances of super computers, cloud-based storage and computing, remote sensing technology, and Earth information systems allow detailed watershed representations and hydrological modeling in a much finer scale for large areas from large basins (e.g., RHESSys model, Tague and Band, 2004; WRF-Hydro, Gochis et al., 2013) to the globe (e.g., WaterWorld, Mulligan, 2013). A search with Web of Science using key words “Distributed Watershed Hydrological Modeling” resulted in 1506 records (1991–2022) in which 95% of the publications occurred during 2001–2022. However, when adding “Forest” in the previous search, only 233 or 15% of the general publications on distributed hydrological modeling were recoded. The number of publications on distributed forest hydrological modeling, as represented by The Distributed Hydrology Vegetation Soil Model (DHVSM, Wigmosta et al., 1994) has been stable since 2010, suggesting a divergent trend in model applications in forest watershed management. Distributed modeling tends to be for large basins that encompasses non-forest ecosystems and link forested watershed processes with downstream with non-forested landscape dominated by agricultural landcovers or urban areas (Zheng et al., 2020). In addition, more models are emerging to address future climate change effects on water resources at both fine and coarse scales during the 21st century (Zhang et al., 2022).

The 33 modeling tools were grouped by temporal and spatial scales

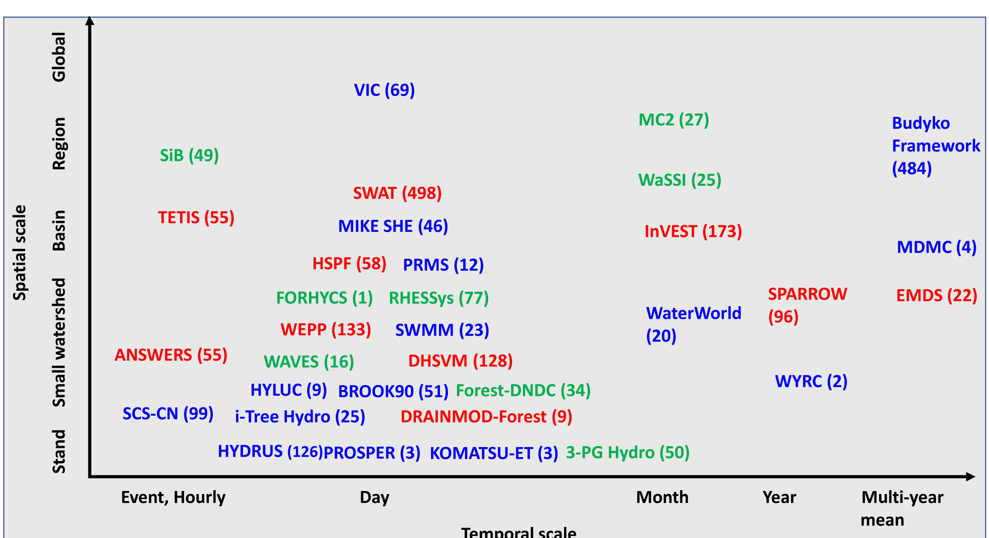

Fig. 2. A comparison of key modeling tools by their spatial and temporal resolutions. Model functions are color coded. Blue: water quantity only, Red: water quality and quantity, and Green: water quantity and carbon. The numbers next to each model represent the approximate number of publications found by a search by Web of Science using model names constrained to forest conditions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to compare model functionality for facilitating model use (Fig. 2). For example, the distributed hydrological model DHSVM has been identified as being most suited for forested watersheds in snowfall-dominated mountain areas (see review in Beckers et al., 2009) while the DRAINMOD-Forest is designed for poorly drained soils with a high groundwater table on flat lands (Tian et al., 2012). These models were selected for their close relevance to forest management, and they were grouped by the five problem areas (Supplement Table S1). Many of the models have several versions for specific applications with improved functionality (e.g., groundwater process) or extended ecosystems (e.g., crop, grass, or forest lands) over time. For example, DHSVM was initially developed in the early 1990s to characterize watershed hydrologic processes and project potential changes with changing climate and land covers in forested watersheds, but it has been adapted to represent urban landscapes, glacio-hydrological dynamics, river thermal dynamics, urban water quality, and forest-snow accumulation interactions (Perkins et al., 2019).

A Web of Science search suggests that SWAT, InVEST, SCS-CN, SPARROW, WEPP, DHSVM, RHESSys models represent the most popular dynamic models for quantifying water quantity and quality and Budyko framework is widely used for long-term mean hydrological analysis (Fig. 2).

Hydrological models vary by assumption, theory, objective, scale, structure, utility, data needs, and transferability. Accordingly, we made recommendations of model use by the five problem areas (Fig. 3). Difficulty of uses are qualitatively determined by data demands to run each individual model. DSS tools for addressing forest water management questions must be designed by purpose, scope, technical complexity, and user expertise. We demonstrate how models can be used to answer real management questions with examples for selected models.

4.1. Managing forested watersheds for synergies and tradeoffs of various ecological services

Clean water supply and carbon sequestration have been recognized as two important ecosystem services of forested watersheds (Sun et al., 2011; Podolak et al., 2015; Sun et al., 2017; Liu et al., 2021b; Murphy, 2020; Vose et al., 2016). Drinking water utilities are continuously seeking ways to maintain forested lands in the headwaters to protect water quality and sustain water supply (Warziniack et al., 2017) to meet the increasing water stress from population growth and climate change. Forest water and carbon cycles are closely coupled (Aguilos et al., 2021; Liu et al., 2020; Kurz et al., 2013; Giles-Hansen, 2021). This carbon gain and water loss relationship is considered as an ecosystem tradeoff (Jackson et al., 2005) and forest productivity and biodiversity may be viewed as ecosystem service synergy (McNulty et al., 2010).

Simulation models for both hydrology and carbon sequestration, and their tradeoffs can date back to the 1960s and 1990s, respectively (Fig. 1; see also a review of forest hydrology models in Golden et al., 2015). Some of these models have been incorporated into Decision Support Systems (DSS) for guiding forest management to minimize environmental impacts while maximizing ecosystem services. The DSSs are considered as central tools with which decision makers can visualize available information, often incorporate geospatial information technology and consider both water supply and demand dynamics, carbon sequestration, and their tradeoffs that are affected by variations of climate, land use, and population growth over time and space (see example in Zhang et al. (2008)). A few examples are discussed in greater details below.

In the U.S., various simulation tools for managing water supply and carbon sequestration have been developed by various agencies. Each State often develops its own plans to guide water withdrawals to meet water demands by people, environmental flows, and other considerations at the watershed level. For example, the U.S. Geological Survey (USGS) supports over 150 open-source software hydrological tools (https://water.usgs.gov/software/lists) that are available to the public free of charge. Some popular models such as HSFP, SWAT, PRMS, SPARROW (Table S1) have been applied in watersheds with mixed land uses (Yang and Wang, 2010) across the U.S. US Environmental Protection Agencies (EPA), as a regulatory agency, supports the development of water quality models such as HAWQS (Hydrologic and Water Quality System) that was developed based on SWAT (Yen et al., 2016; Fant et al., 2017; Ouyang, 2021), and other user-friendly tools such as Watershed Assessment, Tracking and Environmental Results System (WATERS), GeoViewer, and EnviroAtlas. These models provide geospatial data and analysis related to ecosystem services, chemical and non-chemical stressors, and human health (Pickard et al., 2015). The SWAT model was originally created for agricultural lands with support from the U.S. Department of Agriculture (USDA), but it has been revised for applications in forested conditions (see review in Marin et al., 2020). Due to its

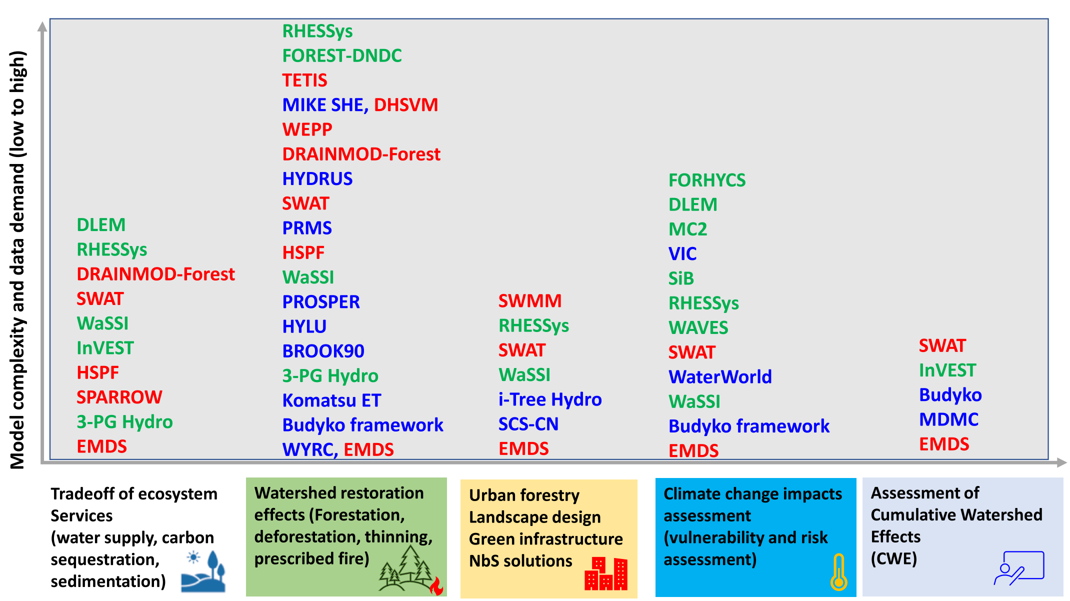

Fig. 3. Model recommendations to address five broad forest watershed management problem areas. Models are ranked by relative complexity and ease of application from low to high. Model functions are color coded. Blue: water quantity only, Red: water quality and quantity, and Green: water quantity and carbon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

simplicity and easy use, the USDA Soil Conservation Service (SCS) Curve Number Method has been widely used to estimate storm runoff for ungagged small watersheds including those dominated by forests (Tedela et al., 2012; Im et al., 2020; Walega et al., 2020). Similar 'curve' types of models have been developed using empirical data from watershed vegetation manipulation experiments (e.g., Douglass, 1983) (See Water Yield Response Curve, WYRC, in Table S1). The WYRC estimates annual water increase as a function of tree basal area removed, an energy index of the watershed, and time since forest removal. In recent years, 'top-down' models rooted in the Budyko energy and water balance frameworks such as Fuh's (Zhou et al., 2015) or Zhang's models (Zhang et al., 2001) have been used to estimate response of long-term mean water yield to forest cover change (Sun et al., 2005,2006; Zhou et al., 2015) and climate change (Heidari et al., 2021).

The USDA Forest Service developed an ecosystem services model, WaSSI (Table S1) (Sun et al., 2011; Caldwell et al., 2012; Liu et al., 2022). The WaSSI model simulates key ecohydrological and carbon fluxes including water yield, ET, gross primary productivity (GPP), and net ecosystem productivity (NEP) by coupling carbon fluxes with ET through water use efficiency (WUE) parameters by land cover type as derived from global flux network data. The WaSSI model is in the public domain, simple to be implemented with minimum data requirements, and thus has been tested worldwide in the U.S. (Duan et al., 2016; Li et al., 2020), Australia (Liu et al., 2018), China (Liu et al., 2013), Mexico, African countries (Bagstad et al., 2018; McNulty et al., 2016), and Europe for assessing effects of forest management, urbanization, drought, and climate change on ecosystem services. A web interface is available to facilitate the model to examine the effects of forest conversion and climate change under different scenarios on water supply stress at the 8-digit Hydrologic Unite Code scale (https://web.wassiweb.fs.usda.gov/). The WaSSI modeling results suggest that forests represent 36% of the total land area in the conterminous U.S., but contribute over 50% of the total surface water yield (Liu et al., 2021b, 2022).

In Spain, various tools have been officially used in decision making for balancing economic cost and benefits to water resources through forest management. For example, García-Prats et al. (2018) developed a novel hydro-economic modeling framework for designing the optimal integrated forest and water management. The model explicitly integrates a 1-D soil hydrological model HYDRUS (Simunek et al., 2005) an allometric model and a management cost database. The model determines the optimal schedule of silvicultural interventions that maximizes the total net benefit at the watershed level. Canopy cover and biomass evolutions over time are simulated using growth and yield allometric equations specific for the species under Mediterranean conditions (García-Prats et al., 2018).

Parsimonious models, such as TETIS (Francés et al. 2007), that describe vegetation dynamics and carbon cycles have advantages over traditional hydrological models. Mechanistic models that accurately reproduce the carbon dynamics allow decision makers to predict vegetation evolution and its effect on water resources, and thus make decisions based on more complete information such as the trade-offs among water and other ecosystem service variables.

In a comprehensive global literature review of 209 studies on the interactions among ecosystem services, Agudelo et al. (2020) identified 26 modeling assessment tools that used a mixed approach combining geographic information systems (GIS), regressions/correlations, and Bayesian networks. They found that InVEST (Sharp et al., 2014; Song et al., 2015; Xie et al., 2017) (Table S1) remains the most widely used tool for quantifying modeling interactions among multiple ecosystem services at watershed and national scales (Ouyang et al., 2016). InVEST can assess the value of 18 different ecosystem services, including carbon sequestration, water yield, nutrient retention, and recreation and tourism (Butsic et al., 2017).

Quantifying the benefits of reforestation to water yield requires a balanced approach and comprehensive tools (Sun et al., 2006; Wang et al., 2008, 2015; Schwärzel et al., 2020). Tradeoffs among ecosystem services (i.e., soil erosion control, increase in carbon storage, and water yield reduction) are well recognized (Lü et al., 2012; Feng et al., 2016). A 'Water Yield-Oriented' practical decision procedure has been developed by Wang et al. (2015) for northern China's drylands to optimize forest structure achieving goals of 'Multiple Function Forests (MFF)'. MFF is designed for controlling soil erosion while maintaining forest biomass, resistance to ice storm damages, and proper water supply with consideration of site soil water carrying capacity (Wang et al., 2008; Xu et al., 2020). Wang et al. (2015) recommended that an "ideal" stand structure of multifunctional forest (MFF) that balance water yield and tree growth.

4.2. *Watershed ecosystem restoration with tree planting, forest thinning, and wildland fires*

Watershed ecological restoration is a major task for many agencies and governments to meet regulatory mandates reviving watershed functions, services, and resilience to climate change (e.g., drought, wildland fires). Strategies and techniques used in watershed restoration vary globally from controlling invasive species (Strauch, et al., 2017) to planting trees for controlling soil erosion and water quality degradation post wildland fires (Elliot et al., 2006; Elliot, 2013). In recent years, prescribed forest burning, thinning (see review in Zhang et al., 2018; del Campo et al., 2022), and species conversion (Sellers et al., 2021), have been advocated in headwater watershed restoration to improve watershed health, enhance wood production, reduce fire risks, and augment water supply (Qi et al., 2022).

4.2.1. *Forest thinning for restoring ecological and hydrological functions*

Thinning increases forest stand resilience to environmental stress such as drought, insect infestation, extreme temperature, or wildfire (del Río Gaztelurrutia et al 2017, Korb et al., 2020, Hernandez-Santana et al., 2011; Boggs et al., 2015) because thinning generally reduces ecosystem evapotranspiration, alters snowpack patterns, and increases total water yield and groundwater recharge at least for the short term (see review in Edwards and Troendle, 2012; Lane and Mackay, 2001; Hawthorne, 2011). However, the hydrological effects of tinning vary greatly (Douglass, 1983; Grace et al., 2006a,2006b; McLaughlin et al., 2013; Edwards and Troendle, 2012; Bent, 1994; Bent, 2001) depending on many environmental factors (del Campo et al., 2022).

Hydrological models have been applied to assess the effects of forest thinning and tree species conversion (Qi et al., 2022) at stand and watershed scales. Schenk et al. (2020) provided a systematic review of 35 modeling studies to quantify the influence of forest clear-cut and thinning on groundwater recharge and springs ecosystems in arid forests. The review suggests that thinning forests resulted in a greater amount of groundwater recharge than clear-cut. Groundwater recharge responded positively and more strongly to reduced sublimation and evaporation in partially thinned forests than in clear-cut areas. The authors also compared several generic process-based and statistical models for studying fires and forest thinning (i.e., RHESSys, MODFLOW-PRMS, SWAT, WaSSI, MIKE SHE, DHSVM) and found that these models require a substantial amount of spatial and temporal datasets that are rarely available for large landscapes. The authors suggest that long-term field data are needed for delineating the optimal amount of thinning for groundwater recharge for a particular aquifer, soil type, or geologic province. Sun et al. (2015) applied the WaSSI model (Table S1) to examine the sensitivity of water yield to forest thinning, global warming and changes in precipitation, and the combination of these hypothetical scenarios across the U.S. They show that the magnitude of water yield response to a 2 °C air temperature rise is about half of that for the scenario of 50% LAI reduction.

Extensive research on the effect of thinning including strip and select thinning on forest hydrology has been conducted across Japan during the 2000 s for better managing Japanese cedar and cypress plantation forests for improving watershed health, biodiversity, and water supply

(Dung et al., 2012; Sun et al., 2014,2015,2016; Shinohara et al., 2015; Momiyama et al., 2021). Relevant modeling tools have been developed to estimate canopy interception (Murakami, 2007; Sun et al., 2014) and evapotranspiration (ET) (Komatsu et al., 2015; Komatsu and Kume, 2020). Komatsu and Kume (2020) provided a comprehensive review on the effects of forest management (e.g., thinning, harvest) on ET – the most important process in determining hydrological response to forest management. This review indicates that large, generalized scale ET models developed in the 1990s, such as BATs (Dickinson, 1986), SiB (Sellers et al., 1986), VIC (Liang et al., 1994), SWAT (Arnold et al., 1998) have been widely used for practical assessments of the impacts of large-scale deforestation on regional to global water cycles. Other ecosystem models such as Forest-BGC (Running and Coughlan, 1988) and BIOME-BGC (Running and Hunt, 1993) developed in the 1990s and their upgraded version (Hidy et al., 2012) describe water, carbon, and nutrient cycles, but have little emphasis on forest management practices at stand or catchment level, thus they have limited practical use. However, the authors suggest models developed for a certain landscape, particular region, forest types (species), and purposes in the 2000 s such as FLATWOODs (Sun et al., 1998a,b), HYLUC (Calder, 2003), KOMATSU-ET model (Komatsu, 2007), KOMATSU-ET model (Komatsu et al., 2015, Komatsu, 2020), WaSSI (Sun et al., 2011), DLEM (Tian et al., 2009) are better suited for practical uses. Answering specific forest management questions at the stand to watershed scales often requires models that tightly couple forest biophysical information (i.e., tree data for the diameter of breast height and stem density) and leaf area index, ET processes (i.e., canopy interception, forest floor evaporation, and tree transpiration). Widely used ET models include the Penman-Monteith equation (McNaughton and Black, 1973) and simplified versions such as the Priestley-Taylor equation (Priestley and Taylor, 1972) or the empirical models (Sun et al., 2011; Fang et al., 2016; Liu et al., 2017).

4.2.2. Wildland fires

Post-fire watershed restoration or use of prescribed fire as a management tool to restore fire-dependent forests requires a clear understanding of the hydrological responses to fires. Our current understanding of how fires and fuel management affect watershed hydrologic processes and functions is limited, and quantitative predictive tools are lacking (Chen et al., 2013; Dahm et al. 2015). Forest fire research has mainly focused on suspended sediment exports (Smith et al. 2011) that could increase by up to three orders in magnitude above pre-fire values. However, hydrological research about wildland fires is continuously increasing in the past decade due to more frequent and catastrophic fire seasons (Hallema et al., 2018).

A few generic tools, RHESSys, WEPP, SWAT, DHSVM, and MIKE SHE models, have been adapted to evaluate the effects of wildfire on runoff and soil erosion (Table S1). RHESSys is a process-based integrated model designed to simulate coupled water, carbon, and nutrient cycling and transport over a heterogeneous terrain (Tague and Band, 2004; Tague et al., 2004). The model is structured as a spatially nested hierarchical representation of the landscape with a range of hydrological, microclimatic, and ecological processes associated with specific landscape objects at different levels. RHESSys is rather data demanding for management decision making, but it has been applied globally under various climatic conditions and ecosystem types mostly for research purposes (Cao et al., 2021). A variant of this model is the RHESSys-WMFire that couples wildfire behaviors to ecohydrology and vegetation dynamics to project the effects of climate change on water and carbon cycles in mountainous watersheds (Kennedy et al., 2017; Bart et al., 2019). The GeoWEPP and WEPPCloud (Lew et al., 2022; Dobre et al., 2022) are evolved from the original WEPP model (Table S1) and used for evaluating wildfire effects on soil erosion and guiding post-fire responses through a web-based user interface (Elliot et al., 2006; Elliot, 2013; Crumbley et al., 2007; Christie et al., 2013). Srivastava et al (2018) combined FlamMap (a fire behavior model) and WEPP to predict the fire impacts on sediment and water quality at hillslope and watershed levels. McMichael and Hope (2007) applied a revised MIKE SHE model to examine the effects of fire size on seasonal and annual streamflow responses for a medium-sized basin in central California. They found that a linear relationship between seasonal and annual streamflow response and fire size and annual flow response was generally higher in wetter years and was affected by stand age. The physically based, distributed DHSVM model has been widely used in mountain watersheds in western U.S. and snow-dominated regions to understand effects of road network and forest management on peak flow, storm runoff and sediment loads under post fire salvage harvest (Surfleet et al., 2014; Surfleet and Marks, 2021). In the meantime, empirical models, remote sensing, and numerical models are embedded in relevant DSS tools for land planning and fire response. Some of these tools are based on a characterization of the vulnerability to fire, whereas others describe the physical processes involved (Padowski et al. 2020).

In the Mediterranean region, programs such as FlamMap that includes BEHAVE, CELLULAR AUTOMATA Model, and Prometheus are well-known fire simulators that can help identify the most fire-affected areas in Spain. Complex models such as RHESSys-Fire (Bart et al., 2019) and Fire-BGC (Fire-BGC team, 2020) are required for mechanistic understanding of the responses of hydrology, biogeochemistry, and sediment transport to fires. FireEarth is a modeling framework that couples fire spread, ecohydrology, and soil erosion models to characterize fire vulnerability and complexity for water management (Padowski et al. 2020). Basso et al. (2021) applied SWAT and CE-QUAL-W2 model to assess fire impacts on water quality in a watershed with reservoirs in Portugal. The CE-QUAL-W2 model was calibrated for water level, temperature, nutrients, total suspended solids, chlorophyll-a, and dissolved oxygen. The impacts of different fire severity were assessed by adjusting land use features (curve number, crop vegetation management factor), and soil properties (soil erodibility).

4.3. Urban forestry

The benefits of urban trees and forests to city dwellers are increasingly recognized for their ecohydrological functions and cost-effectiveness for storm runoff abatement (Nowak and Dwyer 2007; Boggs and Sun, 2011; Hao et al., 2015), water quality improvement, and shading and cooling (Hao et al., 2018; Huang et al., 2022), air pollution filtering (Nowak et al., 2018), and adaptation to climate change (Long et al. 2019). Urban forest distribution, canopy manipulation, and tree species choices can significantly alter urban watershed hydrological processes (Van Stan et al., 2018). However, urban planners rarely consider urban forestry as a tool in integrated water resource management (IWRM). Practicing modern urbanization strategies under various new paradigms of city development such as Low Impact Development (LID), Sponge Cities, and Nature-based Solutions require advanced tools to guide these efforts.

Hydrological and hydraulic engineers have a long history using numerical models (e.g, the Rational Method) to design engineering structures for flood control in an urban setting. Currently, several hydrological models are capable of simulating forest effects on urban hydrology and are open to the broad stormwater management community (Coville et al., 2020). Examples include i-Tree Hydro, SCS-CN, HSPF, SWMM, SWAT, RHESSys, VIC, WaSSI (Table S1). The HSPF and SWMM models are supported by US EPA for managing stormwater in an urban environment while the SCS-CN is developed by USDA Natural Resources Conservation Service for estimating peak flow. HSPF, SWAT, RHESSys, WaSSI, and VIC models have been used in watersheds with mixed land uses for evaluating the effects of urbanization on hydrology (Yang et al., 2011a; Li et al., 2021). Traditional forest hydrology models for water quantity such as DHSVM has been adapted to simulate water quality in urban environments (Sun et al., 2016).

Of particular interest to the urban forested community is the iTree Hydro modeling tool that evaluates how forest and vegetation management impacts urban stormwater volumes and flow rates, and hydrological benefits of other green infrastructure such as LID impacts (Wang et al., 2008; Yang et al., 2011b). The i-Tree Hydro model is managed and supported by the USDA Forest Service (Wang et al., 2008; Yang et al., 2011b). It is a spatially semi-distributed model that simulates runoff quantity and quality for watershed and non-watershed areas subjected to a single precipitation event or continuous weather. iTree-Hydro (https://www.itreetools.org/tools/hydro) can assist urban forest managers and planners to quantify how changes in trees, vegetation, and impervious areas impact local hydrology. (US EPA, 2002). The iTree-Hydro model does not depend on data availability, so it can serve as a planning tool with robust water quantity and quality predictions given data limitations common to most urban areas (Yang et al., 2011b). However, the lumped i-Tree modeling approach does not address the spatial hydrological variability on urban landscapes. Improved computational power and techniques, and the availability of spatial digital data allow a better explicit spatial representation of the watershed and precision management. This is especially important for rather heterogeneous urban watersheds where the hydrological processes are not well monitored and understood. For example, we know little about ET rates from urban land uses since the remote sensing community often ignores urban areas (Mazrooei et al., 2021).

Salvadore et al. (2015) reviewed 43 modelling approaches for simulating the urban hydrological systems at a catchment scale. The authors conclude that urban watersheds are complex, our understanding of the interactions between urban and natural hydrological systems are insufficient, and there is a high degree of model uncertainty due to spatial data availability. Spatial-temporal gaps existed between the physical scales of hydrological processes and the resolution of applied models. Therefore, urban hydrology was often simplified either as a study of surface runoff over impervious surfaces or hydraulics of piped systems.

4.4. Climate change mitigation and adaptation

Man-made climate change and its direct and indirect impacts on forests affect forest water resources (Caldwell et al., 2016; Jones et al., 2020; Liu et al., 2021a; see review in Zhang et al., 2022). The recent IPCC (2021) AR6 suggests that climate change impacts on forests and water resources would likely be more widespread in the next 100 years and beyond. Climate change and its impacts on forest hydrology are not uniform and unpredictable (Vose et al., 2018). For example, streamflow is projected to decrease over southwestern North America in the next 100 years (Reynolds et al., 2015), while the opposite trend is expected over the northeastern regions due to the increased precipitation. Streamflow in other regions may be more variable in the future (Koirala et al., 2014).

To adapt to the changeable climate and moderate its impacts on hydrological regimes, innovative forest management strategies and advanced tools in DSS are urgently needed by land managers and policy makers (Vose et al., 2011,2016,2018). However, predicting hydrological responses to climate change is challenging since there are large uncertainties in future climate change (Yousefpour et al., 2012) and how forests respond to climate (Zhang et al., 2022). Traditional watershed hydrological models such as PRMS, SWAT, MIKE SHE, DHSVM described in Table S1 have been used to address climate change impacts on water yield (see reviews in Gleick, 1989; Xu, 1999; Xu and Singh, 2004; Lu et al., 2009) because these models are all driven by precipitation, air temperature, and potential ET as the primary climatic forcing. Application examples included the VIC (Heidari et al., 2021), and WaSSI (Duan et al., 2016) models for projecting effects of climate change on water supply at the national level in the U.S. Complex landscape models such as RHESSy has been used in China to evaluate the effects of climate change in a water supply basin in northern China (Cao et al., 2021). Distributed hydrological models such as DHSVM for complex terrains with highly variable climate have been applied to study the combined effects of climate change and invasive species in tropical zone of Hawaii (Strauch et al., 2017). In these assessments, climate projections from general circulation models (GCMs) are applied to represent future climate scenarios (Heidari et al., 2021) under different socioeconomic pathways (e.g., RCP8.5). In Germany, Ziche et al. (2021) used the LWF-BROOK90 hydrological model to develop the water balance of seven forest monitoring sites for the historical period of 1961–2019, and the future period of 2010–2100. Two combinations of global and regional circulation models, MPI-ESM-REMO (MPI/REMO) and EC-Earth-RCA4 (ECE/RCA4), and two RCPs (2.6 and 8.5) were used. The results revealed that the study sites would be significantly drier under RCP8.5, while no significant trends were identified under RCP2.6.

The GCMs are developed by climate modelers with different assumptions (Ahmadalipour et al., 2017). The skills of GCMs are rapidly improving representing the complexity of the atmosphere-land surface interactions within the Earth system. However, the spatial resolution of GCMs is generally coarse (>100 km), which would lead to large uncertainties in projecting climate change (precipitation in particular) for a particular watershed or region (Hargreaves, 2010). It is common to use multiple empirically or dynamically downscaled GCM projections for hydrological projection purposes so that the uncertainties can be provided to stakeholders (PINEMAP DSS, 2021). For example, Zhu et al. (2017) used a set of empirical regression models (i.e., fluctuations of groundwater table as a function of precipitation and ET) and projected climate data from four GCMs to assess climate change effects of wetland hydroperiods across the southeastern U.S.

Recognizing the insufficiency of traditional hydrological models in describing the responses of biological processes such as vegetation dynamics to climate change, the global change modeling communities and various agencies have put more efforts into developing models that consider biophysical processes including carbon, water, nitrogen (Aber and Federer, 1992), and energy balances at multiple scales for global applications (Sellers et al., 1986). For example, energy-based land-surface models that simulate the energy balance at soil, atmosphere, and vegetation interfaces by using remote sensing data at finer time scales have been combined with distributed hydrological models to better estimate evapotranspiration and flow routing (see review in Overgaard et al., 2006; Sood and Smakhtin, 2015). Examples of such models include the Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson et al., 1986), the Simple Biosphere Model (SiB) (Sellers et al. 1986), and WRF-hydro (Gochis et al., 2020; Lin et al., 2018).

Describing the true interactions and feedbacks between land surface processes such as forest vegetation functions (i.e., water yield) and climate systems requires a tight coupling among GCMs and vegetation dynamics (Gordon and Famiglietti, 2004; Phipps et al. 2011). Dynamic global vegetation models (DGVMs) can simulate interactions between climate, forests, and hydrology under long-term climate change scenarios (Cramer et al. 2001; Gonzalez et al. 2010; Kim et al. 2017). DGVMs typically include four core components of biophysics, plant physiology, soil biogeochemistry, and dynamic vegetation and land use. Examples of DGVMs include Hybrid V3.0 (Friend et al. 1997), MC2 (Kim et al. 2017), the Lund-Potsdam-Jena (LPJ) (Sitch et al. 2003), CLM (Levis et al. 2004), IBIS (Foley et al. 2005), and DLEM (Tian et al. 2009).

The MC2 model is one type of DGVMs for projecting long-term forest dynamics and water and carbon cycles in response to climate change (Kim et al., 2017; 201; Bachelet et al., 2003) at regional, continental, and global studies (Bachelet et al. 2015; Sheehan et al. 2015; Conklin et al. 2016; Zhou et al., 2019). The monthly MC2 model simulates the competition for light, water, and nutrients between trees and grass at a grid cell (i.e., 10 km by10 km). The biogeochemistry module calculates the water budget (ET, water yield), vegetation productivity (NPP), and the carbon budget (NEP) as affected by air temperature and soil moisture according to vegetation type-specific parameters. The fire module converts carbon stocks into fuels according to species-specific parameters. Fire occurrence is determined using thresholds of two fuel moisture indices. Annually, the biogeography module classifies each grid cell into a vegetation type (Zhou et al., 2019).

Developing climate change mitigation and adaptation strategies and policies for any region or a particular problem requires a concerted effort aided by advanced decision support systems. For example, a DSS was developed by the Pine Integrated Network: Education, Mitigation, and Adaptation project (PINEMAP) to assist forest managers to adapt to climate change in managing loblolly pine forests in the southern U.S. (https://products.climate.ncsu.edu/pinemap/). From the web interface of PINEMAP DSS, users can find historical and downscaled future climate data (precipitation and air temperature at a 4 km scale) from 20 GCMs and two greenhouse emission scenarios (RCP4.5 and RCP8.5), modeled annual water yield, ecosystem productivity results from WaSSI (Sun et al., 2011), stand structure (leaf area index, stem dry biomass), and GPP and NPP simulations from the 3-PG forest growth model at the HUC12 scale (Thomas et al., 2017) (Table S1). Eye-tracking technology is used in developing the PINEMAP DSS. The PINEMAP DSS can be used to assess climate-based risks and opportunities for loblolly pine growth under climate change. The DSS also has the potential to help guide payment of ecosystem services in forest restoration efforts by identifying which sites are most suitable for intensive silviculture and carbon storage and which sites are best for low-density forest management (i.e., thinning) under future climate change (Sun et al., 2015a,b; Sellers et al., 2021).

4.5. Assessment of cumulative watershed effects (CWEs) of environmental change

Watersheds are constantly changing as influenced by many factors from global climate change, wildfire, hurricanes, insect and disease infestations, windthrow, and human disturbances, such as harvesting and urbanization, over time and space. It is essential to assess the cumulative watershed effects (CWEs) in the past and future over a large temporal framework to make cost-effective forest management decisions in designing watershed restoration programs.

Cumulative watershed effects (CWEs) are defined as the actions or disturbance influences on key watershed processes that are individually minor but collectively significant when added to the past, present, and foreseeable future (Reid, 1998). CWEs commonly focus on the combined effects on water quantity, water quality, channel morphology, in-stream wood, and other aquatic habitat attributes or functions (Celestino et al. 2019). Various procedures or tools for assessing CWEs have been developed over the past decades. Three categories of tools have been widely used to assess CWEs, including inventory-based assessment, coupling of simulation models, and decision support systems (DSS).

4.5.1. Inventory-based assessment

The inventory-based assessment is a common approach for CWEs. There are quite a few assessment tools such as Washington Watershed Analysis (Washington Forest Practices Board, 1997), Oregon Watershed Assessment (Watershed Professionals Network, 1999), FEMAT Watershed Analysis Approach (Federal Ecosystem Management Assessment Team, 1994), and British Columbia Watershed Assessment Procedure (EGBC-ABCFP, 2020; Chatwin 2001). Pike et al. (2010) provided an overview of these procedures up to 2010. These inventory-based assessment schemes provide a comprehensive framework including stakeholder involvement, project scoping, field data collection, watershed condition analysis, published information synthesis, and recommendations. The assessed components include water quantity, sediments and morphology, water quality, riparian habitats, and instream wood recruitment, etc. These assessments provide information of risks and uncertainties under the existing and possible foreseeable future conditions for management decisions. One major shortcoming of this inventory-based approach is that it is difficult to capture or address the possible effects of future climate change as a source of deep uncertainty under multiple plausible scenarios. In addition, the synthesis of information is largely dependent on the professional judgment which is always subjective. Nevertheless, the inventory-based assessment is still popular because it can be effectively and easily implemented given the general lack of sufficient data in many watersheds.

4.5.2. Coupling of simulation models

As CWEs involve various watershed processes and functions, it is unlikely that a single model (e.g., a water quantity or a water quality model, or an in-stream wood transport model) can represent all major physical processes. Therefore, it is logical that the coupling of different models can serve the purpose of assessing CWEs. The SWAT model is the most widely used tool to simulate water quantity, sediment, and water quality (Yang et al. 2018), particularly when it couples with other models for the assessment of CWEs. For example, Khairy et al. (2001) combined SWAT with GRASS (Geographical Resources Analysis Support System) to assess mean flow, baseflow, water quality, and sediment loads in the Tangipahoa River watershed, USA. Miller et al. (2007) developed an Automated Geospatial Watershed Assessment tool within GIS by coupling SWAT with the Kinematic Runoff and Erosion model (KINEROS2).

The coupled modeling approach has the advantage of direct evaluation of CWEs under climate change and associated forest disturbances. However, model coupling for CWEs requires a large amount of data for calibrations and validations of the coupled models. In addition, the coupling process between models needs to be robustly built and tested. With the coupling of more models and the inclusion of more processes, the complexities of simulations and uncertainties would increase, which may render this approach hardly to be implemented.

4.5.3. Decision support systems (DSS)

The DSS is a computerized 'knowledge-based' system that assists data collation, analysis, and synthesis for informed decision-making, timely problem-solving, and improved efficiency in dealing with planning and even management (Segal, 2021). DSS can be defined and take many different forms, but over the years they have evolved into interactive and flexible software that allows managers to make sound management and planning decisions when faced with an ill-structured or unstructured problem through direct interaction with data and analysis models (Rauscher et al., 2000). Since 1970 s, multi-objective programming methods have been employed for a wide range of DSS development (Weng et al 2010). These methods provide valuable trade-off information among the conflict objectives, and when coupled to multi-criteria decision analysis help decision makers choose the most desirable and satisfactory alternative through analyzing multiple criteria by which the strengths and weaknesses of various adaptation options could be evaluated (Weng et al 2010). Coupling ecohydrological simulation and multi-objective optimization with evolutionary algorithms represents one of the most sophisticated solutions to forest watershed complexities, offering the possibility to set management schemes with multiple goals including socio-economics.

Reynolds (1999) and Reynolds et al. (2000) built the first DSS called "Ecosystem Management Decision Support (EMDS) system" for assisting the evaluation of watershed conditions. It has several features including logic-based processing for environmental assessments, multi-criteria decision analysis for strategic planning, decision trees, and Bayesian networks for tactical planning. Dai et al. (2004) applied WAS (Watershed Assessment for Sediment) in EMDS to assess the Mona Lake watershed conditions. Watershed DSSs are developed to solve the complex watershed management issues which involves socio-economic and environmental impacts, as well as various natural and human-disturbing factors (e.g., hydrologic and hydraulic condition, human activities) (Weng et al 2010). These complexities together with the uncertainties associated with hydrological exogenous inflows and human demand in the future increase the complexity level, and therefore sophisticated tools capable to work at multi-objective level including the potential tradeoffs among objectives are necessary.

A Web of Science search using key words "Forest Watershed Decision Support System" resulted in about 200 publications with over 70% being from the U.S., Canada, and China. Majority of the literature was published during the past seven years. These DSS tools were created with very different specific decision objectives from protecting water quantity and quality to water allocations for accommodating different water users. Various types of hydrological models (e.g., SWAT, InVEST, WaSSI) have been used in DSS individually or in combination. For example, the DSS system, CAFÉ combines three different ecohydrological models (BIOME-BGC_MuSo, TETIS, and RHESSys) that work at different spatial scales (González-Sanchis et al 2022; Pérez Romero et al., 2022).

4.5.4. Forest disturbance thresholds for managing CWEs

Forest disturbance thresholds can provide a direct and practical guide to support management decisions for protecting hydrological functions and minimizing negative environmental impacts (Wei et al., 2021). The widely used thresholds of forest harvesting (e.g., 20% of a watershed) based on the small watershed studies (e.g., Stednick, 1996) suffer from methodological shortcomings, and thus, may lack reliability. Wei et al. (2021) recommended a robust technique (the modified double mass curve, MDMC; Wei and Zhang, 2010; Li et al., 2018; Giles-Hansen et al. 2019; Zhang et al. 2016) for quantitatively determining forest disturbance thresholds on annual mean flows. This method allows the development of a hydrological response curve between cumulative hydrological effects and forest disturbance over time at the watershed scale. Hou et al. (2023) suggest that hydrological sensitivities and thresholds of responses to disturbances significantly vary depending on local climate, watershed properties, and vegetation conditions.

5. Discussion

The five forest water management issues identified in this study have overlaps as illustrated in Fig. 3 and they are not exclusive. For example, addressing tradeoffs among water supply and carbon services (Problem #1) is an important consideration of climate change mitigation (Problem #4) and accumulative watershed assessment (Problem #5). Similarly, urban forestry planning (Problem #3) requires clear understanding how watershed hydrological response to ecosystem restoration measures (Problem #2) based on NbS principles.

Our literature review suggests that the number of modeling tools has increased over time and models are more complex, integrated, data demanding, and powerful. This review effort focused on tools that have been used in the U.S., Canada, Europe, and East Asia. Using limited examples, we show that these tools and principles promise to be helpful to generate knowledge needed for making informed forest management decisions in other regions as well. However, we also identify challenges in forest hydrological modeling and model applications in watershed management.

5.1. Deficiency of forest hydrological modeling for decision making

Modern watershed management for addressing water shortage and sustainability must adopt an integrated approach that recognizes nature-human system coupling and emphases on NbS (Hao et al., 2018; Springgay, 2019; Liu et al., 2021b, 2022). Decision makings require advanced tools to evaluate uncertainties and risks of forest management decisions that must balance short-term and long-term goals under climate change and other considerations. For example, with the adoption of the United Nations Declaration on the Rights of Indigenous Peoples (https://www.un.org/esa/socdev/unpfii/documents/faq_drips_en.pdf), indigenous values and cultures must be included in local forest watershed management decisions to realize environmental justices in resource governance and use (Jackson, 2018). Inputs from a wide range of stakeholders are critical for developing effective models and DSS tools that can truly assess synergies and tradeoffs of diverse ecosystem services including clean water supply (see review in Jiménez et al., 2014).

Accordingly, we have identified a few broad deficiencies in current modeling tools that may be improved in future research and development. Model users should be aware of these model advantages and limitations. Important areas for improvement include uncertainties in model structure and processes, algorithms, integration, parameter estimates, scaling, data availability, climate scenario generation, and model access and use.

(1) *Model structure and processes*. Forest management decision making is often based on multiple considerations of past, present, and future watershed conditions. The interactions among physical, chemical, biological, and socio-economical processes in a watershed are complex and must be integrated to capture full watershed dynamics. Most watershed models reviewed, especially those developed based on remote sensing, can simulate past and current conditions, but may have difficulties to quantify water quantity and quality responses to novel future conditions. For example, climate change has created novel or extreme hydroclimate conditions in certain regions, such as 'rain on snow', that requires new modeling schemes to deal with emerging flow processes.

Generic hydrological models, such as VIC, PRMS, or MIKE SHE, unlike MC2 or DLEM ecosystem models, do not simulate vegetation dynamics under a changing chemical climate, or forest species shift, and thus have limitations to predict hydrological change under forest cover change. Most forest hydrology applications with general models such as SWAT and WaSSI used leaf area index as a surrogate of forest structure. These models did not explicitly handle changes in forest structure (e.g., LAI, DBH, tree species) in forest management practices (i.e., thinning, prescribed fires). Similarly, traditional hydrological models do not handle biogeochemical processes both above ground and below ground, and in anaerobic conditions (see Forest-DNDC model, Li et al., 1992; 2005) (Table S1). A review of 10 forest hydrology models found that canopy interception is simulated in a similar way and root distribution is considered for root water uptake in all models, but understory and growth are seldom considered (Deraedt et al., 2014).

Challenges in model applications. Process-based ecohydrological models such as RHESSys are not only necessary for researchers to test hypotheses and understand the non-linear hydrological responses, but also are useful to decision makers to conduct scenario analysis seeking alternative solutions. Spatial explicit, temporal variable, and deterministic models (e.g., WAVES) have the advantages of describing the causal relationship between climate, soil, vegetation, and the key processes (e.g., energy, water, carbon, nutrient cycles) in details. However, routine applications of these types of models in forest management are rare due to large data demands and a lack of expertise to use the models. Instead, lumped models (e.g., BROOK90) or simpler empirical models (SCS-CN Method, Budyko framework) (Table S1) that require few inputs or parameters have been adopted for regular use. InVEST has been widely used around the world, but, as a data-driven tool, it is still considered too resource-intensive for routine use in public and private sector decision-making (Agudelo et al., 2020).

In addition to models, the field inventory-based approach for Cumulative Water Assessment will continue to dominate but coupling simulation models within DSS will become more important particularly with the growing concerns of climate change. For example, the MDMC technique for quantifying forest disturbance thresholds (Wei et al., 2021) largely depends on the availability of long-term data on hydrology and forest disturbance. Such data are rare in many watersheds.

(2) *Parameter uncertainty*. Model calibration is needed to derive optimized parameters that may or may not have physical meanings. Matching simulation results with streamflow quantity or quality measured at the watershed outlet is often the sole goal in calibration practices. Little attention has been given to the accuracy of simulated ET, a flux that is often higher than streamflow

but rarely measured spatially at the watershed scale (Sun et al., 2011; Mazrooei et al., 2021). Such a practice may result in the 'equifinality' phenomenon (Beven, 1993) - different sets of parameters may result in the same model outputs. A more serious problem is 'matching the data right for the wrong reasons' in environmental modeling. Multi-criteria model calibrations using flux (i.e., flow and ET) and state variable (e.g., soil moisture, groundwater table, LAI dynamics) data may offer to produce parameters that represent reality (Dai et al., 2010). In addition, modeling should use measured data as much as possible, that is data-driven models, to reduce uncertainties of model parameters. For example, measured values for vegetation LAI or remote sensing-based ET estimates can be used to drive hydrological models (e.g., MIKE SHE, WaSSI) as input variables. It is not necessarily to simulate LAI or ET in this case. By this way, the simulation results might be more convincing than simulated vegetation properties or ET rates (Sun et al. 2011).

(3) *Scale mismatch*. Hydrological impacts from forest management or land disturbances are scale-dependent. Depending on the water resource problems, different modeling tools for the right scales are needed (Fig. 2). For example, unlike fully distributed watershed hydrological models like MIKE SHE, DHSVM, or RHESSys, lumped models (e.g., BROOK90, WAVES), or semi-distributed watershed models (SWAT, PRMS, WaSSI) do not simulate hillslope processes, and thus cannot describe the water and nutrient movement problems in narrow riparian areas, thus they have difficulties to evaluate the effectiveness of Best Management Practices (BMPs) or forest restoration at a patch scale. Similarly, remote sensing-based energy or water balance models (e.g., VIC, WaterWorld) have advantages to examine regional and global water balances but are often too coarse in space and are limited to the time of cloud-free periods to directly address forest stand level questions. In mountainous watersheds with a large heterogeneity, meteorological measurements are often made at low elevation areas nearby. In such a case, there are large uncertainties about the interpolated climate data, precipitation and radiation in particular, for hillslopes. Projections of future climate data from GCMs can be downscaled to a resolution of several kilometers with bias corrections using historical data (Zhou et al., 2019). However, the spatial scale is still too large to be useful in modeling small and median size watersheds.

(4) *Uncertainty of future climate, management, and policy*. Future changes in climate, demographic, land use and land cover, and ecosystem functions are uncertain. Skills of GCMs have improved dramatically in the past three decades to project the future climate regimes and confidences in projections have increased. However, large uncertainties remain in the modeled climate results: different GCMs that have different model structures and assumptions can have different projections in the magnitude of climate warming for any a particular region. Precipitation projections are known to be rather difficult and uncertain. In addition, future greenhouse gas emission patterns are uncertain and are largely dependent on technology, political wills, and ecosystem responses.

Management decisions are not entirely based on model predictions and physical sciences. In the case of prediction of CWEs, professional judgment or traditional knowledge often plays a critical role. All these suggest that there are various uncertainties and challenges involving CWEs. Forest planning horizon is usually long, and the uncertainty involved may propagate over time, resulting in large uncertainty regarding expected outcomes. Novel approaches, e.g., Bayesian statistics, have recently been developed to quantify and analyze the sources of uncertainty (Augustynczik et al., 2017). Moreover, the risks associated with changing climatic conditions such as drought, windthrow, and forest fires, add to the complexity of forest decision-making processes. Future predictions of these risks, however, are also uncertain. Integrated and novel decision-making approaches that can deal with multiple risks and uncertainty are crucial. Such approaches, (e.g., robust decision-making) are still in development and are absolutely essential to support stakeholders' decisions (Radke, 2020). Robust decision approaches seek solutions that can perform best under all future conditions (e.g., climate change). Adopting decision models (e.g., InVEST, SWAT) are emerging to integrate the details of ecological knowledge in the decision process.

Research needs

Modeling and monitoring technologies in forest hydrology and watershed management have advanced tremendously thanks, in part, to the advancement of computational capacity and spatial information sciences. Emerging big-data analytical methods such as machine learning and deep learning offers new means to identify critical processes, develop empirical models using historical forest inventory data, and generate new hypotheses for building more effective models that can describe physical processes and reduce parameter uncertainty in forested watersheds.

Land managers demand DSS that are science-based and user friendly. Locally empirical models (e..g., McLaughlin et al., 2013) are likely more applicable in areas with monitoring data such as the applications combining slash pine forest economics and water yield in the southeastern U.S. (Susaeta et al., 2016). For ungauged watersheds in remote areas or regions, remote sensing-based models are likely to be most useful (e.g., Zhang's ET Curve Zhang et al., 2001; WaSSI). Hybrid models that combine empirical and process-based models (e.g., 3PG-Hydro, WaSSI) are preferred to understand and evaluate the sensitivity of forest processes (e.g., water, carbon) to management actions (Yousefpour and Djahangard, 2021). Trade-offs between model complexity and knowledge gain (e.g., WAVES) should be evaluated to truly develop practical decision support tools that can implemented widely. Multi-criteria DSS are needed and will play an increasing role in future decision making (Heidari, 2022). Designing models and DSS is an iterative process that requires early participation by stakeholders and close collaboration with modelers. Inclusion of stakeholders in the decision process from the beginning may safeguard the realistic management options and address their main goals, concerns, and perceptions on future climate change (Yousefpour et al., 2017).

Watershed assessment is a critical step in the landscape restoration and long-term land planning and management. Better quantification of forest disturbance thresholds is needed to effectively use management resources. Thresholds should be set for not only mean annual streamflow but also peak flows, low flows, and variable targeted water quality goals and aquatic ecosystem integrity. Large variations in the thresholds may exist because hydrological responses vary with watershed climate, soil, vegetation, and forest disturbance levels (Hou et al., 2023).

A modular modeling approach is needed to facilitate interdisciplinary and inter-institutional collaborations. Watershed management agencies need to see water resources as 'one water' because surface water and groundwater are closely connected, and water quality modeling must correctly simulate water quantity flux including ET. Future forest hydrology modeling efforts should incorporate stand structure, tree hydraulic properties, and dynamics of water potentials in the soil–plant-atmospheric continuum. Research should collaborate with national Forest Inventory Analysis (FIA) programs to fully take advantage of the vast data on forest stand properties (i.e., species, leaf biomass) available in many countries (Haas et al., 2022). DSS should have the capacity to simulate long term consequences of forests management at the right scale, integrate modern spatial information systems, graph technology, probability analysis, and artificial intelligence, and be easy to access by multiple stakeholders for informed collaboration and decision making.

6. Conclusions

We reviewed 47 hydrological modeling tools that may find use in addressing five emerging watershed management challenges, including ecosystem service trade-offs quantification, watershed restoration evaluation, urban forestry, climate change mitigation and adaptation, and accumulative assessment of watershed disturbances. Our ability to project hydrological responses to climate change and land use change has increased dramatically during the past decade thanks to the improvement of data availability and computation power. However, few existing forest hydrology models have explicitly integrated forest structure information with ecohydrological processes. Model users should recognize limitations of existing models in describing the heterogeneity of watershed physical and chemical processes under disturbances and novel conditions, model scale mismatch, and model input data availability. Model choices should be based on management objectives and scales, and resource availability to conduct the assessment. Locally developed models or hybrid models with few parameters are most useful for practical applications. Data-driven models assisted with remote sensing technology are effective in watershed assessment and developing DSS. DSS for long-term forest watershed management must consider uncertainty of future climate projections and ecohydrological responses to disturbances, risk of decision making and human actions, social and cultural watershed values, and environmental justice and equality.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary material

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