Review

Interactions between Forest Cover and Watershed Hydrology: A State-of-the-Art Review

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Interactions between Forest Cover and Watershed Hydrology: A State-of-the-Art Review

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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 into diverse debates in the literature. Herein, this state-of-the-art review 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 hydrology. To achieve this goal, this review addressed the interaction of forest cover with climatic conditions, soil types, infiltration, siltation and erosion, water availability, and the diversity of their 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 imprint, 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 when investing in reforestation in watershed hydrology.

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

1. Introduction

Forests cover about one-third of the Earth 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 could positively or negatively affect water storage (i.e., soil water availability) by regulating basic fluxes such as infiltration, and 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 meters 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. Besides, 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, 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 need, trees use various strategies for searching water in a forested watershed, preferring soil water rather than groundwater [33], depending on the period; for example, they could uptake 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 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 state-of-the-art review is to document the influence of trees on water availability and propose a conceptual model of their role in watershed hydrology and the conditions in under which they can increase or decrease water supply. Therefore, after the introduction section, this paper proceeds as follows: (i) Methodology; (ii) origin of precipitation; (iii) conceptual model of the role of trees in watershed hydrology; (iv) relationships between forests, runoff, and soil erosion control; (v) effects of forests on watershed hydrology at various spatial scales; (vi) relationships between tree species and SWA; and (vii) conclusions and future research.

2. Materials and Methods

This state-of-the art review proposed a conceptual model for understanding the role of trees in watershed hydrology and examined the conditions under which they can influence water supply in a watershed hydrology. 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 Boolean operators “AND” and “OR” were used to associate the aforementioned keywords and thus refine the search results. This review focused on English documents (e.g., papers, reports and books) published from 1933 to 2023. The list of references was also used to search for additional published documents. After screening the titles, abstracts, and conclusions, more than 206 documents were selected for inclusion in this state-of-the-art review. Information was extracted from these documents and analyzed by searching for

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relationships between the keywords used and, at least, one of the watershed hydrology components (e.g., runoff, infiltration) targeted in this review relating to water availability. Finally, data was managed using EndNote to ensure accurate referencing.

3. Origine 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]. The numerical study detailed and highlighted how moisture is formed under the effect latent heat fluxes over the ocean and subsequently transport 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 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 forests 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 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 historicity of a targeted area.

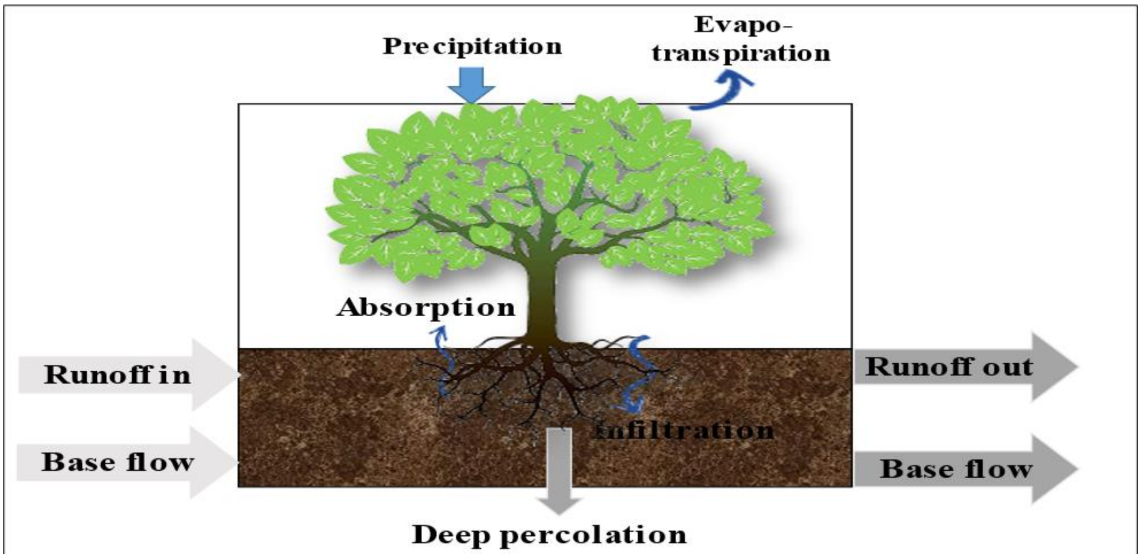
Reforestation in the tropics and subtropics may improve water infiltration, depending on land use, soil texture, and local climate [49]. It is noted that reforestation should regulate water fluxes [51] through infiltration and ET [52] depending on soil properties, which are influenced by a set of factors such as slope/topography [53–55], climate, parent material, time, and living organisms [56]. 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 [57]. Such soil reduces water infiltration, which drives surface runoff, soil erosion, chemical transfer routes, water quality, and irrigation uniformity [58]. Depending on the size of rock fragments and their aggregation to the soils, they could favor infiltration or enhance soil loss [59].

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; and in return this can increase ET loss and modulate streamflow [60]. Meanwhile, forest cover type and annual temperature affect watershed base flow [61]. A decrease in total basal area of pinus trees can lead to an increase in groundwater recharge, cumulative streamflow, and direct runoff [62,63]. These findings indicate that forest is one of the key factors governing base flow in a catchment. Another study corroborates these findings and outlines that high ET reduces stream flows [64]. Besides, changes in forest cover during regeneration modify water flux partitioning [65]. 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 [66]. Notably, there is a correlation between rainfall, base flow, and forest area. Therefore, the greater the forest area the more stable are flow conditions [67].

4.3. Evapotranspiration

ET is a key hydrological process, and the only mechanism that supplies water vapor into the atmosphere [68]. 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 [69]. 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 [70].



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

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

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.

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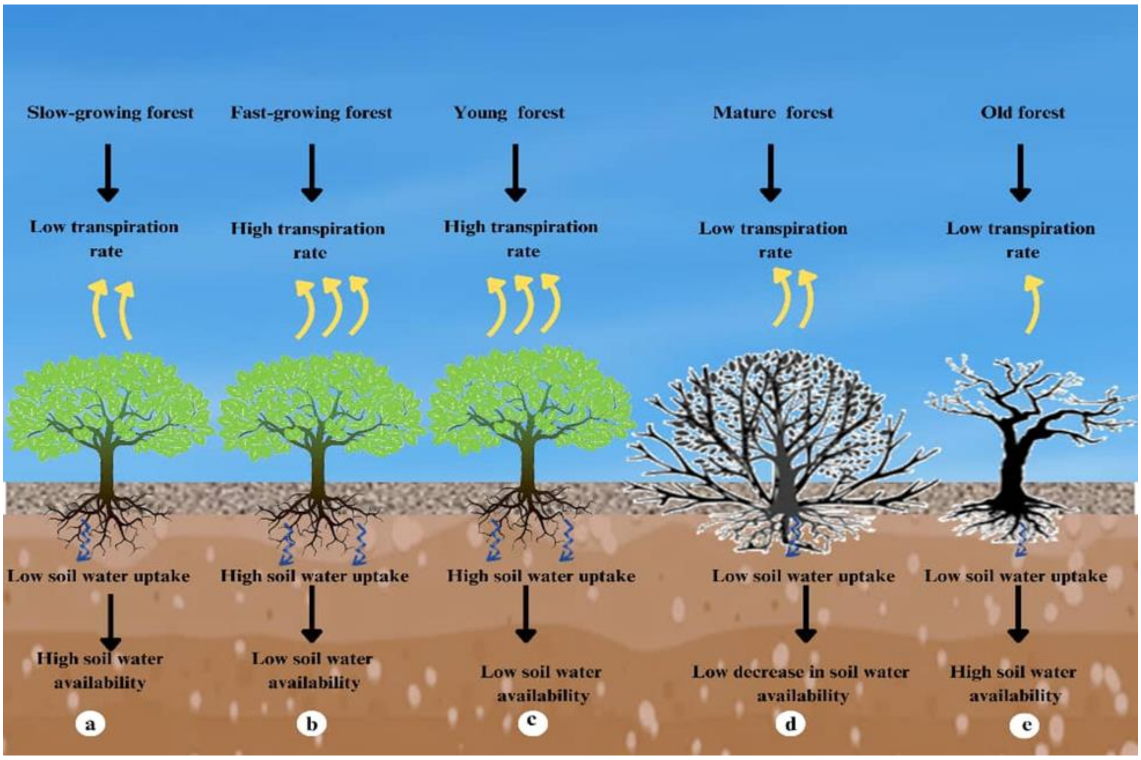

Figure 2. Relationship between trees and a part of vertical water fluxes and soil water availability, illustrating differences between fast and slow-growing forests. Fast-growing forests have a larger impact on soil water availability due to their higher transpiration rates, especially during early ages.

4.4. Soil Water Availability

Soil characteristics such as fractured rock, fracture depth, soil texture, and parental rock interact with vegetation to reduce 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 [71]. Loamy sand sites could have a SWA greater than sandy clay loam or sandy clay [72]. 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.

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

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 [73]. Therefore, modifying natural forests through deforestation may temporarily increase watershed hydrology, directly impacting the annual hydrograph and thus low and peak flows, streamflow regulation, and flood occurrences. These responses occur quite rapidly. The tree canopy water mass balance is the difference between water inputs and outputs (Equation (1)). 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 (D_p), and absorption (Abs) (Equation (2)). Water absorption by roots from the soil depend on tree types, climate, and soil physical properties. Of note, SWA depends on vegetation cover, types, and understory composition. A recent study underscored that groundwater is tightly related to soil water [74]. As such, exotic or native trees with a higher ET rate deplete SWA and can compete for water with other trees. Thus, we argue that soil moisture is somehow associated with vegetation types. The reduction of SWA and groundwater can also be associated with albedo and latent heat flux as they are among the mechanisms responsible for these changes [75].

4.4.1. Relationship between Soil Characteristics and SWA

There is a link between soil properties and trees [76] that can cause a change in SWA [77]. For example, trees can uptake more water from loamy soil, soil with higher organic matter content, or sandy soil than rocky soil [72]. This is possible because tree roots have more difficulty reaching groundwater beyond the vadose zone [78]. 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 [79]. Similarly, a previous study documented that SWA varied in the following order: loamy sand > sandy loamy and sandy clay sites [72].

The reduction of soil particle sizes and tree development lead to organic matter accumulation in the topsoil and thus increase the soil water storage [80]. 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 [81]. 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 uptake 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) [82–84] and forest cover [85,86]. Several scientists have highlighted that climate and trees govern water availability in vegetated areas [87,88], playing an essential role in regulating water security and supply [89,90], and thus affect drainage and runoff characteristics [91]. Climate change variability is one of the main factors affecting precipitation, hydrological processes, and as 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 [68]. Climate change negatively affects the water cycle, freshwater availability, and water security [92–94].

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 enhance and reduced warmth in polar and equatorial regions, respectively [95]. These findings highlight that polar and equatorial region 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 [96]. 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 [97]. However, a variability of responses may exist, depending on environmental and tree characteristics. For example, large ET is more predominant at high altitudes in the north [98]. It is noted that any change in forest structure can affect climate and vice-versa [44].

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4.6. Relationship between Topographic Factors and SWA

Altitude and landscape slopes 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 the landscapes [99]. At high altitudes, vegetation uptakes water from the deeper unsaturated soils, developing significant variability in water consumption strategies [100]. Other researchers have underscored that landscape topography influences tree growth [101,102] and affects mountain forests through its effects on radiation and moisture [103]. Similarly, another study indicates that soil variation and water loss are important factors of the topographic gradient [104]. 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). That probably reduces the soil water stored [105,106], which, in return, influences infiltration and ET [107], subsurface runoff paths, and erosional processes [108]. The largest average soil moisture values occur on topography with a flat surface configuration [109]. 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 [110].

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 [111]. Afforestation reduces runoff and flood peak discharge and controls soil erosion due increased forest cover, canopy structure and density to protect the soil from direct rainstorms. Notably, reforestation could have both positive (decrease wet season runoff) and negative (increase surface runoff) impacts on runoff [112]. The role of forests in reducing soil loss could vary depending on topography. A study outlined that soil loss varied according to the types of slopes, as soil loss from convex slopes was 1.5 times greater than that from concave and uniform slopes [113]. In addition, forest cover can reduce soil degradation [114], depending on climatic factors and rainfall regime. Along this line of reasoning, another research pointed out that runoff and soil loss were negatively correlated with slope value, organic matter content, tree cover percentage, and soil structural stability [59]. Recent research has indicated that fine roots of apple trees reduce SWA [115]. This reduction may depend on the length and shape of the root system. From a holistic viewpoint, our review corroborates the literature on the relationship between trees, runoff, and soil erosion [116] by demonstrating that trees use their canopy and root systems to reduce erosion. However, when doing a careful analysis, we comprehend that this reduction depends on specific conditions (e.g., tree densities, and local climate) and environmental factors such as slope, length of slope, and soil structural characteristics.

5.1. Runoff Responses to Forest 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 depends on forest type and the size of a watershed. There is a straight correlation between the runoff coefficient and the watershed scale, where runoff coefficients may reduce as watershed areas increase. Runoff coefficients depend on both shape and size of a watershed [117]. Moreover, the type of land cover is a crucial factor affecting the hydrological response of a watershed, and the runoff coefficients to peak flow relationships vary from year to year [118].

5.2. Factors Affecting the 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)

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the water table reaches the soil surface [18,119]. The first process, called "Hortonian", occurs under high rainfall intensities [120], while the second mechanism, called "Dunne", happens under low precipitation intensity with shallow water tables [121]. Surface runoff can be influenced by a set of factors, such as vertical vegetation structure, vegetation distribution pattern, and plant diversity [122]. Admittedly, vegetation can reduce runoff [123], intercept rainfall [124], and drain stormwater [125].

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 [126]. Another study showed that afforestation with *pinus* led to a higher runoff reduction than afforestation with *eucalyptus* in high-rainfall areas [127]. Converting natural forests to plantation forests reduces the total amount of runoff [128]. Along the same line of reasoning, they did not recommend afforestation in countries with little precipitation because mature forests reduce the amount of runoff [128]. 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.

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 drawbacks [7,129]. 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 [130]. 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 [131,132] and thus intensify watershed hydrology [133]. On the other hand, Filoso et al. underscored that it does not necessarily increase water yields [134]. These findings suggest that the interaction between forests and hydrological processes varies in time and space [135]. At smaller scale, little 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.

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 [12,128,136–145] and soil erosion while increasing infiltration and ET [146], 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 [147], and their roots can reach water table depth of 12 meters after only two years [148]. 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 are replaced by *eucalyptus* subsurface supply to streamflow substantially decreased under dry period conditions [149]. Similarly, *Pinus halepensis* increases water use [150] and, thus, reduces the amount of moisture stored in the soil [151]. Admittedly, these fast-growing tree (monocultures trees) plantations generally transpire more than slow growing forests due to their high interception loss [152].

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 [153]. This finding may also show that native species are more adapted to water stress than non-native trees [134]. The negative impact of fast-growing forests on water yield is only for a short time because they are generally cut at their youngest age for commercial purposes.

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Fast-growing forests are unsuitable for afforestation in areas with medium precipitation and brackish groundwater [154], and their photosynthetic rates and stomatal conductance are higher than those of slow-growing forests [155]. 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 with *pinus* reduced the annual streamflow yield by 44 mm/a for each 10% of catchment planted when trees aged between 10 and 20 years [16]. Similarly, *eucalyptus* plantation reduced over a 3-year period the annual peak flow by 48 mm when 10% of a catchment was afforested [16]. Another study reported that *eucalyptus* and *pinus* reduced on average runoff by 75% and 40%, 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 [156] and, thus, affect positively and significantly the water yield [157]. For example, studies have concluded that commercial forests and trees, and tree densities can enhance infiltration, increase groundwater and are considered the prime regulators within the water cycle [156–158]. As a result, slow-growing forests are suitable for afforestation projects since they have fewer effects on SWA regarding water consumption.

7.3. Effect of Stand Density on SWA

Research results in West Africa reported that forest densities maximized groundwater recharge [158], which could also be affected by vegetation community types and phenology [159]. Changes in forest densities can alter the hydrologic processes at the watershed scale [38]. Simularly, another study reported that SWA increased with an increase in stand density [160]. However, this may depend on the tree species, stand age, and climate. For example, research finding showed that the plantation of high-density *Pinus sylvestris* significantly reduced the SWA [161]. This finding corroborates the results of another study that suggests to reduce the density of *Quercus ilex* in semi-arid woodlands to prevent excessive water deficit [162]. The reduction in SWA occurred due to tree transpiration [163]. As such, a reduction in stand density may lead to an increase in SWA in native forest areas [164]. Admittedly, competition for resources among trees can also reduce SWA. For example, the results of a study underscore that an increase in understory density led to a reduction in SWA [165].

7.4. Effect of Forest Age on SWA

Forests/trees play several roles 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]. Notably, two temporal scenarios could be presented regarding the influence of tree age on SWA:

7.4.1. Young/Juvenile Forest vs 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 streamflow of a given watershed [167]. 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 [129]. Trees can uptake large amounts of soil water and evaporate more water under various hydrogeologic conditions. At earlier ages, they reduce the amount of SWA. Long-term fluctuations in pioneer forest areas and age structure decreased freshwater in riparian forests [168]. Regrowth stands have a higher transpiration rate than old stands [169,170] and consume an amount of water approximately twice as much as old-growth stands [171]. 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 vs SWA

The second scenario encompasses mature trees, which consume less water and could evaporate less than younger trees (Figure 2d). This statement is supported by research finding in South Africa, which pointed out that *pinus* and *eucalyptus* plantations 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 [172]. These findings align with a study highlighted that regrowth of hardwood forests might take as long as 8–25 years before recovering that of a mature forest [173]. 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 [174] and thus affects water flow regulation [175]. This finding corroborates other studies conducted in the Tropical Atlantic Forest region of Brazil such as that of and, in South Africa, in another study conducted [176]. Mature *eucalyptus* and *pinus* plantation ages positively correlate with water availability [16,177]. Undoubtedly, forest age in forested watersheds is correlated with the regional mean annual streamflow [178], which is one of the factors that increases ET partitioning [179,180].

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 [181]. 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 [182].

7.5. Influence of Forests on Water Quality

Rainfall regimes can combine with forests plantations to modify watershed hydrology. 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 [183]. In such cases, soil properties may be influenced by both tree species and dominant pedogenetic processes [184]. Dense vegetation represents a prominent alternative for reducing colloidal contaminants in surface runoff [185] and promotes water conservation [186]. In such cases, forests can greatly contribute to ecosystem services and natural resources management, including water. The concentration and total amount of nutrients (e.g., phosphorous and nitrogen) transported in runoff can be affected by soil type [187,188] and thus alter water quality. The movement of nutrients, SWA, and soil production are dependent on and regulated by bedrock weathering [189]. Some trees have continuous and deep roots to absorb and recover nutrients and thus mitigate the deterioration of water quality. In such cases, trees can be used for phytoremediation techniques to remove trace metals from the soil [190]. Several researchers have argued that cacao trees remove trace metals of cadmium from the soil [190–192] and reduce soil degradation problems [193,194]. Of note, the conversion of forest soils into pastures and row crops may cause deterioration in the quality of water resources [195].

8. Conclusions and Future Research

Forests can influence the amount of water available at some stages of the hydrological cycle. In this review, the roles of forests were addressed while considering several factors, such as stand density, forest type, tree species, stand age, and soil composition. This review also analyzed the influence of forest cover on hydrological processes. Overall, it was admitted that afforestation could positively affect soil erosion control on degraded soils. Nevertheless, this impact can change due to

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tree litter, forming a layer more permeable to infiltration. The findings showed that trees and watershed hydrology have complex interactions, where the effects could be either 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 type of trees to be planted should be taken into consideration, as fast-growing trees (e.g., *eucalyptus*, and *pinus*) reduce SWA. The strength of this review 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 highlighted that trees' effectiveness in increasing water availability occurs with the use of some specific species used for afforestation on 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 review 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 resource management. This review may prove to be helpful to decision-makers in choosing the best alternative for afforestation strategies in some specific areas.

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