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Review

Interactions Between Forest Cover and Watershed Hydrology: A Conceptual Meta-Analysis

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Abstract: The role of trees in watershed hydrology is governed by many environmental factors along with their inherent characteristics and not surprisingly has generated diverse debates in the literature. Herein, this conceptual meta-analysis provides an opportunity to propose a conceptual model for understanding the role of trees in watershed hydrology and examine the conditions under which they can be an element that increases or decreases water supply in a watershed. To achieve this goal, this conceptual meta-analysis addressed the interaction of forest cover with climatic conditions, soil types, infiltration, siltation and erosion, water availability, and the diversity of ecological features. The novelty of the proposed conceptual model highlights that tree species and densities, climate, precipitation, type of aquifer, and topography are important factors affecting the relationships between trees and water availability. This suggests that forests can be used as a nature-based solution for conserving and managing natural resources, including water, soil, and air. To sum up, forests can reduce people's footprint, thanks to their role in improving water and air quality, conserving soil, and other ecosystem services. The outcomes of this study should be valuable for decision-makers in understanding the types of forests that can be used in an area, following an approach of environmental sustainability and conservation aiming at restoring hydrological services, mitigating the costs of environmental services, promoting sustainable land use, managing water resources, and preserving and restoring soil water availability (SWA) when investing in reforestation for watershed hydrology, which is important for the human population and other activities.

Keywords: erosion; forest age; forest hydrology; runoff; soil water infiltration; water cycle

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1. Introduction

Forests cover about one-third of the Earth's terrestrial area [1] and play a crucial role in environmental sustainability and human life. They significantly contribute to climate change mitigation by absorbing and storing 30% of carbon emissions [2], reducing greenhouse gas emissions [3], providing food to people [4], and offering several ecosystem services, including water provision, soil conservation, and climate regulation. Forests can positively or negatively affect water storage (i.e., soil water availability) by regulating basic fluxes such as infiltration, surface runoff, and evapotranspiration (ET). Natural forests have been exploited [5] and destroyed for agricultural activities, one of the main contributors to soil erosion. From 2000 to 2012, approximately 3.2% of forest cover worldwide was converted into agricultural lands [6]. This conversion could affect soil water availability (SWA). However, the relationships between trees and basic features of the hydrologic cycle (storage and fluxes of water) are complex and contradictory. For example, a scientific paper has argued that deforestation could increase downstream water availability, whereas others have concluded that afforestation increases downstream water availability and intensifies the water cycle [7]. Other researchers have documented that afforestation decreases water yields, especially trees such as eucalyptus and pinus [8–12].

Trees are fundamentally important in regulating streamflow [13]. However, some species can reduce groundwater levels because of climate changes and physiological characteristics that may affect ET [14]. The transpiration of some trees (e.g., *Phyllostachys edulis*) can be affected by multiple factors such as tree age, size, phenological stages, and soil water content [15–17]. Thus, tree transpiration can couple with environmental variables to alter the water cycle and water balance on local and regional scales. To meet transpiration needs [18], trees with deep root systems can extract large volumes of water from depths of 10 m or more [19]. On this topic, researchers have argued that there is an interdependence between vegetation and deep groundwater [20–22]. There is a great need to clarify controversies about the relationship between watershed hydrology, and ultimately the global water cycle. As such, we expect that trees reduce soil erosion, compaction, and surface runoff during precipitation. In addition, the change in the hydrological cycle, particularly in extreme precipitation, can intensify negatively with global warming [23,24]. Likewise, global warming can directly influence precipitation, leading to a greater evaporation rate, and thus surface drying [25]. Similarly, changes in climatological precipitation and evapotranspiration lead to changes in runoff [26].

A conceptual model should consider how tree communities in forested areas can affect the amount of water in the soil and at a watershed outlet, and their role in controlling erosion and reducing runoff. This model also should consider the impacts of fast-growing forest plantations on the water balance and streamflow compared to those of native forests. Various studies have documented large-scale relationships between hydrological effects and deforestation and forestation [27–30]. Others have demonstrated relationships between water cycle components (e.g., precipitation and evapotranspiration) and water vapor residence time [31] and forest maturity [32]. For example, to meet their evapotranspiration needs, trees use various strategies for searching for water in a forested watershed, preferring soil water rather than groundwater [33], depending on the period; for example, they can take up groundwater during dry periods. Regardless of the source, trees affect the partitioning of water between catchment water yield and ET [34,35]. In the end, water extraction and availability are governed by interactions between macropore flow, matrix storage, and the shape of root systems [36], and ultimately these interactions define the ecohydrological functioning of forests [37].

Notably, there is a direct relationship between transpiration and diel fluctuations in streamflow [37], which vary seasonally and spatially [38]. Nonetheless, there is a need for improving the understanding of the interactions between forest cover and watershed hydrology. Hence, the objective behind this conceptual meta-analysis is to document the influence of trees on water availability and propose a conceptual model of their role in watershed hydrology and the conditions under which they can increase or decrease water supply. Importantly, this study primarily focuses on understanding the role of trees in watershed hydrology by examining how forest cover interacts with climate factors, soil properties, water infiltration, soil water availability (SWA), and the ecological diversity of tree species. Additionally, the study explores both the positive and negative influences of afforestation and reforestation on the water cycle, considering a range of factors, including forest density, soil types, climate, and topography.

2. Materials and Methods

This conceptual meta-analysis proposes a conceptual model for understanding the role of trees in watershed hydrology and examines the conditions under which they can influence water supply in a watershed. To develop this conceptual model, we integrated environmental factors (e.g., soil characteristics, climate conditions, topography) and forest-related factors (e.g., forest cover type and tree species) to understand their interactions and influence on watershed hydrology. This model aims to assess how different tree species, forest densities, and management practices affect components of the water cycle, such as evapotranspiration (ET), water infiltration, and soil water availability (SWA). Additionally, the model examines the interactions between forests and groundwater recharge, streamflow, and erosion control, considering tree physiology and environmental variables. Based on this model and the literature, we suppose that: (i) SWA and groundwater recharge are higher in watersheds covered with native forest species compared to areas with commercial forest species, and (ii) reforestation with native species in tropical regions improves watershed hydrology more effectively than fast-growing plantations. Thus, scientific documents were searched from literature databases (e.g., Scopus, google scholar and Web of Science) using keywords including "forest cover", "planting trees", "trees", "water protection", "water availability", "infiltration", "reduce runoff", "watershed", "rainforest", "climate", "soil compositions", "evapotranspiration", "vegetation", hydrologic cycle", "topography", "forest age", "base flow", "watershed". It is noted that the Boolean operators "AND" and "OR" were used to associate the keywords and thus refine the search results. This conceptual meta-analysis focused on documents in English (e.g., papers, reports, and books) published from 1933 to 2024. The list of references was also used to search for additional published documents. After screening the titles, abstracts, and conclusions, 216 documents were selected for inclusion in this conceptual meta-analysis. Information was extracted from these documents and analyzed by searching for relationships between the keywords used and at least one of the watershed hydrological components (e.g., runoff, infiltration) targeted in this conceptual meta-analysis relating to water availability. Finally, data were managed using EndNote to ensure accurate referencing.

3. Origin of Precipitation

Numerical studies have illustrated that precipitation is recycled over a long distance through trees' evapotranspiration that drives winds and moist air transport [31,39,40]. Of note, 90% of water evaporated every year precipitates back onto oceans, and the remaining 10% feeds the land branch of the water cycle [39]. The major sources of moisture have their origins in large regions characterized by vertically integrated moisture flux divergence [41]. The North and South Atlantic sources are globally the first and second largest sources of moisture for precipitation over the continents, respectively [39]. A numerical study detailed and highlighted how moisture is formed under the effect of latent heat fluxes over the ocean and subsequently transported in the atmosphere before reaching the soil surface in the form of precipitation [39]. The effect of orography is a factor that is susceptible to limiting the moisture from the ocean, and thus reducing the oceanic contribution in terms of precipitation. Notably, there are other sources (e.g., land evaporation) of precipitation. For example, a previous study pointed out that land evaporation provides 40% of terrestrial precipitation, of which 57% is back on land in the form of precipitation [42]. It is worth noting that terrestrial precipitation, evaporation recycling, and moisture exportation mainly occur over the continents [43]. A decline in precipitation may be linked to deforestation [44]. Of note, moisture recycling is strongly associated with forest expansion. Thus, the larger the expansion, the larger the moisture recycling. Water is precipitated on large regions either by advection from the surrounding areas external to the region and evaporation, or transpiration from the land surface of the region [45]. Notably, precipitation recycling in forests significantly influences the isotopic composition of precipitation in northwestern Amazonia [46].

4. Conceptual Model of the Role of Trees in Watershed Hydrology

4.1. Soil Characteristics and Water Infiltration

Some trees reduce water on rocky substrates (saprolite, fractured bedrock), particularly when the source is deep below ground, using around 49% for transpiration during dry seasons and 28% during wet seasons [47]. Trees that grow in less favorable soil/subsoil conditions consume deepwater reserves due to root adaptation to enhance drought tolerance [48]. The hydrologic response to drought can be either mitigated or exacerbated by forest vegetation, depending mainly on the amount of water used by vegetation and the response of the forest population [38]. In a restoration project, clayey soils recovered infiltration faster than sandy soils [49,50]. This could occur because the aggregating forces in sandy soils are weaker than those in clayey soils. Thus, high soil aggregation is one of the characteristics that can explain and justify high infiltration, which can greatly depend on the history of a targeted area.

Reforestation in the tropics and subtropics may improve water infiltration, depending on land use, soil texture, and local climate [49]. This infiltration occurs as a result of the influence forests have on the hydraulic properties of the soil [51]. It is noted that reforestation regulates water fluxes [52] through infiltration and ET [53] depending on soil properties, which are influenced by a set of factors such as slope/topography [54–56], climate, parent material, time, and living organisms [57]. Reducing soil organic matter content can adversely affect root penetration, thus reducing water infiltration and compromising the role of trees in mitigating erosion. Also, infiltration time would diminish independently of the rainfall's intensity and duration in a mechanically terraced area: the compaction reduces soil infiltration and root penetration. Substrates controlled by regolith and rocks impose drought conditions on oak forest stands [58]. Such soil reduces water infiltration, which drives surface runoff, soil erosion, chemical transfer routes, water quality, and irrigation uniformity [59]. Depending on the size of rock fragments and their aggregation to the soils, they could favor infiltration or enhance soil loss [60].

4.2. Streamflow Versus Base Flow Partitioning

Base flow is correlated with forest extension and is crucial to maintain the water yield of a watershed. There is a correlation between changes in forest ET and riparian water table height and riparian area, which can increase ET loss and modulate streamflow [61]. Meanwhile, forest cover type and annual temperature affect watershed base flow [62]. A decrease in total basal area of *pinus* trees can lead to an increase in groundwater recharge, cumulative streamflow, and direct runoff [63,64]. These findings indicate that forest is one of the key factors governing base flow in a watershed. Another study corroborates these findings and outlines that high ET reduces stream flows [65]. In addition, changes in forest cover during regeneration modify water flux partitioning [66]. Other variables, including soil composition and climate conditions, may be among possible factors affecting groundwater recharge and base flow. For example, a study explained that precipitation, soil texture, and forest cover modulate groundwater recharge, while vegetation cover and groundwater depth affect base flow [67]. Notably, there is a correlation between rainfall, base flow, and forest area. Therefore, the greater the forest area the more stable are flow conditions [68].

4.3. Evapotranspiration

ET is a key hydrological process, and the only mechanism that supplies water vapor to the atmosphere [69]. It is noted that reforestation leads to higher ET and reduces groundwater recharge and streamflow [51,70]. It is responsible for the coupling of the land surface energy balance with the terrestrial and atmospheric water balances. The relationships between trees, water availability, and water fluxes are linked to hydrologic processes such as groundwater recharge (balance between ET and infiltration) and surface runoff, as shown in Figures 1 and 2. Research conducted in Ghana and southern Burkina Faso reported that ET consumed 72% of the annual precipitation [71]. In the Amazon Basin in Brazil and Peru, the forest canopy can induce significant moisture fluxes between land and atmosphere, leading to a precipitation–ET loop [72].

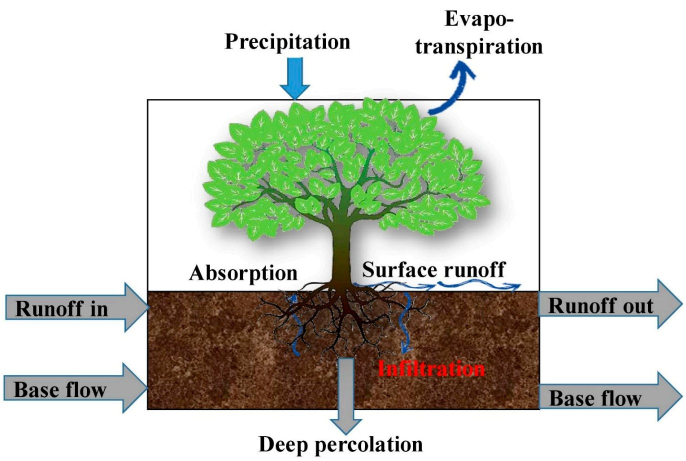

Figure 1. Conceptual models of water mass balance of a tree canopy delineated by the upper control volume and the soil water of the underlying control volume of the porous media. In this figure, the tree canopy refers to the upper layer of a standalone tree, formed by its leaves and branches.

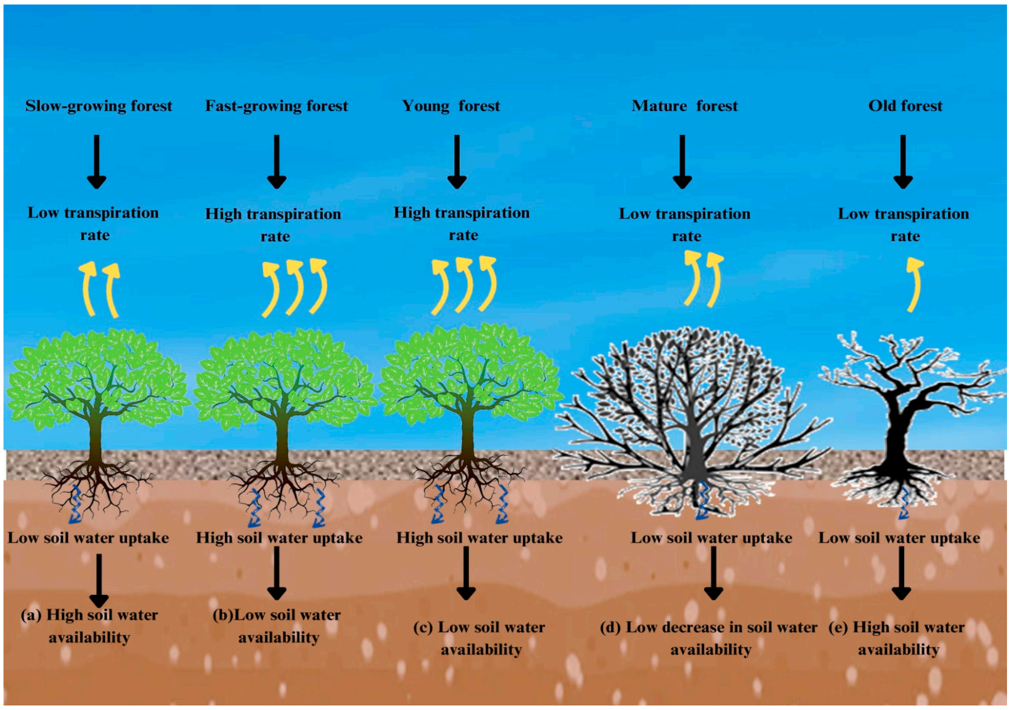

Figure 2. Relationship between trees and a part of vertical water fluxes and soil water availability, illustrating differences between fast- and slow-growing forests. Fast-growing forests have a larger impact on soil water availability due to their higher transpiration rates, especially when young.

4.4. Soil Water Availability

Soil characteristics such as fractured rock, fracture depth, soil texture, and parental rock interact with vegetation to reduce soil water availability (SWA), which is used here to refer to soil water storage, soil water recharge, rivers, basins, and watershed recharge (Figure 1). Since SWA varies among different substrates and different types of soil (e.g., sand, silt, clay, etc.) and land use land cover, it also influences water quality [73]. Loamy sand sites could have SWA greater than sandy clay loam or sandy clay [74]. Interactions between trees and soil water can be influenced by natural conditions (e.g., topography and slope) and parent material (i.e., geologic material). In such cases, trees can remove more water from the soil if the parent material mostly comprises organic matter.

SWA is the sum of water in the unsaturated zone (vadose zone) and the saturated zone (water table). Figure 1 represents conceptual models of water mass balances of a tree canopy and underlying soil matrix. Forest cover is one of the crucial parameters in forest management that alters the accumulation of water in the vadose and saturated zones of the soil [75]. Therefore, modifying natural forests through deforestation may temporarily modify watershed hydrology, directly impacting the annual hydrograph, and thus low and peak flows, streamflow regulation, and flood occurrences. These responses may occur quite rapidly. The tree canopy water mass balance is the difference between water inputs and outputs (Equation (1)).

$$\frac{\Delta H_2Otree\ canopy}{\Delta_t} = P + R_{in} + Abs - ETP - R_{out} - Inf \quad (1)$$

$$\frac{\Delta H_2O\ .soil}{\Delta_t} = Inf + Gr_{in} - Gr_{out} - D_p - Abs \quad (2)$$

In Equations (1) and (2), P is precipitation, R_{in} runoff in, *Abs* absorption, *ET* evapotranspiration, R_{out} runoff out, *Inf* infiltration, Gr_{in} groundwater in, Gr_{out} groundwater out, D_p deep groundwater percolation, $\Delta H_2Otree\ canopy$ the water mass balance of a tree canopy over time interval Δt, and ΔH_2Osoil SWA mass balance in the soil over time interval Δt.

When water reaches a tree, a part is lost through ET, and another part infiltrates the soil, and thus increases SWA. Soil water depletion is the difference between the sum of water inputs (infiltration (*Inf*) and groundwater in (Gr_{in})) and water outputs (groundwater out (Gr_{out}), deep groundwater percolation (D_p), and absorption (*Abs*)) (Equation (2)). Water absorption by roots from the soil depends on tree type, climate, and soil physical properties. Of note, SWA depends on vegetation cover, type, and understory composition. For example, exotic or native trees with a higher ET rate deplete SWA and can compete for water with other trees [76]. Thus, soil moisture is somehow associated with vegetation type. A reduction in SWA and groundwater are also associated with albedo and latent heat flux as they are among the mechanisms responsible for these changes [77].

Relationship Between Soil Characteristics and SWA

There is a link between soil properties and trees [78] that can cause a change in SWA [79]. For example, trees can take up more water from loamy soil, soil with higher organic matter content, and sandy soil than rocky soil [74]. This is possibly because tree roots have more difficulty reaching groundwater beyond the vadose zone [80]. In such a case, soil porosity should be considered because this property can give a false impression that forests retain water. SWA varies from one site to another, depending on soil textures. For example, capillary and hydraulic barriers enable layered soils to hold more water (presence of perched water tables) than nonlayered ones [81]. Similarly, a previous study documented that SWA varied in the following order: loamy sand > sandy loamy and sandy clay sites [74].

The reduction of soil particle size and tree development lead to organic matter accumulation in the topsoil, and thus increase the soil water storage [82]. Notably, biological soil crusts play a paramount role in increasing soil porosity and micro-topography, thus enhancing infiltration while increasing runoff by the secretion of hydrophobic compounds as well as clogging of soil pores upon wetting [83]. Tree–soil–water availability (TSWA) constitutes a complex system in which trees can increase water yield depending on soil composition. In a landscape with a high elevation, moisture could be more favorable to trees because they do not need to take up water from the deeper soil. This interaction occurs due to the slope angle's control on SWA. In the TSWA system, water yield can be increased or decreased depending on the characteristics of trees, soil saturation, and infiltration capacity.

4.5. Combined Effects of Forests and Local Climate on SWA

There is a synergic effect between forests and local climate on SWA. In this regard, researchers have reported that climate has considerable impacts on water balance components (such as runoff, precipitation, and ET) [84–86] and forest cover [87,88]. Several scientists have highlighted that climate and trees govern water availability in vegetated areas [89,90], playing an essential role in regulating water security and supply [91,92], and thus affect drainage and runoff characteristics [93]. Climate change variability is one of the main factors affecting precipitation, hydrological processes, and the final runoff response. There is an interrelationship between the water cycle and climate change. Notably, evaporation, precipitation, and precipitable water are key components of the water cycle that influence global climate change [69]. Climate change negatively affects the water cycle, freshwater availability, and water security [94–96].

In the future, interannual climate variability could be stronger in the Pacific and Indian Oceans and weaker in the Atlantic, while interdecadal climate variability is expected to increase and reduce warmth in polar and equatorial regions, respectively [97]. These findings highlight that polar and equatorial regions are susceptible to receiving longer precipitation periods than the Pacific and Indian Oceans. These findings may also indicate that different climate change scenarios can lead to different patterns of change in the terrestrial water cycle [98]. In watershed areas covered by exotic tree plantations in south-central Chile, increasing and decreasing trends in evaporation and percolation rates were registered because of climate change, respectively [99]. However, a variability in responses may exist, depending on environmental and tree characteristics. For example, large ET is more predominant at high altitudes in the north [100]. It is noted that any change in forest structure can affect climate and vice versa [44].

4.6. Relationship Between Topographic Factors and SWA

Altitude and the landscape slope can determine plants' behavior, modifying SWA and increasing relative humidity through the ET of unused water in (turgescence) and on (intercepted) leaves. A previous study reported that topographic position and slopes interact together to form a thermal gradient and water stress for trees across landscapes [101]. At high altitudes, vegetation takes up water from deeper unsaturated soils, developing significant variability in water consumption strategies [102]. Other researchers have underscored that landscape topography influences tree growth [103,104] and affects mountain forests through its effects on radiation and moisture [105]. Similarly, another study indicates that soil variation and water loss are important factors of the topographic gradient [106]. Thus, in certain cases, the slope gradient can reduce runoff, reduce soil moisture, and enhance ET, which may be associated with biophysical changes (for instance, deeper roots). This probably reduces the soil water stored [107,108], which in turn influences infiltration and ET [109], subsurface runoff paths, and erosional processes [110]. The largest average soil moisture values occur on topography with a flat surface configuration [111]. However, the drainage system could reduce the soil moisture in a determined area. An increase in water table depth may lead to a decrease in the role of the topography of the land surface and the spatial distribution of water when the water table is deep and close to the bedrock surface [112].

5. Relationships Between Forests and Runoff and Soil Erosion Control

Runoff is another important hydrological process and has various responses to forests at different scales (e.g., large, medium, and small scales). Certain vegetation types are more appropriate for reducing erosion than other trees. Forest, pepper, bush, and intercropping are types of vegetation that can minimize erosion [113]. Afforestation reduces runoff and flood peak discharge and controls soil erosion due to increased forest cover, canopy structure, and density to protect the soil from direct rainstorms. Afforestation of grasslands and shrublands reduced the annual runoff by an average of 44% (±3%) and 31% (±2%), respectively [9]. For example, a study conducted in the US revealed an increase in average annual runoff by 10–40 mm in areas where the forest cover of a watershed was decreased by 10% [114]. Notably, reforestation can have both positive (decreased wet season runoff) and negative (increased surface runoff) impacts on runoff [115]. The role of forests in reducing soil loss can vary depending on topography. A study outlined that soil loss varied according to the types of slope, as soil loss from convex slopes was 1.5 times greater than that from concave and uniform slopes [116]. In addition, forest cover can reduce soil degradation [117], depending on climatic factors and rainfall regimes. Along this line of reasoning, another study pointed out that runoff and soil loss were negatively correlated with slope value, organic matter content, tree cover percentage, and soil structural stability [60]. Recent research has indicated that fine roots of apple trees reduce SWA [118]. This reduction may depend on the length and shape of the root system. From a holistic viewpoint, our conceptual meta-analysis corroborates the literature on the relationship between trees, runoff, and soil erosion [119] by demonstrating that trees use their canopy and root systems to reduce erosion. However, when performing a careful analysis, we comprehend that this reduction depends on specific conditions (e.g., tree density and local climate) and environmental factors such as slope, length of slope, and soil structural characteristics.

5.1. Runoff Responses to Forests at Multiple Scales

Runoff response can be influenced by various factors, including forest type, soil properties, and watershed scales. The annual runoff response to land cover change may depend on forest type and the size of a watershed. There is a linear correlation between the runoff coefficient and the watershed scale, where runoff coefficients may reduce as watershed areas increase. Runoff coefficients depend on both the shape and size of a watershed [120]. Moreover, the type of land cover is a crucial factor affecting the hydrological response of a watershed, and the runoff coefficient-to-peak flow relationship varies from year to year [121].

5.2. Factors Affecting Surface Runoff

Surface runoff, or overland flow, is generated within a watershed and can be explained by one of two scenarios: (i) the precipitation rate exceeds the infiltration capacity of the soil column, or (ii) the water table reaches the soil surface [18,122]. The first process, called "Hortonian", occurs under high rainfall intensities [123], while the second mechanism, called "Dunne", happens under low precipitation intensity with shallow water tables [124]. Surface runoff can be influenced by a set of factors, such as vertical vegetation structure, vegetation distribution pattern, and plant diversity [125]. Vegetation can reduce runoff [126], intercept rainfall [127], and drain stormwater [128].

Plantation type and age can impact runoff and hydrologic processes. For example, mature plantations rather than young plantations can have a direct impact on soil erosion and runoff [129]. Another study showed that afforestation with *pinus* led to a higher runoff reduction than afforestation with *eucalyptus* in high-rainfall areas [130]. Converting natural forests to plantation forests reduces the total amount of runoff [131]. Along the same line of reasoning, they did not recommend afforestation in countries with little precipitation because mature forests reduce the amount of runoff [131]. However, old trees may not contribute much to erosion control. Contrary to young trees, unused water in mature forests evaporates and then contributes to air moisture, which can lead to precipitation, and thus replenish groundwater. Other factors, such as changes in forest cover, also affect total runoff and its components (e.g., surface runoff, interflow, groundwater flow) within a watershed [62].

6. Effect of Forests on Watershed Hydrology at Various Spatial Scales

The effect of forests on watershed hydrology varies in time and space. For example, at a large spatial scale, forest restoration can enhance precipitation recycling due to atmospheric drawdown [7,132]. Large-scale deforestation can have a detrimental effect on watershed hydrology. A study documented that the average terrestrial water storage and runoff dynamics in the Amazon Forest are approximately ten times more significant in deforested areas than in forested areas [133]. On the one hand, studies have pointed out that in some regions of the world, large-scale forest restoration can result in higher water yields [134,135], and thus intensify watershed hydrology [136]. On the other hand, Filoso et al. underscored that it does not necessarily increase water yields [137]. These findings suggest that the interaction between forests and hydrological processes varies in time and space [138]. At smaller scale, few insights were found in the literature about the interaction between reforestation/afforestation and precipitation, and thus it is difficult to postulate that small-scale forest expansions can generate enough moisture recycling to increase rainfall. In the same way, a study carried out in Espírito Santo, southeastern Brazil, revealed a negative relationship between forest cover and watersheds with low annual rainfall, showing that the average minimum streamflow was more sensitive in these situations, while areas with higher precipitation exhibited the opposite effect [139].

7. Relationships Between Tree Species and SWA

7.1. Fast-Growing/Commercial Trees

Certain fast-growing trees, such as *Eucalyptus globulus* and *E. grandis urophylla*, *Larix principis-rupprechtii*, and *Pinus radiata*, reduce water availability in the soil [12,131,140–149] and soil erosion while increasing infiltration and ET [150], as shown in Figure 2b. This occurs during both their growth stage and their adult stage. Industrial *eucalyptus* overuses stored water when planted in sandy soils [151], and their roots can reach a water table depth of 12 m after only two years [152]. In such cases, commercial trees function as natural drains, lowering the water table and enhancing local evapotranspiration, a practice known as biodrainage.

A recent study showed that multiple decades of forest operation reduced deep soil moisture reservoirs, illustrating that when *Radiata pinus* trees were replaced by *eucalyptus*, subsurface supply to streamflow substantially decreased under dry-period conditions [153]. Similarly, *Pinus halepensis* increases water use [154], and thus reduces the amount of moisture stored in the soil [155]. Admittedly, these fast-growing tree (monocultures trees) plantations generally transpire more than slow-growing forests due to their high interception loss [156].

Fast-growing forests have growth and ET rates higher than native forests (Figure 2a). During their growth, they reduce SWA through their root systems, which can reach the groundwater level in a short period. This finding indicates that forest types have a crucial role in water yield because of their different ET magnitudes [157]. This finding may also show that native species are more adapted to water stress than non-native trees [137]. The negative impact of fast-growing forests on water yield only lasts for a short time because they are generally cut at their youngest age for commercial purposes. Fast-growing forests are unsuitable for afforestation in areas with medium precipitation and brackish groundwater [158], and their photosynthetic rates and stomatal conductance are higher than those of slow-growing forests [159]. This indicates a relationship between the type and age of trees and SWA. Research findings in South Africa indicated that over a 5-year period of afforestation, *pinus* reduced the annual streamflow yield by 44 mm/a for each 10% of watershed planted when trees aged between 10 and 20 years [16]. Similarly, over a 3-year period, *eucalyptus* planting reduced the annual peak flow by 48 mm when 10% of a watershed was afforested [16]. Another study reported that *eucalyptus* and *pinus* reduced runoff by 75% and 40% on average, respectively [9].

7.2. Slow-Growing Forests

In contrast to fast-growing forests, slow-growing forests consume less water, and therefore have fewer impacts on SWA (Figure 2a,b). This finding indicates that some species are more tolerant to droughts than others. Trees can suppress runoff movement [160], and thus positively and significantly affect the water yield [161]. For example, studies have concluded that commercial forests, trees and tree densities can enhance infiltration, increase groundwater, and are considered prime regulators within the water cycle [160–162]. As a result, slow-growing forests are suitable for afforestation projects since they have fewer effects on SWA regarding water consumption. Similarly, a study by Younger et al. [163] in rural basins of the southeastern US found that evergreen forest cover was positively associated with ET, whereas deciduous forest cover exhibited a negative relationship. These findings show the complexity existing between forest cover and watershed hydrology.

7.3. Effect of Stand Density on SWA

Research results in West Africa reported that forest density maximized groundwater recharge [162], which could also be affected by vegetation community types and phenology [164]. Changes in forest density can alter the hydrologic processes at the watershed scale [38]. Similarly, another study reported that SWA increased with an increase in stand density [165]. However, this may depend on the tree species, stand age, and climate. For example, research findings showed that the plantation of high-density *Pinus sylvestris* significantly reduced the SWA [166]. This finding corroborates the results of another study that suggests reducing the density of *Quercus ilex* in semi-arid woodlands to prevent excessive water deficit [167]. The reduction in SWA occurred due to tree transpiration [168]. As such, a reduction in stand density may lead to an increase in SWA in native forest areas [169]. Admittedly, competition for resources among trees can also reduce SWA. For example, the results of one study underscored that an increase in understory density led to a reduction in SWA [170]. These findings align with a study conducted in Slovakia that highlighted that this capacity depends on forest cover, stand density and vertical structure, tree species composition, and spatial distribution of forests within watersheds [171]. These findings are consistent with a study conducted in Renqiu City, Hebei Province, China [172]. Likewise, forest type can influence the amount water in a watershed.

7.4. Effect of Forest Age on SWA

Forests/trees play several roles in increasing (through infiltration) and decreasing (via evaporation) SWA depending on several factors, including forest age. A relationship between SWA and forest age involves time and space. It was found in the literature that water infiltration increases with forest age [166,173]. Notably, two temporal scenarios can be presented regarding the influence of tree age on SWA, as follows.

7.4.1. Young/Juvenile Forest Versus SWA

The first scenario is that during their growth, young trees accumulate a large quantity of biomass, grow faster, consume much water, have high ET rates, and reduce the amount of SWA or existing water in a watershed (Figure 2c). Young *pinus* have ET rates greater than old *pinus*, and thus may reduce the streamflow of a given watershed [174]. As trees pass through multiple phenological phases before reaching maturity, from the juvenile phase to the adult phase, the amount of water they use, and associated ET rates, may vary across stages of growth (Figure 2). ET rates decrease with forest age [132]. Trees can take up large amounts of soil water and evaporate more water under various hydrogeologic conditions. At younger ages, they reduce the amount of SWA. Long-term fluctuations in pioneer forest areas and age structure decrease freshwater in riparian forests [175]. Regrowth stands have a higher transpiration rate than old stands [176,177] and consume an amount of water approximately twice as much as old-growth stands [178]. This suggests that stand age in plantations is a crucial factor which could be managed to increase water yield since juvenile trees affect water yield more negatively than old trees.

7.4.2. Mature and Old Forests Versus SWA

The second scenario encompasses mature trees, which consume less water and can evaporate less than younger trees (Figure 2d). This statement is supported by research findings in South Africa, which pointed out that *pinus* and *eucalyptus* plantations of 30 and 15 years of age, respectively, appeared to return streamflow to pre-afforestation levels [16].

A previous study highlighted that annual water use had decreased from 679 to 296 mm for 50-year-old and 230-year-old stands, respectively [179]. These findings align with a study that highlighted that regrowing hardwood forests might take as long as 8–25 years before recovering the annual water use of a mature forest [180]. Mature and old-growth forests have moderate ET and consistent water yield, while managed forest plantations provide low water yield, particularly during the dry season [181], and thus affect water flow regulation [182]. This finding corroborates other studies conducted in the Tropical Atlantic Forest region of Brazil and in South Africa in another study [183]. Mature *eucalyptus* and *pinus* plantation ages positively correlate with water availability [16,184]. Undoubtedly, forest age in forested watersheds is correlated with the regional mean annual streamflow [185], which is one of the factors that increases ET partitioning [186,187].

The transpiration rate of trees varies in the following order: young forests > mature forests > old forests (Figure 2). Likewise, there is a relationship between the height of a tree and water stress on a watershed scale. For example, tall trees have very high evapotranspiration rates and therefore experience great water stress [188]. The relationship between forest age and SWA follows the previous order, indicating that young forests consume more water than mature and old forests (Figure 2e). In such a case, plants can passively use their roots to enable water redistribution in the soil profile [18]. The effect of forest age on SWA depends on other factors, including the types of trees and climatic conditions. Of note, forest type, species, age, environmental conditions, and forest management practices are among the factors enabling water-use efficiency [189].

7.5. Water-Related Ecosystem Services and the Role of Forests

The relationship between water-related ecosystem services and forest cover is crucial for ensuring water supply and maintaining watershed health. It is noted that runoff generation mechanisms can alter water quality, particularly in agricultural lands where runoff may contain pesticides and affect the soil properties of the downstream buffer zones [190]. In such cases, soil properties may be influenced by both tree species and dominant pedogenetic processes [191]. Dense vegetation represents a prominent alternative for reducing colloidal contaminants in surface runoff [192] and promotes water conservation [193]. The concentration and total amount of nutrients (e.g., phosphorous and nitrogen) transported in runoff can be affected by soil type [194,195] and thus alter water quality. The movement of nutrients, SWA, and soil production are dependent on and regulated by bedrock weathering [196]. In such cases, forests can greatly contribute to ecosystem services and natural resource management, including water. Of note, some trees have continuous and deep roots to absorb and recover nutrients and thus mitigate the deterioration of water quality. Therefore, trees can be used for phytoremediation techniques to remove trace metals from the soil [197]. Researchers have argued that cacao trees remove trace metals of cadmium from the soil [197–199] and reduce soil degradation problems [200,201]. Of note, the conversion of forest soils into pastures and row crops may cause deterioration in the quality of water resources [202].

The role of forests in improving water quality is well documented through studies carried out around the world. For example, the results of a study conducted in the southeastern U.S. reported that protecting forest cover can strengthen the resilience of drinking water resources and significantly decrease total nitrogen, total phosphorus, and suspended sediment in watersheds [203]. Similarly, a study conducted in Greece assessed the ecosystem services provided by woodlands and forests in a watershed, revealing higher values for soil conservation and water retention services [204]. Brogna et al. [205] carried out a numerical study in Wallonia, in the southeast of Belgium, and reported that one-third of water quality variability is explained by forest cover in the watershed. These findings indicate forest cover can prevent eutrophication in a watershed. In other words, the health of a watershed is somehow associated with forest cover. However, a minimum of forest cover in a watershed is required to ensure the sustainability of ecosystem services. For example, a study conducted in Jambi Province, Indonesia, suggested that a minimum of 30% forest cover and a maximum of 40% plantation cover in a watershed are necessary to guarantee water-related ecosystem services [64].

8. The Links Between Forest Cover and Sustainable Development Goals

Forests are habitats and shelters for more than 80% of terrestrial species and therefore are essential in allowing the possibility of life on land [206], and they can substantially contribute to mitigating some of the problems that humanity is currently facing, including climate change, hunger, and loss of biodiversity. For example, forest preservation and plantation align with the sustainable development goals (SDGs) [207], and can help promote environmental sustainability and serve as a promising policy to achieve several of their targets. For example, they can help achieve SDG 1 (no poverty), SDG 2 (zero hunger), SDG 6 (clean water), SDG 10 (reduced inequalities), SDG 13 (climate action), and SDG 15 (life on land) [208]. Forests reduce the costs associated with ecosystem services, provide homes for many people and habitats for several animal species, reduce global warming by producing oxygen and renewing the atmosphere, store CO_2 in the soil, allow nutrient recycling, and provide food to animals and people, among other benefits [209]. This indicates that forest concessions support the implementation of sustainable use and management of ecosystems' goods, enhancement of socioeconomic development, and increase national economy through employment creation [210,211]. Preserving forest areas is a way to promote environmental sustainability by reducing CO_2 emissions into the atmosphere [212], which are expected to increase global temperature by 1.5 °C by 2050 [213]. Likewise, Mondal et al. [214] have suggested preserving forest areas to achieve SDG target 15.1, which suggests quantifying "*forest area as a proportion of total land area*". A numerical study highlighted that global forests absorbed around 3.56 billion tons of CO_2 between 1990 and 2019, which corresponds to nearly half of the carbon emissions caused by the use of fossil fuels during the same period [215]. Therefore, forest preservation and plantation are among the most promising approaches that can substantially contribute to achieving the goal of net-zero carbon emissions, thus reversing the current trends of global warming. In the same way, another study stressed that the forest sector enables climate change mitigation and strengthens sustainability initiatives [216].

9. Conclusions and Future Research

Forests can influence the amount of water available at some stages of the hydrological cycle. In this conceptual meta-analysis, the roles of forests were addressed while considering several factors, such as stand density, forest type, tree species, stand age, and soil composition. This conceptual meta-analysis also analyzed the influence of forest cover on hydrological processes. Overall, it was found that afforestation could positively affect soil erosion control on degraded soils. Nevertheless, this impact can change due to tree litter, forming a layer more permeable to infiltration. The findings showed that trees and watershed hydrology have complex interactions, where the effects could either be positive or negative on SWA, watershed yield, and groundwater recharge. The effects of forests on watershed hydrology mainly depend on the type of aquifer and other characteristics such as local or regional climate, canopy type, soil composition, tree density, and landscape topography. The types of trees to be planted should be taken into consideration, as fast-growing trees (e.g., *eucalyptus*, and *pinus*) reduce SWA. Based on the reviewed studies, it is evident that native forest species contribute more to SWA and groundwater recharge due to their lower evapotranspiration (ET) rates compared to fast-growing species. Similarly, the reviewed studies indicate that reforestation with native species can more effectively reduce soil erosion than commercial tree species plantations. The strength of this conceptual meta-analysis lies in the fact that it encompasses a range of evidence about the interaction between trees and watershed hydrology, as well as how different environmental and geological factors can affect this complex relationship. The novelty of this study lies in highlighting that trees' effectiveness in increasing water availability occurs with the use of some specific species used for afforestation in large-scale watersheds, where trees increase groundwater recharge. Afforestation with proper trees can help increase SWA. Admittedly, less dense forests are more likely to increase the different components of the water cycle than denser forests. Also, trees can be used as a phytoremediation technique to reduce transport of chemical elements in surface runoff and thus limit soil degradation and water contamination. Regarding the impacts of trees on runoff, they could reduce it, depending on the type of forest cover (e.g., plantation versus native forests), stand age, density, and species. One of the limitations of this conceptual meta-analysis is that it did not explore the relationship between tree roots and SWA in depth. Further research is necessary to identify other factors (such as shapes and directions of root systems) that may impact the relationship between trees and other components of watershed hydrology. In conclusion, our conceptual model demonstrates that native forests play a crucial role in natural resources management. This study may prove to be helpful to decision-makers in choosing the best alternative for afforestation strategies in some specific areas. Moreover, the results of this study can provide stakeholders and decision-makers with a sustainable alternative to help mitigate the climate crisis in the ongoing race toward zero carbon emissions.

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