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Review

Science of forests and floods: The quantum leap forward needed, literally and metaphorically

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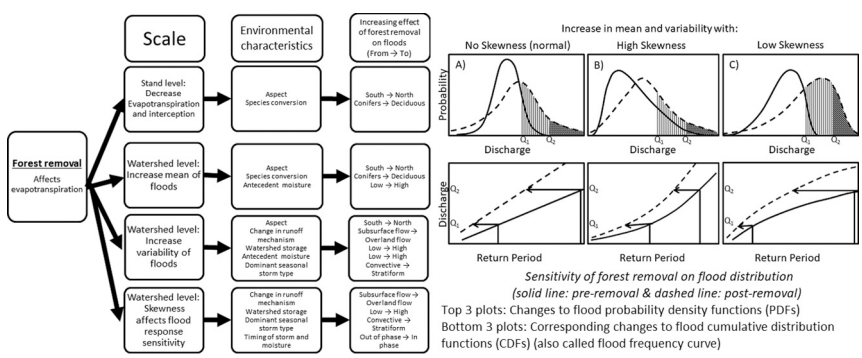
HIGHLIGHTS

- Traditionally, hydrology research used a deterministic approach to analyze extremes.
- Properly investigating hydrological extremes must be done with probabilistic approach.
- Probabilistic approach reveals outcomes diametrically opposite to deterministic ones.
- Probabilistic outcomes reveal larger effects on large floods over larger watersheds.
- Dichotomy and confusion between approaches hinder policymakers on role of forests.

GRAPHICAL ABSTRACT



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ABSTRACT

A century of research has generated considerable disagreement on the effect of forests on floods. Here we call for a causal inference framework to advance the science and management of the effect of any forest or its removal on flood severity and frequency. The causes of floods are multiple and chancy and, hence, can only be investigated *via* a probabilistic approach. We use the stochastic hydrology literature to infer a blueprint framework which could guide future research on the understanding and prediction of the effects of forests on floods in environments where rain is the dominant form of precipitation. Drawing parallels from other disciplines, we show that the introduction of probability in forest hydrology could stimulate a gestalt switch in the science of forests and floods. In light of increasing flood risk caused by climate change, this probabilistic framework can help policymakers develop robust forest and water management plans based on a defensible and clear understanding of floods.

1. Introduction

Understanding and predicting the effects of forest removal on floods is important for land-use management worldwide, especially under a changing climate. For decades, there have been attempts to develop generalizing principles on how treatments applied to forest areas (*e.g.*, clearcutting, thinning, intensive silvicultural plantation, species conversion, *etc.*) affect floods *via* meta-analyses designed to consolidate

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numerous site-specific historical studies on the topic. For example, literature syntheses including 50 or more studies over a wide variety of watershed sizes and climate regimes have failed to establish all-encompassing generalizations on the relation between forest disturbances and floods as there was "difficulty in extrapolating the results obtained elsewhere" (Guillemette et al., 2005, p. 138) and "consensus views have been difficult to achieve" (Grant et al., 2008, p. 3). There appeared to be no definitive connection between observations and predictions of how the forest disturbances would affect the watershed scale flood response. After close to a century of research and experimentation, the current state of hydrological science on how the watershed flood regime responds to forest disturbances still lacks clarity and it "remain[s] enigmatic in the present" (Eisenbies et al., 2007, p. 81). Recent deep-learning experiments have suggested that the issues are not from a lack of data as there are "… significantly more information in large-scale hydrological data sets than hydrologists have been able to translate into theory or models" (Nearing et al., 2021, p. 1). Some recent studies have suggested that forests may affect floods (*e.g.*, Johnson and Alila, 2023; McEachran et al., 2021).

The 'enigmatic' state of hydrology related to the effects of forest removal on floods stems from disagreements over why and how forest cover would mitigate larger floods as compared with other land cover types (*e.g.*, Alila et al., 2009, 2010; Alila and Green, 2014; Bathurst, 2014; Birkinshaw, 2014). Consequently, there has been confusion and debate in determining policies around effective flood mitigation management (*e.g.*, Bradshaw et al., 2009; Carrick et al., 2019). Traditionally, forest hydrology research has predominantly used the Chronological Pairing (CP)-based approach which defined the effect of forest removal as the difference between the forested (untreated) and disturbed (treated) watersheds flood magnitudes under the same precipitation event (Alila et al., 2009, 2010). This involves the Before-After Control-Impact (BACI) experimental design (*e.g.,* Bathurst et al., 2011a, 2020; Dymond et al., 2021), in which two neighboring watersheds of similar physiographic and climatic characteristics are paired, with one of them remaining undisturbed while the other would have the treatment of interest applied to it. A calibration (pre-disturbance) equation is developed for this pair during the period where there are relatively no disturbances, typically derived through linear regression of peak flows between the two watersheds. Afterwards, a treatment or disturbance is introduced to one of the paired watersheds while the other is left as a control. A post-disturbance regression equation is then developed between the paired watersheds. Most forest hydrology research has involved determining the magnitude of a flood event in untreated (forested) and treated (disturbed) watersheds under the same storm event, and the differences in flood magnitude between the two watersheds were assumed to be the effect of forest disturbance as determined through a comparison of pre- and post-disturbance regression equations.

The outcomes of these CP-based studies have generally indicated that forest removal affect small and medium-sized flood events in smaller watersheds and the effect decreases until it has little to no influence on larger events (*e.g.,* Fahey and Payne, 2017), or at larger scales (*e.g.,* Calder et al., 2007). Some studies have claimed that the point at which forest removal did not affect floods to be as low as 2 (MacDonald and Stednick, 2003; Thomas and Megahan, 1998), 5 (Beschta et al., 2000), or 10-year (Bathurst et al., 2011b, 2020; Birkinshaw et al., 2011; Calder et al., 2007) flood events. Inferences from smaller-scale CP-based studies have often been extrapolated to larger watersheds (*e.g.,* Hewlett, 1982; Calder et al., 2007), which further perpetuated the confusion on the effects of forests on floods.

These CP-based studies have attempted to explain physically, using a thought experiment, that large floods are not affected by forest removal because watershed water storage and vegetation interception and evapotranspiration (ET) become overwhelmed by a sufficiently large storm event. Once these factors are overwhelmed, the amount of precipitation that becomes runoff would be the same regardless of the presence or absence of forests. This explanation has been repeated for over a century and continues to be found in recent forest hydrology textbooks (Amatya et al., 2016; Brooks et al., 2012; Chang, 2012) and used in recent studies (*e.g.,* Soulsby et al., 2017; Bathurst et al., 2020). To summarize, in CP-based studies, prediction of the effects of forests on larger floods were mostly inferred from the quick convergence of two linear regressions, which stripped the frequency-dimension from floods as it was not designed to evaluate an effect on frequencies (*i.e.,* making them deterministic) (Alila et al., 2009), while the understanding of such effects was based on a self-fulfilling prophecy on a per-event basis (*i.e.,* reductionist viewpoint) (DeWalle, 2003). Moreover, these regression analyses were originally designed to evaluate an effect on the magnitude of the average flood response using analysis of variance (ANOVA) but was improperly extended to make inference on events smaller and larger than the average (extremes) (Alila et al., 2009).

In the Frequency Pairing (FP) approach (Alila et al., 2009), the effect of forest removal is defined as the difference between the forested (untreated) and disturbed (treated) watersheds flood magnitudes only when they are of the same frequency of occurrence, or conversely as the difference in frequencies for the same flood magnitude. This pairing and interchangeability between frequency and magnitude are a result of the inextricable link between flood magnitude and frequency, and how floods occur in Nature (Alila et al., 2009). The FP approach is done through examining changes in the flood frequency curve (ffc) between the treated and untreated watersheds. The ffc can be predicted using various approaches such as empirically using observed field data, derived through modeling simulations, regionally through isolating hydrologically homogenous regions, or even normalized ffcs to allow transferability from one watershed to another, and we will be considering all methods equally valid when explaining and using the ffc throughout this paper.

The FP-based approach contrasts the CP-based approach as the time-dimension of floods is retained through the frequencies/return period of flood events (stochastic) and inferences are applied to all floods through changes in the ffc (holistic). Differences in the research questions and hypotheses posed under CP and FP lead to differences in the analyses used to isolate and quantify the effect of forests on floods while controlling for confounding factors, regardless of how the data are generated (*i.e.*, field measured or model simulated). The rare FP-based studies in forest hydrology literature as well as FP-based studies in the wider hydrology literature have led to conclusions diametrically opposite to those of the CP studies, namely: i) forest disturbance affects not only the small and medium but also larger floods; ii) effects can increase with event size; and iii) forest disturbances can affect large floods in small and large watersheds in environments where rain or snow is the dominant form of precipitation (rain/snow environments) (Alila et al., 2009, 2010; Duncan, 1995; Green and Alila, 2012; Huang et al., 2018; Hurkmans et al., 2009; Johnson and Alila, 2023; Kay et al., 2006; Kuraś et al., 2012; McEachran et al., 2021; Nainar et al., 2021; Preti et al., 2011; Reynard et al., 2001; Schnorbus and Alila, 2013; Siriwardena et al., 2006; Slater et al., 2021; Svoboda, 1991; Te Linde et al., 2010; Zhang et al., 2018).

In the general sciences, a dichotomy created by two fundamentally different frameworks is not uncommon, but as biologist Richard Dawkins explained: "When two opposite points of view are expressed with equal intensity, the truth does not necessarily lie exactly halfway between them. It is possible for one side to be simply wrong" (cited by Shermer, 2006). The fundamental differences between CP and FP, in understanding floods or other extreme events, illustrate how these two frameworks are incompatible with each other and the continued coexistence only further propagates confusion. In this paper, we aim to shed light on these seemingly perpetual and problematic issues in order to demystify the relationships between forest removal and floods. We showcase how the FP framework is the only proper method to understand extreme events and necessary for inferring the causes of floods. This will be achieved through: i) comparing and contrasting the CP and FP frameworks, ii) proposing a physical model to demonstrate how

forests can affect floods under the proper framework, iii) exploring whether there is a point at which forests ceases to affect increasingly larger and rarer flood events, and iv) discussing the potential implications of applying the proper framework in extreme event investigations.

2. Non-causal CP *vs.* causal FP frameworks

In environments where the dominant form of precipitation is rain, the simultaneous random occurrence of two hydro-meteorological factors largely determines the magnitude of floods: antecedent moisture condition (AMC) and storm event precipitation input. AMC at the catchment-scale can consist of many processes such as soil moisture, lake storage, snowpack levels, groundwater levels, and so on. Vegetation can affect AMC as, for example, converting forests into herbaceous vegetation land cover can increase soil moisture and result in increased watershed streamflow (*e.g.* Özkan and Gökbulak, 2017; Zhong et al., 2020). This can differ in other environments, such as in snow dominated regimes, where other hydro-meteorological factors, such as snow accumulation and energy to drive snowmelt, can affect floods (Alila et al., 2009; Green and Alila, 2012; Johnson and Alila, 2023). Hence, an experimental design that investigates, in a deterministic framework, the effect of one factor at a time, while all others are constant, does not explain how floods occur in Nature. These *ceteris paribus* experiments and ensuing inferences cannot be generalized outside of their sterilized settings, and although useful as a pedagogical exercise in classroom and textbook settings, they do not allow causal inference. Cartwright (1983, p. 45) thoroughly described the non-transferable nature of these deterministic generalizations and asserted that "… *ceteris paribus* generalizations, read literally without the '*ceteris paribus*' modifier, are false." An example of how *ceteris paribus* generalizations can be misleading is Cartwright's (1983) simple illustration of how the cooking time of potatoes is affected by adding salt to the boiling water while simultaneously moving to different altitudes. For illustration, the same reasoning of Cartwright's (1983, p. 50) around-the-kitchen-table example can be applied to the effects of forest removal on floods. A version of her example modified to forest removal – flood relations is:

> For example, (*ceteris paribus*) increasing storm size increases the magnitude of floods; decreasing AMC decreases it. Refining, if we speak more carefully, we might say instead, 'Increasing storm size while keeping AMC constant increases the magnitude of floods; whereas decreasing AMC while keeping storm size fixed decreases it … But neither of these tells what happens when we allow both the storm size and AMC to change simultaneously, and *randomly*, as they occur in Nature. Here we think that there is a precise answer about what would happen, even though it is not commonly considered in traditional forest hydrology.

The debate over causal relationships derived from deterministic *versus* stochastic approaches is not new, within or outside hydrology. Klemeš (1978, p. 291) stated "a very popular misconception is to identify causality with determinism… A causal relationship is not necessarily a deterministic one and a deterministic relationship is not necessarily causal." This sentiment is also echoed in other fields outside of hydrology where "As in many other fields, methods based on correlation and univariate regression are still the most common data-based tools to analyze relationships in Earth system sciences. Such association approaches are useful in daily practice, but provide few insights into the causal mechanisms that underlie the dynamics of a system" (Runge et al., 2019, p. 2). Scientists in other disciplines (*e.g.*, epidemiology) arrived at similar conclusions, namely a stochastic approach can lead to causal inferences, in the context of extremes, insofar as the phenomena under study manifests in Nature, as "the probabilistic definition … appears to best fit the characteristics of a useful definition of causation" (Parascandola and Weed, 2001, p. 905). They recognized how "causes are multiple and chancy" and hence "chance instead of determinism plays a growing role in science" (Karhausen, 2000, p. 59).

Cartwright (1983, p. 6) stated that "seldom outside of the controlled conditions of an experiment are we in a situation where a cause can legitimately be inferred". Therefore, non-causal deterministic physics and predictions cannot be used to make scientifically defensible inferences about cause-effect relations especially when dealing with a watershed response, the domain of which is stochastic in the first place. Inferring causality requires a properly controlled experiment, which necessitates the forest removal effect being defined as the difference between pre- and post-removal flood magnitudes of equal frequency, and not equal chronology.

Pertinent to all sciences, pairing is fundamental to the design of the experiment meant to isolate the effect of a disturbance on a system's response. Frequency Pairing (FP) is well established in the wider hydrology, climatology, and other scientific disciplines when studying extremes (*e.g.* Howe et al., 1967; Wigley, 1985; Katz, 1993; Allen and Ingram, 2002; Stott et al., 2004; Katz et al., 2005; Gilli and Këllezi, 2006; Rivas et al., 2008). However, in traditional forest hydrology, CP has dominated over a century of literature and to this day continues to do so (Bathurst et al., 2011a, 2011b, 2018, 2020, 2022; Birkinshaw et al., 2011; Dung et al., 2012; Fahey and Payne, 2017; Kelly et al., 2016; Peskett et al., 2021; Xiao et al., 2022). Most forest hydrologists continue to mistakenly interpret CP and FP changes in magnitude as interchangeable (*e.g.* Verry et al., 1983; Brath and Montanari, 2000; Lewis et al., 2001; Brath et al., 2006; Eisenbies et al., 2007; Tonina et al., 2008; Bathurst et al., 2018, 2020; Goeking and Tarboton, 2020), or that they are reconcilable and can co-exist (*e.g.* Lewis et al., 2010; Bathurst, 2014; Birkinshaw, 2014; Bathurst et al., 2018, 2020). More recent studies which investigated forest removal peak flow relations using both methods, with an adequate record length, have demonstrated how CP- and FP-based analyses led to different conclusions especially on the effects on the larger events (Alila et al., 2009; Birkinshaw et al., 2011; Green and Alila, 2012; Schnorbus and Alila, 2013, and references therein). Alila et al. (2009) and Green and Alila (2012) maintain how CP and FP frameworks are irreconcilable, for several fundamental reasons not the least of which is the fact that they can lead to diametrically opposite conclusions, especially on how forests and forest removal affect the larger floods.

Comparing pre- and post-removal frequency distributions, equal in all but for an intervention of interest, is akin to the call for comparing factual to counter-factual scenarios in a probabilistic framework in the relatively new science of causation (Comolatti and Hoel, 2022; Pearl, 2009). This science transformed causality from a nebulous concept into a paradigm in its own right with significant applications across many disciplines. For instance, early applications in climate change science (*e.g.* Stott et al., 2004) generated a rigorous healthy debate (*e.g.* Trenberth et al., 2015; Otto et al., 2016; Shepherd, 2016; Stott et al., 2016), which triggered the launching of a new field of research now commonly known as *Attribution Science* (Christidis et al., 2020; Frischkorn, 2017; Huggel et al., 2013; Stott et al., 2016). Attribution science studies can be divided into single-event and general causation categories based on the focus of attribution. The focus of single-event attribution studies is investigating how changes can affect the risk of a specific event, such as the 2003 European heatwave (Stott et al., 2004). In contrast, general causation studies focuses on understanding and predicting how changes can affect the distribution of extremes, such as the increasing likelihood and frequency of United Kingdom summers exceeding 30–40 °C as a result of climate change (Christidis et al., 2020). Climate change science has long-recognized that attribution and causation cannot be investigated in a deterministic view as seen in the 2003 European heatwave study where the authors argued that the deterministic framework forces an 'ill-posed' question when investigating the extreme heatwave (Stott et al., 2004).

The understanding of the environmental controls on the flood frequency distribution and its ffc, pioneered by Eagleson (1972) and Klemeš (1978), is now a well-established field of study in wider hydrology, but has not been widely used in traditional forest hydrology

research, likely due to the historical over-reliance on the CP framework. For the first time, we bring such literature to bear on the topic of forest removal effects on floods in a rain environment from which we infer a physical model governing the relationship between forest removal and flood magnitude-frequency.

3. Proposed physical model of the effects of forest removal on floods

> The flood frequency curve represents one of the most comprehensive and compact descriptions of a catchment's storm response. It is the culmination of interactions, across both time and space, between climatic inputs, that is, rainfall influxes and evaporative effluxes (radiant energy), and properties of the catchment's landscape, for example, topography, soils, and vegetation (Robinson and Sivapalan, 1997, p. 2981).

FP requires a probabilistic approach to prediction using the ffc, which necessitates also that the physics governing floods be understood under the same probabilistic framework. The above quote by Robinson and Sivapalan (1997) eloquently summarizes how the ffc encapsulates all the physical processes that can affect floods into a comprehensive package. As such, the effects of forest removal on floods should be understood and quantified by evaluating how the removal may affect the flood frequency distribution and its ffc (*e.g.* its mean, variance, and skewness parameters). It is widely recognized and well-understood, outside of forest hydrology, that the magnitude and, especially, frequency of extremes are highly sensitive to even small changes in the mean, variance, and skewness parameters (Allen and Ingram, 2002; Katz, 1993; Katz and Brown, 1992; Taleb and Douady, 2013; Wigley, 1985). This physical understanding of removal effects on the flood frequency distribution is referred to as 'stochastic physics'. Stochastic physics aims to go "…far beyond a "statistics only approach" and tries to place the statistics in a physical framework to provide an understanding of those factors which govern the spatial [and temporal] structure of floods in a physical sense" (Dawdy and Gupta, 1997, p. 274). The previously mentioned emulated version of Cartwright's example demonstrates how storm event size and AMC are stochastic processes and hence the understanding of these factors, even with the simplified emulation, must be done through stochastic physics. Understanding a system through stochastic physics is widely used in other fields such as climatology, physics, biology, chemistry, neuroscience, and so on (*e.g.* Lin and Neelin, 2000; Palmer, 2001, 2016, 2019; Blomberg, 2007; Van Kampen, 2007; Palmer and Williams, 2008; Hoel et al., 2013; Possingham et al., 2013; Sudakov et al., 2022). In snow environments, Green and Alila (2012) hypothesized a generalizing guiding principle that forest removal-induced changes in the mean and variance of the flood frequency distribution are primarily due to alterations in the moisture available for runoff and the efficiency with which such runoff is delivered to the outlet of the watershed.

Here we conceptualize the stochastic physics governing forest removal flood relations through a proposed model inferred from the historical stochastic hydrology literature related to the environmental controls of the general flood magnitude-frequency relation in the rain environment. The proposed model helps identify which among those controls might be affected by forest removal and how changes in such controls translate into effects on the flood frequency distribution (Fig. 1). The model starts with understanding how forest removal can affect the flood frequency distribution and its ffc parameters across scales (stands to watersheds) where different environmental characteristics can affect different parameters and how these characteristics can amplify the effect of forest removal on floods. A stand is defined as a unit of trees that are similar in age, composition, structure, and physical environment, but the spatial area of a stand can vary depending on management practices or physical characteristics of a particular environment such as vegetation, soil, topography, and so on (Kohm and Franklin, 1997; Nocentini et al., 2021). Likewise, watersheds can vary in size as they can be nested within each other (Nowak, 2008) and are defined by topographic divides and other physiographic features (Band, 1986; De Hon, 2010). As the exact spatial size of a stand and watershed can vary due to so many factors, Fig. 1 aims to account for the 'catchment-scale heterogeneity' (Nearing et al., 2021), by focusing on the watershed-level, and can cover a wide range of scales. Forest removal at various scales can affect different environmental characteristics, and these environmental characteristics can increase or exacerbate the effect of forest removal on floods from one type of environmental characteristic to another. For example, forest removal, at a stand-level scale, can reduce ET and interception while shifting forest removal from predominately south- to north-facing slopes can exacerbate the effect of the forest removal on floods. Fig. 1 makes references to the stand level but focuses mostly on the watershed scale.

The resulting changes in mean and variance of floods translates to changes in the probability density function (PDF) (Fig. 1, panels A-C) and the corresponding cumulative distribution function (CDF) (which is also the ffc) below the PDFs depending on the skewness of the floods within a given watershed. The PDFs/CDFs showcase how skewness can dictate the sensitivity and different changes to flood frequency and magnitude as a result of forest removal. Some factors that can increase skewness of the ffc would be: lower soil water storage potential (*e.g.*, Gioia et al., 2008; Hashemi et al., 2000; McCuen, 2001; McCuen and Smith, 2008) or the seasonality of precipitation and the in-phase timing of storm events with AMC (*e.g.,* Sivapalan et al., 2005; Viglione et al., 2009), and these factors are described above the PDF plots. The main focus of this model is on understanding the physical controls that affect these parameters and *why* and *how* forest removal can affect such controls with an emphasis on how forest removal and its effects on ET would directly affect factors that influence floods. The highlighted environmental characteristics were selected based on the subsequent stochastic hydrology syntheses; however, it may not be fully comprehensive and only serves as a conceptual framework model to build upon and expand with future research.

3.1. Stochastic understanding of the role of AMC and storage on floods

Out of all the hydro-meteorological factors affecting floods, AMC is likely to be the most altered by forest removal as it suppresses ET and reduces interception, which in turn increases moisture. This change in moisture can affect the ffc as increases in AMC can increase the mean and variance of the ffc (Fig. 1). Past studies have found AMC played a significant role in controlling the ffc and AMC can have more effect on floods than storm events in some cases (Gioia et al., 2012; Merz and Blöschl, 2009; Struthers and Sivapalan, 2007). Díaz-Granados et al. (1984) showed that changing AMC levels can cause considerable shifts to the ffc with increasing effects for higher return periods. Svoboda (1991) revealed how different parameters of the ffc, such as the mean, variance, and skewness, change across a wide range of AMC. De-Michele and Salvadori (2002) further expanded on previous works by showing that AMC that varied in wetness and probability resulted in significant increases to both the mean and variance of the flood regime. They also showed that higher probabilities of wetter AMC resulted in more severe larger floods (up to tripling the magnitude of the 100-year flood event). Sivapalan et al. (2005) also showed how probabilistically varying AMC increased both the mean and variance of floods, which translated to an upward shift and an increase in steepness of the ffc, respectively. AMC has been shown to affect flood magnitude-frequency response even in urbanized catchments (Hettiarachchi et al., 2019). It has been shown that the flood return period can be much higher than the return period of the associated rainfall event due to AMC, where drier AMC results in larger differences than wetter AMC (Viglione et al., 2009). This means that increasing AMC shifts the flood return period closer to the rainfall return period or, in other words, decreasing the flood return period and making it more frequent. Incorporating AMC as a random variable in

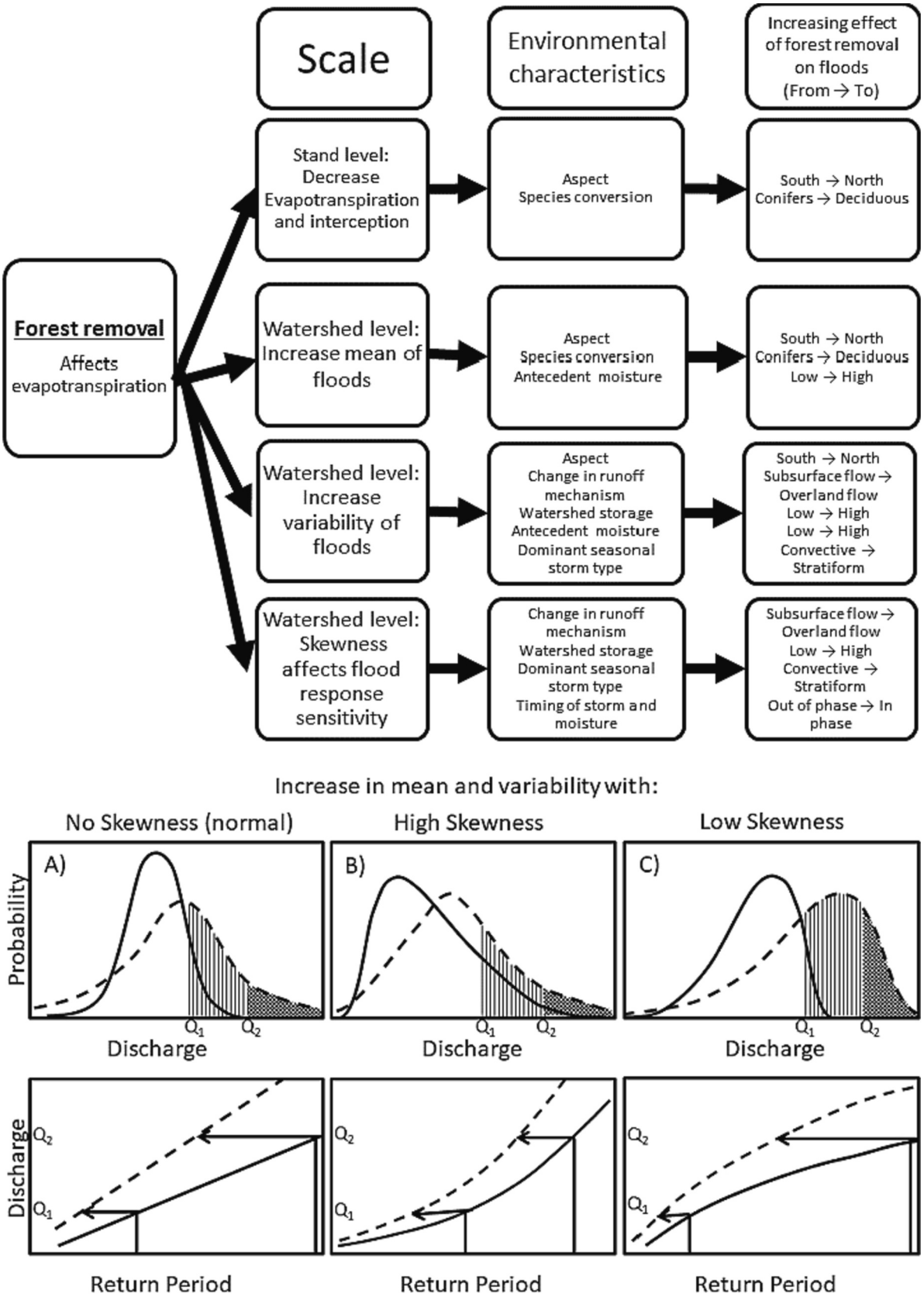

Fig. 1. A conceptual framework model featuring how forest removal can interact with environmental controls to affect flood magnitude-frequency relationships in the rain environment. The probability density functions (PDF) shows different scenarios of increases to the mean and variability and its effects with: A) no skew, B) high skew, and C) low skew with the corresponding cumulative distribution functions (CDF) below. These *ceteris paribus* depictions may not necessarily portray what occurs in Nature as these factors likely can change simultaneously. The statistical parameters pertain to conventional moments. In the PDF/CDF plots, the solid and dashed lines represent pre- and post-removal curves, respectively.

flood magnitude-frequency modeling can greatly improve runoff estimations (Shaw and Walter, 2009).

Understanding and predicting the effects of forest removal on AMC in a probabilistic framework are imposed by the way the flood response manifests in Nature, where any particular event magnitude can be generated by many combinations of soil wetness and storm characteristics. The probabilities of all of these possible storm events falling on all the possible AMC levels can only be accounted for through a frequency distribution framework, as it incorporates all of these possible scenarios. This is a significant departure from some traditional hydrological modeling approaches where typically only the mean of AMC (or one AMC state at-a-time) were considered when investigating the flood regime; thus, they do not account for the dynamic and random nature of the governing factors such as AMC or storm input (Flores-Montoya et al., 2016).

Forest removal can increase AMC due to a reduction in ET, resulting in a reduction in the storage potential of the watershed as there will be less available space to store incoming precipitation. As a consequence of decreased water storage potential, changes in runoff mechanisms, such as from subsurface to overland flow, can occur and result in step changes in the ffc (Rogger et al., 2012; Samuel and Sivapalan, 2008; Sivapalan et al., 1987, 1990) which can increase the variability and skewness of the ffc (Fig. 1). Furthermore, it is much more likely to propagate heavy-tailedness than to maintain light-tailedness in either case where flood-producing processes aggregate additively or multiplicatively (Merz et al., 2022). As a consequence, changing even one of the flood-producing process, such as the aforementioned change in runoff mechanism, from light-tailed to heavy-tailed due to forest removal may lead to floods increasing in heavy-tailedness and therefore increasing skewness. This phenomenon is further exacerbated if forest removal changes more than one flood-generating process which is likely to occur in Nature due to the "… multiple, compound or synergistic drivers … " (Runge et al., 2019, p. 6) involved in generating extreme events such as floods. The inherent (pre-removal) variability and skewness of the ffc are foundational to forest removal - flood analyses because they determine how sensitive any particular flood regime is to even slight shifts in the ffc. This effect is not only limited to small or medium magnitude flood events, but can extend to higher magnitude events. Studies have found that watershed storage was one of the main factors affecting the skewness of flood frequency distributions (McCuen, 2001; McCuen and Hromadka, 1988; McCuen and Smith, 2008). This is because frequency distributions tend to move upwards and change curvature as watershed storage decreases (*e.g.* Hashemi et al., 2000). Threshold processes can also influence the skewness of the ffc. Storm events that exceed the storage threshold over a large portion of the watershed can result in outlier events, which in turn cause higher skewness in ffc's (Gioia et al., 2008). These ffc studies show that watershed storage, and by implication forest disturbance, can have far reaching consequences on large floods as it can affect higher order moments, hence the variability and skewness of the ffc, and potentially having a greater effect on the upper tail of the flood distribution.

3.2. How different seasonal storms and changes in timings can stochastically affect floods

Seasonality of storm characteristics and timing with respect to AMC can also affect how sensitive the flood regime is to forest removal. Under CP, it is assumed that forest removal has the most impact on floods during the growing season when the trees are actively transpiring, while tree removal should have the least impact on floods during the dormant season when transpiration is expected to be lower or non-existent. As a result, it is also assumed that moisture in the dormant season would be similar in both pre- and post- removal periods as there should be lower ET regardless of whether trees are present or not (*e.g.* Hornbeck, 1973). This deterministic *ceteris paribus* line of reasoning neglects the influence of other factors, and the random nature of some of their components such as rainfall characteristics, seasonality of rain, and AMC. It is likely that floods will respond differently to different storm types and to the timing of different AMCs when the storm events arrive during different seasons (Fig. 1). These factors affect the sensitivity of seasonal flood response to forest removal *via* the higher order moments; hence the variance and skewness of the ffc could differ between seasons. Some stochastic hydrology studies have shown that the skewness of the flood regime increases as the rainfall skewness increases, regardless of soil storage, and that rainfall skewness can act as the upper limit of the ffc skewness (McCuen, 2001; McCuen and Smith, 2008). Climatic variability affects floods directly through the seasonal variability of storm characteristics and indirectly through ET and rainfall, which in turn affect the AMC (Merz and Blöschl, 2009; Sivapalan et al., 2005). Moreover, forest removal can shift the timing and seasonality of floods in some cases (McEachran et al., 2021).

Environments that have distinct AMC and storm seasonality can experience a coupling effect on floods, which can cause the impacts of forest removal to experience "resonance" under certain conditions. Sivapalan et al. (2005) identifies resonance as occurring when high AMC and storm seasonality are in-phase with each other, leading to increases in the ffc, particularly the skew, as a result of increases to the mean and variability of the ffc translating to increasing the magnitude and decreasing the return period (frequency) of flood events. Resonance can cause even modest changes to AMC as a result of forest removal to have their impact on floods amplified. The shape and steepness of the ffc can drastically change between seasons as a result of the timing and seasonality of different storms coinciding with different levels of AMC (Sivapalan et al., 2005). Again, the slope and shape of the ffc, which are surrogates of the variability around the mean and skewness of the floods, respectively, are key indicators of the sensitivity of the flood regime to disturbance (*e.g.* Berris and Harr, 1987; Green and Alila, 2012). This is a direct consequence of the long-recognized fact in hydrology, climatology, and other disciplines that even modest increases in the magnitude of events in the upper tail of a light-tailed cumulative distribution function (CDF), with lower variability in the CDF, can result in large increases in their frequencies (*e.g.* Allen and Ingram, 2002; Taleb, 2012; Taleb and Douady, 2013; Taleb et al., 2020).

3.3. Other forest-related factors which can affect floods

Forest removal interaction with topographical aspect can also affect the ffc. The forest removal can disrupt the energy and water balance by increasing insolation and reducing ET, respectively, and exacerbate differences between watersheds with different aspects. In turn, this can affect the mean and variance of the ffc (Fig. 1). For example, Moreno et al. (2016) showed that various forest thinning scenarios shifted the probability density function of flood events to the right and resulted in net increases to the mean and variance of high flood events with larger increases in runoff on north- compared to south-facing slopes.

Changes to forest species and plantation density can also affect the ffc. Generally, coniferous trees are known to have higher annual ET rates than deciduous trees due to physiological differences (Ford et al., 2011; Rao et al., 2011). Converting the dominant species in a watershed to one that has higher ET rates would lead to lower AMC and streamflow (Swank et al., 1988; Swank and Douglass, 1974), which could affect the mean and variance of the ffc (Fig. 1). A recent study found that after clearcutting in watersheds naturally dominated by deciduous trees, one that was subsequently converted to coniferous trees experienced much smaller changes in the ffc compared to another that was regenerated with the same deciduous species shortly after treatment where, for the watershed that was converted to be coniferous-dominated, the post-harvest ffc closely resembled the pre-harvest ffc which contrasted with the ffcs for the watershed that was allowed to regenerate with deciduous trees where the post-harvest ffc diverged from the pre-harvest ffc (McEachran et al., 2021).

3.4. The need for stochastically understanding floods at the larger scales

The wider stochastic hydrology literature provides the foundation for the proposed physical model (Fig. 1). This model provides a stochastic framework to understand how forest removal and management can interact with various environmental characteristics across spatial scales. This deviates from some CP-based concepts that attempt to impose understanding derived at the smaller stand or hillslope level scale and extrapolate it to the larger watershed scale. This 'extrapolation' may be partly responsible for the 'enigmatic' state of forest hydrology mentioned in the introduction, and this proposed model (Fig. 1) provides a new structure for understanding extreme events such as floods. This sentiment has been mentioned in the past where Keith Beven (1987), said: "[t]he extension of laboratory scale theory to the catchment scale is unjustified and that a radical change in theoretical structure (a new paradigm) will be required before any major advance can be made in [predicting catchment-scale rainfall-runoff responses]", and that "[s]uch a theory will be inherently stochastic and will deal with the value of observations and qualitative knowledge in reducing predictive uncertainty (Keith Beven as cited by Nearing et al., 2021, p. 1).

The model highlights the understanding of the ffc and its controlling parameters (mean, variance, and skewness), and shows how changes in these parameters can affect floods. The effects can apply to floods of all magnitudes and frequencies. Forest removal may have a larger effect on larger and rarer flood events than compared to smaller and more frequent events, which manifests as larger changes in return periods to rarer events. Furthermore, differences in some parameters, such as skewness, can amplify the changes to the more infrequent events. This phenomenon has been empirically observed where there was a larger effect of forest harvesting on the larger, infrequently occurring peak flows (McEachran et al., 2021).

4. Does a flood event size beyond which forest removal have no effect exist?

The ultimate hypothesis related to forest removal effects on floods is whether a no-effect threshold return period (beyond which the removal has no effect) exists, and if it does, how large is this threshold? A closer scrutiny of the stochastic hydrology literature reveals how the influence of many of the previously discussed environmental controls of the ffc in general do not support this hypothesis (*e.g.* Díaz-Granados et al., 1984; Wood et al., 1990; Shen et al., 1990; Svoboda, 1991; Guillot, 1993; Naghettini et al., 1996; De-Michele and Salvadori, 2002; Gaume, 2006; Mosquera-Machado and Ahmad, 2007; Cœur and Lang, 2008; Lawrence et al., 2014; Carré et al., 2016). Comparisons of pre- and post-harvest ffcs, in a snow environment, using observed and simulated data revealed that any "no-effect" threshold continued to move to higher return periods as the record length increased (Alila et al., 2009; Green and Alila, 2012; Schnorbus and Alila, 2013). A study which simulated 1000 years of peak flows, for the same watershed in a rain environment under logged and forested conditions, failed to establish a "no-effect" threshold, but instead revealed two pre- and post-harvest frequency curves diverging for return periods <100 years and then running parallel for return periods >100 years (Birkinshaw et al., 2011). Other FP-based studies, also in a rain environment simulating long flood records with and without forests in large watersheds, revealed similar outcomes where tree removal increased floods across all return periods, and the effects increased with event size (*e.g.* Svoboda, 1991; Reynard et al., 2001). These modeling studies illustrate how forest disturbances affect all sizes of floods with these effects persisting across a wide range of record lengths and return periods, suggesting that a "no-effect" threshold may not exist. If and when a threshold does exist, it can only be evaluated through the causal probabilistic framework. Moreover, these studies suggest that forest removal can have an increasing effect on larger flood events, especially in regards to changes in their frequency. This effect is not limited to only small watersheds but has also been seen in FP-based studies, mostly outside traditional forest hydrology literature, which investigated larger watersheds ranging from 1000's to 10000's km^2 (Brath et al., 2006; Hurkmans et al., 2009; Johnson and Alila, 2023; Kay et al., 2006; Preti et al., 2011; Reynard et al., 2001; Siriwardena et al., 2006; Svoboda, 1991; Te Linde et al., 2010; Zhang et al., 2018).

At longer return periods, the pre- and post- forest removal ffc will likely run parallel, as seen in previous studies (*e.g.* Birkinshaw et al., 2011, Fig. 8). This is due to the gradient of extreme values (GRADEX) concept, where the ffc upper tail properties can be derived from the rainfall frequency curve (Brodie, 2020; Carré et al., 2016; Cœur and Lang, 2008; De-Michele and Salvadori, 2002; Gaume, 2006; Guillot, 1993; Guillot and Duband, 1967; Lawrence et al., 2014; Mosquera-Machado and Ahmad, 2007; Mota et al., 2018; Naghettini et al., 1996, 2012). Although previously mentioned "no-effect" threshold examples focused on the effects of forests on floods (Alila et al., 2009; Green and Alila, 2012; Johnson and Alila, 2023; Schnorbus and Alila, 2013), the GRADEX concept applies regardless of land use within the watershed. Theoretically, GRADEX would be applicable under a wide variety of land use and land cover scenarios ranging from old-growth forests, representing minimum disturbance, to grazed shrubland or agriculture, and even to a completely paved watershed, representing maximum disturbance, as the ffc in any of these scenarios would eventually mirror the rainfall frequency distribution at a high enough return period. GRADEX applies to both disturbed and undisturbed ffcs; however, the return period at which the diverging ffc changes slope to mirror and become parallel to the rainfall frequency distribution will differ. This is due to disturbed watersheds having higher AMC and reduced available moisture storage while the reverse applies to undisturbed watersheds. This causes the disturbed watershed to become more easily saturated which translates to the disturbed ffc mirroring the rainfall slope at an earlier return period than the undisturbed ffc. The differences between the point at which the ffcs mirrors the slope of the rainfall magnitude-frequency curve creates a persistent gap between the two ffcs at the upper tails with the gap being a function of the differences in available moisture storage between the disturbed and undisturbed watersheds. As such, the influence of forests persists unchecked across all frequencies since the pre- and post- removal ffcs will not converge. In summary, these ffcs are expected to mirror rainfall frequency curves at higher return periods, with the post-forest removal ffc mirroring the rainfall frequency curve at a shorter return period than the pre-forest removal ffc. Any sign of convergence of the two ffcs has been shown to be a consequence of limited record lengths (*e.g.* Alila et al., 2009; Green and Alila, 2012; Kuraś et al., 2012; Schnorbus and Alila, 2013; Bathurst et al., 2020).

Physical factors and environmental controls that influence floods can continue to affect the frequency of high return period flood events and forest removal that affect these will lead to changes to the high return period flood events. This idea has been echoed in the past for the rain (*e.g.* Duncan, 1995) and snow (*e.g.* Green and Alila, 2012) environments where medium-sized storm events or a modest snowpack melt, respectively, coinciding with high AMC, led to increased frequencies of high return period flood events. For example, Kim et al. (2019) determined that AMC can affect a wide range of flood events, where a 25-year storm event can produce an 800- or 3-year flood event or that a 15-year flood event can be caused by a 2- or 200-year storm event depending on if it coincided with high or low AMC, respectively. Similarly, different soil types have been seen to affect large flood events with no apparent no-effect threshold (Díaz-Granados et al., 1984; Shen et al., 1990). A study that examined the runoff curve number (CN) method, which was developed by the United States Department of Agriculture Natural Resources Conservation Service and is still widely used, also showed that a wide range of soil properties and storage affect floods with no apparent no-effect threshold at which such controls cease affecting floods (Svoboda, 1991).

Collectively, these FP-based studies contradict the non-causal CP-

based perceptions that forest removal has diminishing effects on larger flood events. FP-based causal inferences reveal that forest removal continue to affect larger flood events unchecked and, under certain conditions, even more so compared to small and medium events. More research is needed to identify the conditions (if any) under which the upper tails of the pre- and post- forest removal frequency distributions turn into a single curve, and hence determine the flood event size beyond which forest removal cease having an effect. However, this needs to be properly investigated as past studies have used relative changes to the magnitudes of flood events to support claims on the effects of forest cover diminishing with an increase in event size (Bathurst et al., 2011a; Birkinshaw et al., 2011; Jones, 2000), but these relative changes are irrelevant and potentially deceptive (Green and Alila, 2012) since they do not properly reveal the effects of forests on the larger and rarer flood events. Nevertheless, investigating the effect of forests on floods must be through the FP framework to stop the over-century-long confusion which has plagued forest hydrology research related to the understanding and prediction of the effects of forests on extreme flood events.

5. Discussion and conclusion

In 1930, a paper highlighted that over a century of work investigating the effects of forests and vegetation on streamflow, floods, and erosion were not practically useful and that scientific advancements were hampered by the inherent difficultly of isolating the numerous complex variable interacting among each other in watersheds (Lowdermilk, 1930). After almost a further century of research and experimentation in forest hydrology that has seen the body of relevant literature grow much larger, this phenomenon is still valid. This is likely due to the persistence of CP-based 'understanding' where "… our [hydrology] community still holds deeply subjective and nonevidence-based preferences for models based on a certain type of 'process understanding' that has historically not translated into accurate theory, models, or predictions" (Nearing et al., 2021, p. 1).

In lieu of the more dominant deterministic-reductionist framework in forest hydrology, this paper argues the case for a probabilistic and holistic approach to causal inference, well established in other disciplines, as being the only way to control the experimental design and isolate the effects of forests on floods. Therefore, understanding and predicting the effects of forests on floods should be conducted using a flood frequency distribution framework. Others are calling for a more rigorous application of the same FP-based framework to other areas, such as droughts (Vogel and Kroll, 2021).

Although the various environmental controls outlined in the proposed physical model (Fig. 1) and their effects on floods have been studied, these were often considered in isolation from other factors which neglects the potential interactions among each other as it would realistically occur in Nature. To our knowledge, there are no studies done in the rain environment that used the FP framework to understand how changes in the various physical controls could simultaneously affect floods or other extreme events in the context of forest hydrology and physically explain these changes in terms of flood frequency distribution and its parameters. This paper lays out the framework in which future investigations should be carried out and offers a glimpse into the potential consequences of forests on floods. Different types of forest disturbances affect these physical controls differently, and thus cause different effects on the ffc. The proposed physical model (Fig. 1) can be extended to infer how disturbances and other hydrological changes and their effects on the environmental characteristics, beyond the ones covered in this paper, can affect floods. For example, forestry roads or cutbanks can enhance runoff delivery and increase flood magnitude and frequency, whereas converting forests which are dominated by deciduous trees to coniferous trees can decrease flood magnitude and frequency through the higher interception and ET rates of coniferous compared to deciduous trees and the corresponding changes to soil water storage potentials. Furthermore, forest disturbances may affect small-scale processes, such as stemflow, forest floor interception and evaporation, and so on, but our physical model is not meant to be (and cannot be) all encompassing. It should be used for building upon in future research.

The stochastic physical understanding of the multiple and chancy causes of floods can be applied in other disciplines such as geomorphology, ecology, engineering, and so on. Changes to the hydrological regime, either from management practices and/or climate change, can result in increasing the frequency and magnitude of small, medium, large, and very large floods. These changes in turn increases the risk of changes in fluvial ecosystems and can translate into destabilizing fluvial stream channels beyond natural variability (Schmidt and Potyondy, 2004), altering the services provided by riparian zones and aquatic ecosystems (Naiman et al., 2005; Resh et al., 1988; Talbot et al., 2018), and necessitating the redesigning of engineered structures so as to withstand larger and more frequent floods (Fluixá-Sanmartín et al., 2018).

The contrasts between CP- and FP-based studies is fueling debate on contentious land use and land cover policies related to the effects of forests on floods. Unrelenting debate and confusion on the role of forests in flood mitigation is occurring world-wide (*e.g.* Lu et al., 2001; Penning-Rowsell et al., 2006; Bradshaw et al., 2007, 2009; Carrick et al., 2019; Black et al., 2021). Policy changes in response to flood crises have generally not been based on developing new ideas, but rather on using existing ideas that were already part of widespread public or professional discourse (Penning-Rowsell et al., 2006). Despite this, progress has been made and inasmuch as some countries have recognized the role of reforestation in flood risk mitigation, especially under a changing climate (*e.g.,* Lu et al., 2001; Bradshaw et al., 2007; Black et al., 2021).

Future work should focus on the stochastic physical understanding of how different types of forest management practices, such as clearcutting, selective harvesting, species conversion, and so on, affect floods, doing so through utilizing and expanding the proposed model (Fig. 1). Also, the proposed framework can be expanded to include other indirect processes that forest removal may affect which were beyond the scope of this paper. For example, forest removal machinery and operations can compact the soil which can reduce infiltration and potentially storage and can shift runoff that was primarily saturation-excess to Hortonian-runoff. Furthermore, future research can deepen the understanding of how different environmental characteristics can potentially affect multiple parameters simultaneously, beyond the ones listed in Fig. 1. For example, a change in runoff mechanism and watershed storage potential affects multiple parameters (variability and skewness) (Fig. 1). Future research should also account for the ever-changing state of forests due to vegetation dynamics, non-vegetative factors such as soil properties, and climate changes, which necessitates non-stationary frequency analyses of floods (*e.g.,* Johnson and Alila, 2023). Moreover, future studies could illuminate the influence and mechanisms by which the effects of land-use management and climate change can act synergistically to amplify, or antagonistically to mitigate, the risk of flooding.

CRediT authorship contribution statement

Henry C. Pham: Conceptualization, Visualization, Writing – original draft, Writing – review & editing. **Younes Alila:** Conceptualization, Supervision, Writing – review & editing.

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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