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Hydrological responses to large-scale changes in land cover of river watershed: Review

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Abstract: Despite many studies on the hydrological responses to forest cover changes in micro and mesoscale watersheds, the hydrological responses to forest cover alterations and associated mechanisms through the large spatial scale of the river watershed have not been comprehensively perceived. This paper thus reviews a wide range of available scientific evidence concerning the impacts exerted by the forest removal on precipitation, water yield, stream flow, and flow regimes. It is concluded that there is no statistical correlation between forest cover and precipitation and water yield at the micro and mesoscale. In contrast, there is a relative correlation coefficient ($r = 0.77$, $p < 0.05$) between forest cover and water yield at large scales (>1000 km^2). These findings help our understanding of the hydrological response to forest disturbance at large and regional scale and provide a scientific perception to future watershed management in the context of human activities and natural hazards.

Keywords: high flow, land use-land cover, large scale change, low flow, runoff

INTRODUCTION

Viable management of the changes on the earth's surface like land use and land cover (LULC) is one of the big challenges faced by society. Besides the vulnerability of ecosystem, LULC is two main factors globally driving environmental changes leaving potential extreme effects on human livelihoods [Olson *et al.* 2008]. The major causes of LULC include economic development, increase in population, and competition for food production [Lambin et al. 2003]. Such alterations may appear in the form of hydrological and climatological responses [Guzha *et al.* 2018]. It is commonly accepted that land use change is a key environmental factor extremely impacting river basin hydrology. Land use changes caused by human activities can affect hydrological processes such as infiltration, evapotranspiration, and the interception, resulting in changes in the surface flow [Bronstert *et al.* 2002; Dias *et al.* 2015; Zhang *et al.* 2016]. Also, it is reported that LULC impacts profoundly on water quantity such as groundwater flow and surface runoff in the frame of watershed scales [Zhu, Li 2014]. However, it is important to understand the great influence of LULC changes on surface runoff and streamflow for sustainable management of river basins. It was globally agreed [Kashaigili 2008] that river ecosystems have experienced changes as a result of river regulations altering the flow regime. River flow response to hydrologic alterations is dependent on the catchment characteristics that include the underlying geology, physiographic, vegetation cover, and rainfall patterns [Berhanu *et al.* 2015]. The interaction between these attributes is variable in space and time and induces complexity, which may not yet be predicted in hydrology.

Researchers investigated that LULC can change the whole water balance that exists between stream discharge and evaporation of river basins [Defries, Eshleman 2004; Garg *et al.* 2017]. Among the various types of LULC change, forest removal by human activities and natural disasters is the major cause of alterations in diverse hydrological processes such as streamflow, evapotranspiration, and snowmelt process [Garg *et al.* 2017; Obahoundje *et al.* 2017]. Since earlier, much attention has been paid on the importance of forests for the provision of water-related benefits. Also, in many regions of the world, forest hydrology has significantly contributed to sustainable development within national strategies [PAYEUR-POIRIER, NGUYEN 2017]. Forest cover can play a vital role in sustaining water management. It is widely argued that forests work actively as "sponges" by increasing infiltration rates and soil water retention, and as "pumps" by enhancing evapotranspiration rates [BRUIJNZEEL 2004; GUZHA *et al.* 2018]. Accordingly, forest-dominated watersheds demonstrate less stream flow rates than watersheds dominated by other urbanized and industrialized lands. COSTA *et al.* [2003] and FARLEY *et al.* [2005] reported that forest removal results in alterations in albedo condition, aerodynamic roughness reduction, and plant canopy reduction. As a consequence, it causes a reduction in evapotranspiration (*ET*), which in turn has impacts on streamflow. Accordingly, forests are presumed to be significant for hindering flood occurrence [BATHURST *et al.* 2017] and increasing dry season flow and preserving rainfall patterns [WILK *et al.* 2001].

Numerous studies have illustrated that highly reduced forest-dominated watershed cover relatively increases the stormflow quantity and annual streamflow of the affected area [BROWN *et al.* 2013; CHAPPELL, TYCH 2012; COSTA *et al.* 2003; HLÁSNY *et al.* 2015]. These conclusions have been based on the data from small watersheds of a few square kilometers. Although in recent decades, large-scale watershed studies have been receiving much attention owing to environmental issues having cumulative impacts on large spatial scales, the potential hydrological effects of large-scale changes in land cover, particularly forest clearance are not well quantified. In addition, large river watersheds have different land uses, heterogeneous geology, different types of soil, and different topography. It is therefore not confirmed that the conclusions drawn from small-scale studies are suitable for large-scale watersheds [WILK *et al.* 2001]. Meanwhile, some studies (COSTA *et al.* [2003], CUI *et al.* [2007], D'ALMEIDA *et al.* [2007], ARIAS *et al.* [2018], HOU *et al.* [2018], LEE *et al.* [2018]) have been carried out on the hydrological impacts of land cover change in large watersheds, but the results were not strictly consistent with each other; even consistent conclusions could not be drawn when compared with small scale studies. The reasons are attributed to insufficient data and the complexity of large-scale watersheds [CUI *et al.* 2012]. For example, studies conducted by WILK *et al.* [2001], THANAPAKPAWIN *et al.* [2007], ARIAS *et al.* [2018] and LEE *et al.* [2018], have stated that hydrological influences of forest cover changes in large river watersheds were insignificant. In contrast, CUI *et al.* [2007], D'ALMEIDA *et al.* [2007], HOU *et al.* [2018], and OGDEN *et al.* [2013] have reported significant hydrological alterations in response to forest cover changes in many other large watersheds. These inconsistencies can be attributed to the application of diverse tools and research methods and key complexities of large-scale river watersheds [CUI *et al.* 2012]. Therefore, there is a need for further analysis and investigation of hydrological responses to forest cover changes in large watersheds.

In the current article, we review the hydrological responses to land cover changes in large river watersheds. We also provide a detailed review of the existing literature on the hydrological impacts of land cover changes by human activities and natural disasters. The aim of the present paper is (1) to highlight the key findings from the existing literature; (2) to provide the available evidence with respect to the impacts of forest cover on streamflow, peak flows, low flows, and rainfall within various scales of watersheds; (3) to analyze the inconsistent results retrieved from observation methods and different hydrological models. Although much more attention is paid to large scale watersheds than small scales studies, the inclusion of small-scale watershed results may help better interpret the inconsistencies exist among the outcomes.

LINKAGE BETWEEN FOREST COVER AND PRECIPITATION

Understanding the interactions between forest cover and climate variability is essential to the sustainable management of river watersheds where forest cover plays a vital role in controlling the water cycle of the region [ARIAS *et al.* 2018; BENNETT, BARTON 2018; LEWIS *et al.* 2015]. It was initially argued that tropical deforestation could result in regional and global cooling with corresponding decreases in rainfall [BENNETT, BARTON 2018], it was also reported that albedo caused by forest removal would diminish surface temperature, lessen evaporation and rainfall in the middle and upper tropical troposphere. Field observations in agricultural watersheds have demonstrated that the conversion of tropical forest to cropping system led to increases in flow after several years as a consequence of changes in soil infiltration and vegetation transpiration [NEILL *et al.* 2013]. In recent decades, few studies have revealed that seasonal patterns of rainfall have notably changed across the Amazon rainforest with a negative trend in the dry and early rainy seasons [ESPINOZA VILLAR *et al.* 2009; MARENGO 2004]. However, the findings have different trends and various results. [SAMPAIO *et al.* 2007] found that great decreases in precipitation take place when the deforested area exceeds 40% of the Amazon (Fig. 1). Reductions in evapotranspiration influence the water vapor content of the surrounding atmosphere; thus, this alteration in water cycling can modify downstream precipitation [SPRACKLEN *et al.* 2012; SWANN *et al.* 2015]. Another scenario was presented by SWANN *et al.* [2015] in which 35% of the domain is dedicated to cultivated crops in the year 2050, causing an indicative change in precipitation (Fig. 2). According to the findings mentioned above, removal and conversion of forest cover to croplands in large scales lead to a decrease in evapotranspiration and precipitation. Wang *et al.* [2011] analyzed forest cover and water yield relationships in three different regions of northern China, namely the Loess Plateau, Northwest China, and Northeast China using published data. The authors found that there was no statistical correlation between forest cover and precipitation (r = 0.08, p > 0.05) at micro- and mesoscales from 50 up to 1000 km^2, whereas the forest cover and precipitation relationship were consistently correlated at large (>1000 km^2) scales (r = 0.77, p < 0.05) in Loess Plateau (Fig. 3). They also found a significant correlation (r = 0.48, p < 0.05) between forest cover and precipitation in Northwest China, as shown in Figure 4. However, the relationship between forest cover and precipitation was insignificant (r = 0.28, p > 0.05) in Northeast China, as shown in Figure 4. Furthermore, studied conducted in Amazon on deforestation impacts on precipitation and rainfall frequency revealed that changes in forest cover results in rainfall alterations. For example, NEGRI *et al.* [2004] and KNOX *et al.* [2011] stated that their results were consistent and in agreement with previous studies indicating that changes in forest cover of large basins (Amazon) would lead to decreased precipitation. However, BRUIJNZEEL [2004] concluded that impacts of forest changes or conversion to grasslands and croplands in small basins on precipitation would be smaller than the average decrease of 8% anticipated for a complete conversion of the basin to grassland. The overall conclusion is that the greater aerodynamic roughness of natural forests and higher evapotranspiration compared with grassland and croplands would result in increased atmospheric humidity and moisture convergence, thus leading cloud formation and precipitation generation [BRUIJNZEEL 2004; PIELKE *et al.* 1998]. There are two primary methods for addressing the interactions between land cover change and precipitation, which are firstly time series analysis of rainfall

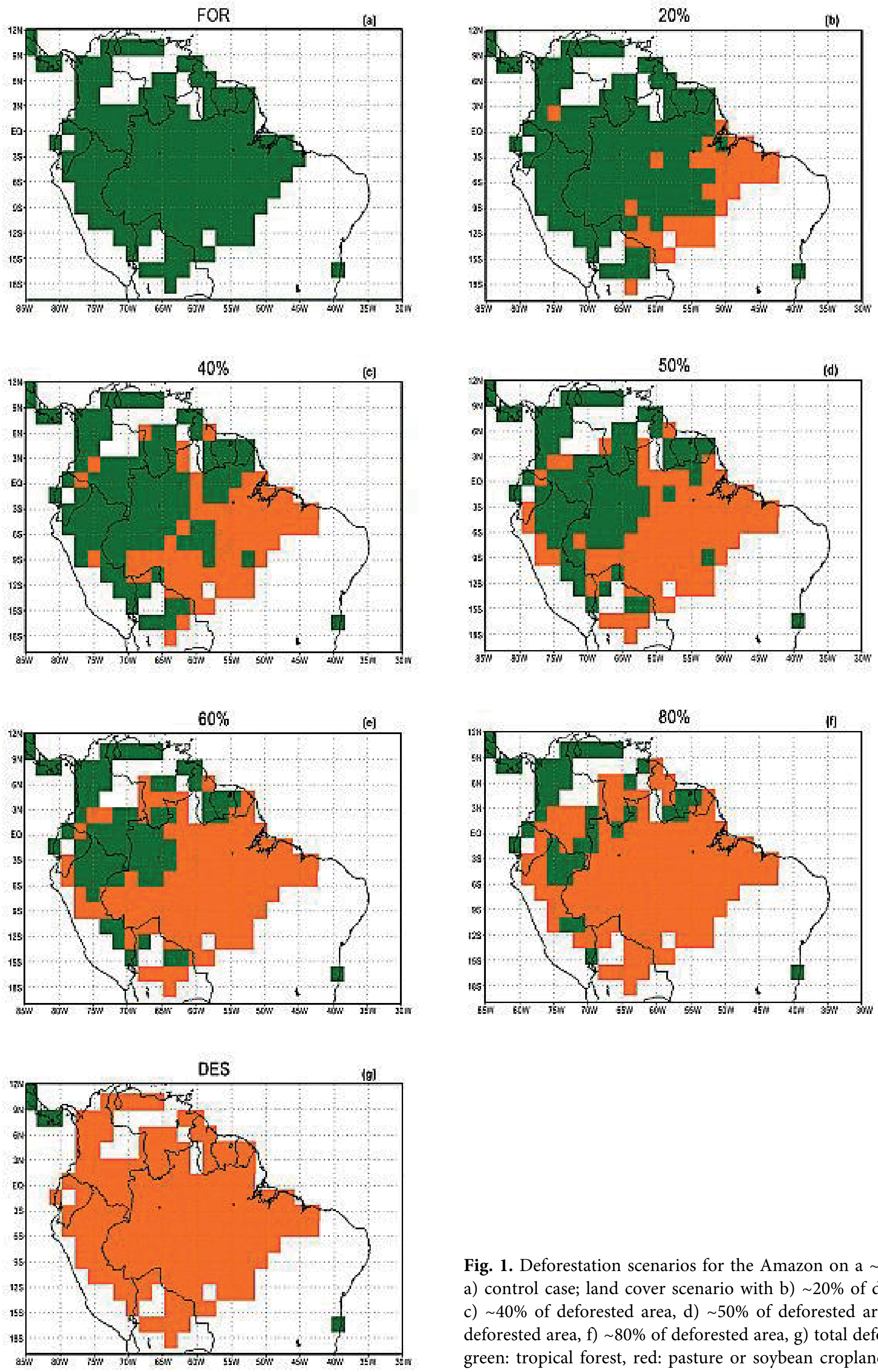

Fig. 1. Deforestation scenarios for the Amazon on a ~2° lat/lon grid: a) control case; land cover scenario with b) ~20% of deforested area, c) ~40% of deforested area, d) ~50% of deforested area, e) ~60% of deforested area, f) ~80% of deforested area, g) total deforestation case; green: tropical forest, red: pasture or soybean cropland; source: SAMPAIO *et al.* [2007]

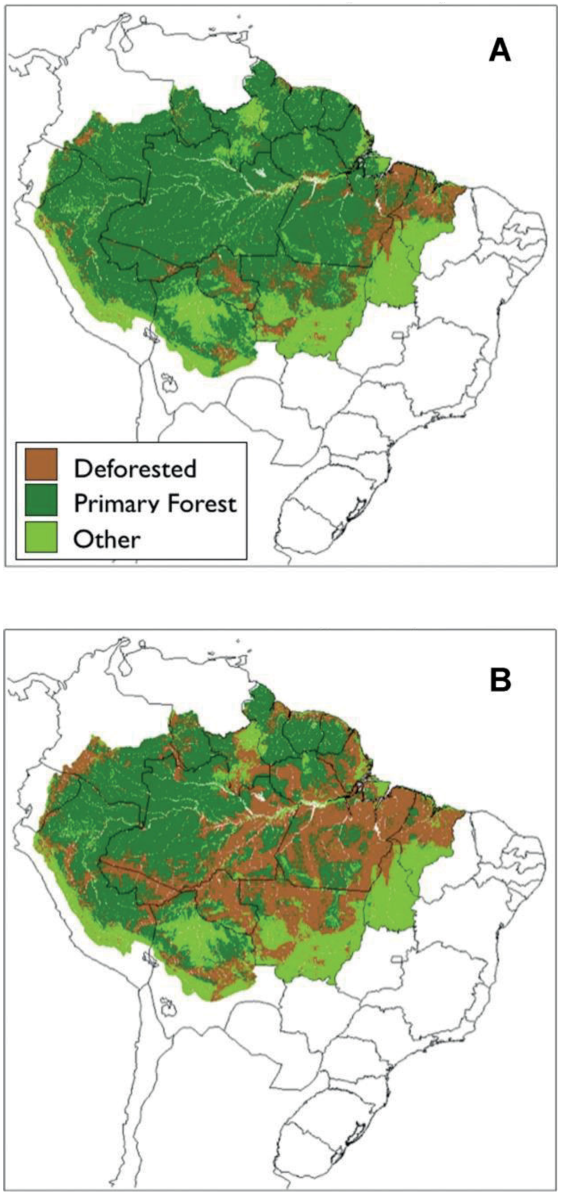

Fig. 2. SimAmazonia Land Use Projections and map of regions; the land use projections of the SimAmazonia scenario is shown for (A) the year 2002 (current land use), and (B) the year 2050 (future land use); the different land use categories of primary forest, deforested, and other are identified by dark green pixels, brown pixels, and light green pixels respectively; source: SWANN *et al.* [2015]

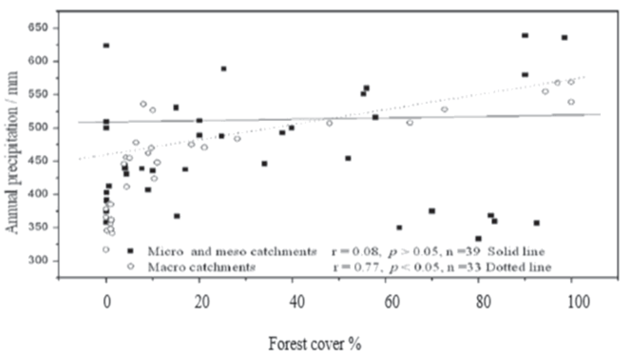

Fig. 3. The relationship between forest cover and annual precipitation in Loess Plateau; source: WANG *et al.* [2011]

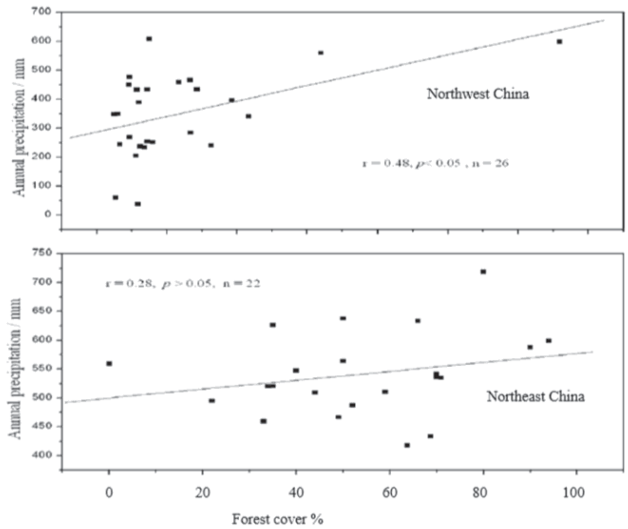

Fig. 4. The relationship between forest cover and annual precipitation; source: WANG *et al.* [2011]

records concerning changes in land cover and secondly, simulation studies of regional climates. Here, we only elaborate time series approach.

Empirical evidence of land cover impacts on temporarily changeable rainfall at large and regional scale are inabundant in literature [PIELKE 2001; PITMAN 2003], and frequently lacking in data consistency. Also, the researchers have not widely taken weather fluctuations into account at large scales, nor have they implemented statistical methods in trend analysis.

However, scientific evidence is increasing that the impact of land cover is noticeable on climate and any alterations in land cover can affect regional and global climate on time scales [PIELKE *et al.* 2007]. MEHER-HOMJI [1980] did not find a remarkable increase in total rainfall but found a negative trend in the number of rainy days within 100 years' time series analysis in Western Karnataka, India. WEBB *et al.* [2005] collected a series data of land cover and rainfall for Sao Paulo, Brazil for the period (1962–1992) and investigated trends in precipitation as affected by changes in forest cover. But they did not find a strong correlation between forest cover and total rainfall; the reason was primarily attributed to the distance of the region to the coast. Meanwhile, the authors reported a significant positive correlation between forest cover and the number of rainy days consistently emerge. The concluding remark was that there was no overall trend for a decline in precipitation over the work period. In past decades, some authors documented trends to be either insignificant or weakly significant. MOOLEY and PARTHASARATHY [1983] documented records for 306 stations from 1871 to 1980 in India; OJO [1987] collected data from 60 stations for analyzing rainfall trends between 1901 and 1985 in West Africa; TANGTHAM and SUTTHIPIBUL [1989] documented significantly negative relationship between annual rainfall and remaining forest area in Northern Thailand between 1951 and 1984 whereas a positive relationship between the number of rainy days and forest area. In recent times, a study conducted by PETCHPRAYOON *et al.* [2010] in the Yom watershed which has a large basin area of 25,180 km^2 in Northern Thailand over 15 years (1990–2006). The study area covered two flood-prone provinces, and data collected in six stations. The precipitation time series results showed no significant changes in precipitation which are similar to the results of COOK and BUCKLEY [2009] that reported insignificant trends in the monsoon season length ($p < 0.05$) in central Thailand between 1951 and 2005.

HYDROLOGICAL METHODS FOR ASSESSING LULC IMPACTS ON HYDROLOGY

Determining the impacts of forest cover changes on the hydrological response in large river watersheds explicitly require removal of the effects of climate change and any non-land cover change factors. Due to the difficulty in implementing the paired experimental watersheds method in large river basins, scientists and engineers typically use the isotopic technique, statistical methods, and hydrological modelling to evaluate the influences of forest cover changes on annual runoff [CUI *et al.* 2012]. While the various methods referred to here have their own weaknesses and strengths, and their applications are highly reliable on the aims of study and availability of high-quality data. Hydrological methods have significantly developed over the past three decades with respect to their greater complexity from rational methods to distributed models and their various usage in many applications such as land use and land cover change, flood forecasting, and rainfall-runoff modelling [SONG *et al.* 2015].

Numerous methods are thinkable to identify potential influences of land cover changes on watershed hydrology. Several studies (LIN and WEI [2008], ELFERT and BORMANN [2010], CORNELISSEN *et al.* [2013], ALADEJANA *et al.* [2018], BIRHANU *et al.* [2019], GEBREMICAEL *et al.* [2019], ZHANG *et al.* [2020]) have referred to three main methods (Tab. 1) used to quantitatively analyze the impacts of land cover changes on watershed hydrology which are experimental method (Paired catchment), multivariate statistics (time series analysis), and hydrological model method. In the paired catchment method, two catchments with similar characteristics like shapes, climate, area, vegetation cover, and soil type are selected and observed. The land cover of one of the two catchments is artificially altered (treatment), while the other properties remain the same. The second catchment remains stable (control) and is referred to as the reference catchment. The paired catchment method establishes statistical relationships for catchment outlet responses (e.g. runoff and peak flow) between two paired catchments in the period of calibration where both of the catchments are undisturbed. The standard method for revealing changes in the paired catchment is through ordinary least-square (OLS) regression [ZÉGRE *et al.* 2010]. The paired catchment method is generally applied to small catchments with good results, but the method is difficult to apply to the large-scale catchments because finding two identical large basins with the same conditions is difficult [LI *et al.* 2009]. In addition, the other limitations of this technique are the number of few samples used for model development and chronological pairing of the events. Change detection by regression requires normally distributed and independent residuals variance, and linearity between response and explanatory variables [ZÉGRE *et al.* 2010]. For example, ALILA *et al.* [2009] investigated the issues arise from chronologically pairing of events and showed how inappropriate pairing and statistical analysis resulted in erroneous estimates of changes in runoff magnitude because neither the pairing nor the tests account for changes in variance or the event frequency.

Another method is statistical analysis which has been used to study the impacts of land cover changes on watershed hydrology. Statistics is a beneficial tool for analyzing non-replicated and serially correlated data of a single watershed. This method can be an alternative approach to investigating the hydrological impacts of forest cover change or land cover disturbance in large-scale watersheds [LIN, WEI 2008]. The statistical method can be applied to analyze the changing trend in hydrologic and climatic data, while the spatial heterogeneity of the basin and the mechanisms of LULC and climate change on the water cycle cannot be determined [ZHANG *et al.* 2020]. However, this method can be performed when a good quality and long-term data on LULC and hydro-climatic variables is available [SARAIVA OKELLO *et al.* 2015].

With the development of computer programs, geographic information system (GIS) and remote sensing approach, much attention has been paid on hydrological models to detect the effects of LULC on hydrological alterations in river basins. Hydrological models can provide a framework to conceptualize and investigate the relationships between land cover changes and hydrological processes. Among these models, the application of physically based and distributed hydrological models to the study of land cover disturbance impacts on hydrology is the most utilized because such models can directly establish relationship between model parameters and land surface characteristics [LEGESSE *et al.* 2003]. However, the physical models require more parameters and greater calibration as the degree of physical representation of relevant processes in the model increases [CORNELISSEN *et al.* 2013]. In addition, the excessive complexity

Table 1. Hydrological impacts of deforestation using hydrological methods

Location	Catchment area (km^2)	Type of analysis	Type of impact (result)	Reference
Upper Gilgel Abbay	1 656	statistical	high flow index increased (29.27) low flow index decreased (0.12)	RIENTJES *et al.* [2011]
The Tocantins River	175 360	statistical	increased streamflow 24%	COSTA *et al.* [2003]
The southeast Tibetan plateau	2 500 000	physical model	increased runoff and flooding	CUI *et al.* [2009]
The Minjian River	24 000	statistical	increased water yield 38 mm·y^{-1}	CUI *et al.* [2012]
The Hunte River	2 141	physical model	increased runoff 0.04–0.84%	ELFERT and BORMANN [2010]
The Pennar River	54 970	physical model	increased runoff 256 mm	GARG *et al.* [2017]

Source: own elaboration based on literature.

of models in the form of over-parameterization makes model calibration highly challenging [UHLENBROOK *et al.* 2004]. In conclusion, to gain better model predictions, we need to evaluate and improve models using variable techniques such as parameter optimization, operational management, and uncertainty analysis.

ANNUAL STREAMFLOW CHANGES CORRESPONDING TO LAND COVER CHANGES

The integration of hydrological and anthropic components of the watersheds results in water flow, and knowledge of water flow is reflected in water availability. For that reason, attempts have been made to better understand the relationship between forest cover changes and streamflow status and to comprehend the real situation of these resources with the aim of supporting watersheds. Streamflow is imperative for surface and subsurface water resources. Nonetheless, the phenomenon of rainfall-runoff within a watershed is the result of the interaction of various factors, but the rainfall-runoff relationship is mainly driven by the interaction of climate, soils and land cover [GWATE 2015]. Increases in population, and subsequently in food security requires further removal of vegetation cover to achieve farm production and built-up settlement needs of the communities which have profoundly altered the amount and timing of river flows. As a result, the water ecosystem has dropped, and water resources have become stressed [CARLISLE *et al.* 2011]. Accordingly, it is crucial to comprehend the combination between land cover change and streamflow generation in a watershed as this impacts the water balance of the catchment.

Land use and land cover or vegetation cover can play a vital role in driving hydrological alterations in the watershed. The alterations involve changes in water requirements for irrigation and urbanization, and changes in hydrological processes of groundwater recharge, infiltration, and runoff. Furthermore, land cover change can be considered as a major concern in watershed management as it may cause increased flood events, soil erosion, and reduced recharge of the aquifer. For the concerns above, numerous studies have been carried out on the effects of land cover changes on streamflow [GEBREMICAEL *et al.* 2013; GETACHEW, MELESSE 2012; GWATE 2015; RIENTJES *et al.* 2011]. For example, conversion of forest-dominated lands to cropland between 1985 and 2011 periods in Angereb watershed in Ethiopia reduced the mean of dry flow by 46% [GETACHEW, MELESSE 2012].

It is evident that hydrological alterations due to land cover changes do not occur only in a specific region; rather they take place in different parts of the world. GWATE [2015] observed increased streamflow in Quaternary catchment in South Africa during the 2004 and 2013 periods stating that the increases in streamflow were due to the expansion of cultivated lands (92%) and the decrease in wooded land (35%) and grassland (9.8%). There is a general consensus confirms that alterations in season flow can be attributed to the changes in land cover and land uses. The increased peak flow which occurs in the wet season and declined base flow which occurs in the dry season at El Diem station of Blue Nile watershed between 1970 and 2010 were attributed to the changes made by converting the basin vegetation cover into croplands and grasslands over the large area of the watershed [GEBREMICAEL *et al.* 2013]. In addition, YAN *et al.* [2013] found that clearance of forest area to farm production and settlements in upper Du basin, China over the periods 1978 and 2007 resulted in observable changes in streamflow.

It is proved that surface runoff is higher and groundwater flow is lower in cleared lands due to the lower infiltration of rainfall into the shallow and deep aquifer. Inversely, in vegetative basins runoff is lower as a result of the greater infiltration of rainfall into the ground [GYAMFI *et al.* 2016]. Another example of this phenomenon is the research conducted by [SIRIWARDENA *et al.* 2006] in Comet River basin with a catchment area of 16,440 km^2 in Australia where the catchment was largely cleared of natural forest cover from 83% to 38% led to increasing in the runoff by approximately 40%. WEI and ZHANG [2010] carried out a study in Willow River watershed with a basin area of 2860 km^2 situated in the middle of British Columbia, Canada, for a duration over 50 years data on hydrology. The total cumulative forest clearance over the study period accounted for 31.9% of the total catchment. The results revealed that an average of 58.7 mm per annual streamflow was increased as a result of forest disturbance.

However, investigations on the impacts of land cover changes on streamflow and surface runoff have presented different and contrasting results. For example, GUZHA *et al.* [2018] conducted a review studies for 37 catchments in East Africa to assess the influence of land cover changes on surface runoff and stream flow. The investigators used three different methods in their study, namely field experiments in six catchments, modeling studies in 20 catchments, and trend analyses in 12 catchments. Although results from modeling studies and fields experiments demonstrated that forest cover loss could lead to increases in streamflow approximately 16%, the trend analyses of stream discharge indicated a lack of significant trends in streamflow regimes as a result of land cover changes. Thus, such results do not support the common findings that forest clearance results in increased annual stream flow as summarized results above. Furthermore, WILK *et al.* [2001] reported insignificant hydrological changes in the Nam Pong River Basin with an area of (12,100 km^2) in Northeast Thailand while the forest cover of the basin was reduced by 53%. The wide variability in quantities of the hydrological alterations could be attributed to the interactions between diversely site-specific factors such as basin slope, soil infiltrability, and vegetation age and type.

Precipitation event is another factor impacting on inconsistencies in annual streamflow responses as frequent intensive rainstorms in wet soil lead to high surface runoff rates and subsequently higher discharges [HAMILTON *et al.* 2008]. This indicates that rainfall intensities can mask the impacts of land cover changes on stream flow regime. Similarly, NADAL-ROMERO *et al.* [2016] concluded that the impacts of vegetation cover on peak discharges are insignificant with increasing size of the hydrological events. Those contradictory results can also be attributed to significant complexities in large scale river basins where numerous components, processes, and their interactions contribute to the direction of the research. Altitudes, topography, and geographic locations also have the potential to influence streamflow trends and buffer the role of forest cover in runoff generation in river basins. In Northern China, a study conducted by WANG *et al.* [2011] who concluded that regional variability could buffer the crucial role of vegetation cover in generating surface runoff within watersheds, and the forests located at higher altitudes with steeper slopes produce higher precipitation, lower evapotranspiration and, subsequently higher magnitude of surface runoff. Bi *et al.* [2014] discussed that spatial scale of the watershed can influence changes in hydrological variables as a result of land use/cover change, stating that large river basins tend to show relative buffering capacity which could mask the impacts of land cover changes. Guzha *et al.* [2018] found the majority of the watersheds that demonstrate insignificant trends in the hydrological variables have basin area bigger than 1000 km^2. This argument may support the conclusion drawn by Rodriguez *et al.* [2010] that the hydrological changes corresponding to land cover change were not detected at large scale watersheds compared to the clear signals were detected at small scales. The most likely explanation for the lack of signal at large scales could be attributed to the non-linear integration of the climate feedback and variety of land uses and land cover history which tends to increase in heterogeneity with increasing basin size. To summarize, land cover change effects on streamflow at large scale are difficult to verify because of the impact of other confounding factors, such as the extent of connectivity between stream networks and flow paths in basins which might impact how land cover change and land use convert to hydrological outputs [Blöschl *et al.* 2007]. Also, the lack of clear and noticeable trends in streamflow patterns as affected by land cover changes could be attributed to the impact of spatial scale.

INFLUENCE OF LAND COVER ON FLOW REGIME

FLOW REGIME CHANGES

Streamflow regime is one of the approaches that addresses the complexity of streamflow response via the process of organising rivers and streams systematically into the groups that are very similar in terms of their flow characteristics [Poff, Ward 1989]. The temporal scale of river flow spans from minutes (flash floods) to years (supra-seasonal droughts), while the spatial variability is controlled by watershed attributes such as land cover, topography, prevailing climate, soils, and geology [Piniewski 2017]. However, the natural and anthropogenic effects such as water withdrawal, dam construction, and diversions may be other factors driving the shape of the flow regimes. Hydrologically, flow regimes can be classified into two patterns, which are low river flow (streamflow droughts) and high river flow (floods). Flow regime classes can be achieved on the basis of streamflow characteristics by using hydrologic indices with five streamflow metrics: timing, duration, frequency, magnitude, and rate of changes. These metrics are used as hydrologic alterations [Piniewski 2017]. Low river flows and high river flows have adverse impacts on mankind and natural systems. For example, several extreme droughts have taken place in Poland in the last three decades, 1992, 1993, 2006, and 2008. Inversely, destructive floods occurred in 1997, 2001, and 2010 causing vast damages to urban places and dozens of fatalities in Poland [Piniewski *et al.* 2017]. Thus, understanding the effects of land use and land cover changes on river flow regimes is of critical importance for sustainable river basin management. It has globally become evident that river ecosystems have altered due to river regulation modifying the flow regimes [Kashaigili 2008]. Here, low flow and high flow regimes as two hydrological indicators are being addressed in more details.

LOW FLOW AND DRY SEASON FLOW

Low flow regime term could give different meanings to different interest groups. To many it may be regarded as the actual flows in a stream or river taking place during the dry season of the year, others could be associated with the length of time and the conditions occurring between flood events while the others may be interested in the influences of changes in the total flow regime of a stream or river on sustainable water yield or riverine ecology. International glossary of hydrology, as cited in Smakhtin [2001] defines low flow as " flow of water in a stream during prolonged dry weather". This definition does not clearly differentiate between low flows and droughts. Low flows are a seasonal phenomenon and an integral part of flow regimes of the streams and rivers. Whereas, a drought is a natural event caused by a less than normal precipitation for a prolonged period. Knowledge about the impacts of forest cover change on low flow regime is beneficial to planning water resources, sustainable watershed management, and environmental flow strategy.

In regions with seasonal rainfall, the distribution of streamflow throughout the year is often of utmost greater significance than total annual water yield [Bruijnzeel 2004]. One of the forms of resource degradation presumed to follow from land cover changes is a disturbance in stream flow regimes of river basins. There are contradictory results of the impacts of forest removal on low streamflow regime during the dry season. However, the circumstances associated with short term catchment experiments maybe notably different from the situations in the longer term. The exposure of bare soil after forest cutting to intense rainfall, the compaction of topsoil layer by machinery, and the increases in impervious surfaces such as roads and settlements, all contribute to progressively reduced rainfall infiltration opportunities in cleared basin. As a consequence, the sponge effect of the forest cover is lost. When the critical stage is reached, diminished dry season flows necessarily follow. LULC as a driving factor is reported in the literature for the decline in low flow. For example, Rientjes *et al.* [2011] evaluated the impacts of land cover change on low streamflow (Tab. 1) in Upper Gilgel Abbay catchment (1656 km^2) in Upper Blue Nile River basin and revealed that despite an increasing trend in annual rainfall, the low flow index based on the 5% exceedance declined by 18% for the period 1982–2000 and 67% for the period 2001–2005 and related this to the decrease in forest cover from 51% in 1973 to 17% of the basin in 2001. However, the authors hypothesized that land cover change as a biological factor had caused considerable change to low flow during the last four decades was consistent with the findings of [Gebremicael *et al.* 2013] for the Upper Blue Nile watershed using the integrated results of the statistical tests, SWAT model, and land use detection tool (Tab. 2).

On the other hand, despite the contribution of irrigation activities to low flow reduction, expansion of eucalyptus tree stands in the area due to the demand for the construction boom reduces the base flow (low flow) of the watershed because the roots of eucalyptus trees are well developed in the dry areas and enable the trees to uptake the water stored in the depth of the soil during the dry season; this analysis is supported by Enku *et al.* [2014]. It is assumed that land with lower vegetative cover is subject to high surface runoff amounts, low infiltration rate, and reduced groundwater recharge. The reduced infiltration rate and groundwater recharge ultimately result in lowering the water

Table 2. Mann–Kendall (MK) test results for the seasonal and annual flow at El Diem station

Season	Kendal's tau	Statistical summary (S)	*P*-value	Trend
Wet (June–September)	0.34	237	0.003	significantly increasing
Dry (October–February)	–0.37	–259	0.001	significantly decreasing
Short (March–May)	0.41	285	0.001	significantly increasing
Annual	0.25	175	0.028	significantly increasing

Explanation: P = probability.
Source: GEBREMICAEL *et al.* [2013].

table and intermittence of once-perennial streams. Based on these assumptions, BEWKET and STERK [2005] analyzed low flows at monthly and daily time steps and found that low flows declined at a rate of 1.7 mm per annum with time (1960–1999) as a result of destruction of natural vegetative covers, expansion of croplands, overgrazing and increased areas under eucalypt plantations. These findings imply that the increased area under eucalypt trees is a major contribution to increased transpiration. Thus, eucalypt plantation can drastically cause reductions in stream flow. The role of eucalypts in drying up streams during the dry season is also referred to in a study in Northern Australia by HUTLEY *et al.* [2000]. The study indicated that despite high-water use through transpiration, the eucalypt trees extracted much water from soil moisture and groundwater during the dry season; this could explain the decrease in base flow as a result of high-water use of eucalypts. However, it is said that deforestation at a regional scale may not affect the observed low flow regime [GEBREHIWOT *et al.* 2010]. LE TELLIER *et al.* [2009] could not find the relationship between forest cover and low stream flow.

Methods of forest clearance could have the possibilities to increase low river flows [JOHNSON 1998]. The small scale catchment studies, summarized by [HORNBECK *et al.* 1993], demonstrated that reduction in forest cover of 25% was necessary before any changes were observed and increases low flow regime during the growing season. Some disparity was observed in their results from different sites; this variability was attributed to different techniques of tree clear-felling; with the biggest influence following clearance in the lower altitude zones of the catchment and least when the trees were felled in strips. In contrast, forest regrowth or regeneration can reduce low stream flows through water use, evaporation, and rainfall interception. In general, mature trees have a greater consumption of water than other vegetation types. The mature trees intercept more precipitation, and their transpiration rates are greater, resulting in higher evaporation rates compared with other types of vegetation. The anticipated effect on the flow patterns would, therefore, be a general decline in flows as the forest grows. These findings are from small scale catchments and do not help draw an informative conclusion on the impacts of forest cover on low stream flows. Therefore, more approaches and recent findings from large scale watersheds are being analyzed.

Bayesian regression is an approach that could be applied to examine the hypothesis on infiltration-evapotranspiration trade-offs between the "sponge effect" and evapotranspiration demands of forest cover on dry season flows. Forest cover impacts both soil infiltration and evapotranspiration. Soil infiltration can be improved by organic matter in soils, and macropores are generated through activities of tree roots and soil fauna [BONELL *et al.* 2010]. How much of the infiltrated water reaches the groundwater to support dry season flows is a function of transpiration demands of forest cover, soil characteristics, and geology of the basin. The net effect of decrease or increase in forest cover on dry season flows is dependent on the trade-off between increases in stream flow by enhanced soil moisture recharge on the one hand and decreases in soil and groundwater storage that feeds dry season flow on the other hand due to the higher water use of forest trees compared with pasture and cultivated crops [KRISHNASWAMY *et al.* 2018].

Recently, KRISHNASWAMY *et al.* [2018] tested three hypotheses on the expected effect of forest cover loss or gain on dry season flows in the Terraba River basin with (4 774 km^2) in Costa Rica. They summarized the hypotheses in three points: (1) forests have higher evapotranspiration rates than other types of land cover such as agriculture, pasture, and grasslands, thus losses or gains in forest cover lead to losses or gains in dry season flows; in this regard, forest cover has a negative impact on dry season flow; (2) forest cover can increase infiltration into soils and recharge to groundwater that feeds low flows in dry seasons (positive effect) and this is called "sponge effect"; (3) forest cover has higher evapotranspiration which might be balanced by higher recharge effects of forests on low flows compared to other types of land cover, so losses or gains in forest cover could produce insignificant or no effect on flow (zero effect). By using the Bayesian regression models, they detected a strongly positive impact of forest cover on low stream flow, indicating an increase in dry season flow with greater forest cover for the whole Terraba watershed. The regression slope approach also predicted a gain of 3.3 mm low stream flow for an increase of 1% forest cover. Sometimes hydrological roles of forest cover in changing low stream flow magnitudes have been masked by climate variability and other hydrological factors. Therefore, scientists and researchers have developed new approaches e.g. HOU *et al.* [2018] developed a single watershed method combining the modified double mass curve (MDMC) and the time series multivariable autoregressive integrated moving average model to detach climate variability and other factors from the impact of forest cover on dry season flow changes in two large watersheds, the Zagunao watershed (2 441.77 km^2) and the Meigiang watershed (6 310.13 km^2) in China. In the Zagunao River basin, low stream flow decreased by 15.5 mm (9.7%) on average as a consequence of 15.6% forest reduction due to forest harvesting from 1976–2004. Whereas a 40% increment in forest cover resulted in a 6.3 mm·y^{-1} decrease in dry season runoff.

However, both deforestation and afforestation led to significant reductions in dry season flows over the disturbed period. Likewise, LIU *et al.* [2015] studied low flow regime (flow magnitude, frequency, duration, timing, and change rate) in Meijiang River basin with (6 983.2 km^2) which is located in the upper reach of the Lake Poyang basin in China. Their findings demonstrated that deforestation decreased the low flow magnitudes by 30.1% with 30.5 day advancing in the average timing, while reforestation increased the low flow magnitudes but not very significantly, and recovery of these changes through forest regrowth might take much longer time than expected due to severe soil erosion and resulting loss of soil infiltration capacity after deforestation. These results are beneficial to water supply and support water resource managers to manage the river basins and minimize negative hydrological effects of deforestation in the context of growing land use changes. GUO *et al.* [2008] used the Soil and Water Assessment Tool (SWAT) model to examine hydrology and streamflow responses to land use/land cover and climate changes in the Xinjiang River basin (15,535 km^2) of the Poyang Lake in China. They concluded that land cover changes might have a moderate effect on annual streamflow, which strongly impacts seasonal streamflow and changes the annual hydrograph of the watershed.

Due to the vegetation and associated seasonal divergences of its influence on evapotranspiration, increase of forest cover after conversion of agricultural lands to forest decreases wet season stream flow and increases it in the dry season, thus reducing drought severity in the dry season. In summary, deforestation at small scale watersheds leads to increase in low stream flows. In contrast, deforestation or forest loss at large scales could reduce low river flow and worsen drought severity in the dry season. Forest cover can increase infiltration into soils and helps recharge the groundwater that feeds low stream flows (sponge effect of forest cover). Also, forest cover can keep its balance between higher evapotranspiration and higher recharge effects on dry season flow (neutral effect).

HIGH FLOW REGIME AND FLOODING

The impact of forest loss and reforestation on flooding is a hotly debated issue among researchers and scientists all over the world. The linkage between forest clearance and the severity and frequency of flooding has been one of the long-standing debate, but with little evidence to go on [VAN DIJK *et al.* 2009]. Land use in the river basin is considered as a potential control on flood generation, and catchment management may, therefore, provide additional means of flood protection under defined circumstances. On the contrary, indifferent land management practices may raise flood risks under certain circumstances [BATHURST *et al.* 2017]. Flood discharge can increase due to changes in land cover, and flood peak flow may augment after logging. TARIGAN [2016] investigated forest conversion impacts on flood frequency for 23 years (1990–2013) in Batanghari River basin where covers about 10,000 km^2 in Indonesia. Results of the study showed that forest conversion into other land use types such as oil palm plantation was the reason for the increasing trend of flooding frequency in the watershed. Conversion of forest-dominated lands to cropland between 1985 and 2011 periods in Angereb watershed in Ethiopia increased the average of high flow by 39%. Further land cleaning and development will lead to dramatic change of runoff and streamflow which is dominantly observed in urban areas due to surface sealing and low infiltration rate [KOLERSKI, KALINOWSKA 2019]. However, the influence of land management on watershed response to extreme rainfall events is an area in which there are considerable scientific uncertainties and poorly conceived policy. Specifically, while forests may decrease floods for small to moderate storm events, there is increasing evidence that this impact is reduced as rainfall increases to more extreme levels [LÓPEZ-MORENO *et al.* 2006; SIKKA *et al.* 2003]. Despite this, the extent to which forest cover changes can alter downstream flood peak discharge is dependent on the proportion of catchment affected and on the location of the alterations to the basin.

The forest cover is one of the ecosystem-based adaptive measures to control flood-related risks being commonly discussed in the empirical literature. Numerous studies demonstrate that floods mostly take place on account of reduced forest area [BADOLA, HUSSAIN 2005; BHATTACHARJEE, BEHERA 2017; DAS, VINCENT 2009]. In contrast, VAN DIJK *et al.* [2009] reported that flood hazard could not be directly linked to forest clearance. In general, forest cover, however, is perceived as a bio-physical barrier against flood disaster, particularly in ecosystems such as coastal and river belt areas [OHIRA *et al.* 2012]. For example, repeated occurrences of flood in the Ganga–Brahmaputra belt in India are frequently attributed to large scale deforestation which increases the rate of sedimentation and accretion, thereby decreasing the carrying capacity of the river and thus causing frequent inundations [BHATTACHARJEE, BEHERA 2018]. A study by BRANG *et al.* [2006] stated that forests can prevent floods but cannot stop large scale floods totally. That is why researchers often disapprove of the direct links between forests and floods because the hydrological systems are so complex to find out the exact causality between land cover and natural processes. It is argued that the disturbance of natural forests and unsustainable land cover practices can result in increased runoff rate on account of decreased infiltration rates, but the degree of the impact is dependent on the scale and type of flood events [CALDER, AYLWARD 2006]. These arguments suggest that with an increase in forest cover and natural vegetation areas, there is an effectual increment in the infiltration rate, evapotranspiration and water retention capacity of catchments which result in less severity of floods.

It is found that historical land cover changes at large scale can impact volumes and flood peak discharges. For instance, a study carried out by OLANG and FÜRST [2011] in the Nyando River Basin, Western Kenya, with the area of 3550 km^2 revealed that the detected land cover changes have amplified flood runoff volumes and peak discharges within the sub-catchments. This impact was more severe within the upstream areas where higher rates of forest clearance and cropland expansion were uncontrolled. However, the relative rise in the peak discharges was noted to diminish with increasing storm amounts. This indicates that land cover changes do not have a strong influence during significant rainfall events. Although catastrophic floods have been mostly linked to forest cover changes in watersheds, TRAN *et al.* [2010] showed evidence that the overall increasing trends of catastrophic floods in the Huong watershed (2830 km^2) mainly resulted from climate variability and the developments of roads and dyke infrastructures in the river basin. In summary, recently, BHATTACHARJEE and BEHERA [2018] published a new article providing strong empirical evidence that forest cover reduces the occurrence of flood events and damages to human lives and house properties. This evidence implies forests can make floods less severe. Despite these evidences, social, demographic, and climate parameters can play a vital role in determining the extent of flood damages.

SUMMARY AND CONCLUSIONS

Hydrological studies in large-scale watersheds are limited primarily due to the lack of a commonly-accepted methodology. Paired catchment method is mainly applicable to small scale watersheds. Therefore, when the results from small scale catchments are compared with large scale river basin response to land cover change, contradictory results are produced. Numerical and physical-based hydrological models are mainly used in large-scale river basins. However, these models are generally dependent on scientific data derived from small catchment studies, and this can be problematic when it is applied to large river basins. In this paper, we provide a detailed review of the existing body of literature and empirical evidence on the hydrological responses of large-scale river watersheds to land cover changes. The review highlights the impacts of land cover changes, particularly forest clearance on precipitation, water yield, streamflow, and flow regimes. We mainly focus on long-term empirical evidence and time-series results from large-scale watersheds.

Available evidence indicates that significant decreases in precipitation occur when the deforestation in the watershed exceeds 40% of the Amazon. The precipitation alteration after forest clearance over some parts of Amazonia (eastern) is associated with an increase in albedo and reduction in evapotranspiration associated with the lower surface aerodynamics roughness, the lower leaf area, and the short rooting depth of short vegetation and crops compared to natural forests. In some parts of China (the Loess Plateau, Northwest China, and Northeast China) the findings show that there is no statistical correlation between forest cover and precipitation at the micro- and mesoscales up to 1000 km^2. However, the forest-dominated basin and precipitation relationship were consistently correlated at scales bigger than 1000 km^2. This suggests that conversion of natural forests into agricultural lands and settlement at large-scale effects cloud formation thus resulting in a decrease in precipitation over the long term. However, these conclusions cannot be applied to all the large-scale watersheds because there are some factors, such as forest type, soil characteristics, geology, morphology, and geographical location impacting the hydrological processes and water cycle in river basins. The finding of some of the observations is inconsistent with other studies because the data are derived from different scales of watersheds. These results imply that the spatial scale of the river basin plays a vital role in determining the hydrological impacts of forest cover for long-time studies.

Furthermore, the analysis implies that forest removal at the watershed and regional scale leads to an increase in high flow and flooding in wet seasons, while it leads to worsening dry season flow. However, the overall results do not support the common findings that forest cutting results in increased annual streamflow. Results from the reviewed articles demonstrated that the three common hydrological methods (paired catchments, statistical analysis, and physical models) have their own specific drawbacks. The spatial heterogeneity of the basin and the mechanisms of LULC and climate change on the water cycle cannot be determined using statistical method. Despite the fact that physical models can provide a good framework to investigate the relationships between land cover changes and hydrological processes, they require more parameters and greater calibration as the degree of physical representation of relevant processes in the model increases. To conclude, forest type is an essential factor affecting total runoff response to forest cover change in multiple spatial scales of river basins while hydrological regimes tend to be a more influential factor in large watersheds. These findings have profound implications for upscaling hydrological issues and developing more applicable methods in forest hydrology and also support useful information to guide watershed managers in the context of multiple spatial scales of watersheds. This review generally addressed the impacts of land cover changes on watershed hydrology based on scientific evidence, measured data and modeling results. Future research should focus on hydrological impacts of forest disturbance at large-scale basins using calibrated and improved physical models with taking model sensitivity and uncertainty into consideration.

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