PERSPECTIVES

Large-scale deforestation and plantation threaten the water supply for local and regional communities in Indonesia by altering streamflow conditions.

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HYDROLOGY

Deforestation, forestation, and water supply

A systematic approach helps to illuminate the complex forest-water nexus

By **Mingfang Zhang**[1] *and* **Xiaohua Wei**[2]

Forests as natural reservoirs and filters can store, release, and purify water through their interactions with hydrological processes. For humans, a clean, stable, and predictable water supply is one of the most valuable ecosystem services provided by forests. Yet, globally, forests have undergone many changes driven by human activities (logging, reforestation, afforestation, agriculture, and urbanization) and natural disturbances (wildfires and insect infestations). From 2010 to 2015, tropical forests declined by 5.5 million ha year^{-1}, whereas temperate forests expanded by 2.2 million ha year^{-1} (*1*). The effects of both deforestation and forestation (reforestation and afforestation) on water supply have generated serious concerns and debates (*2*, *3*), particularly after recent catastrophic fires in Australia and the western United States. However, hydrological consequences of forest changes are never simple, and future research and watershed management require a systematic approach that considers key contributing factors and a broad spectrum of response variables related to hydrological services.

Zhang *et al.* showed the consistent tendency of deforestation to increase annual streamflow (*4*). More than 80% of deforested watersheds had annual streamflow increases ranging from 0.4 to 599.1%, mainly owing to reduced evapotranspiration after 1.7 to 100% forest cover loss (*4*). The large variations in the magnitude of changes depend on the scale, type, and severity of forest disturbance, climate, and watershed properties (*4*, *5*). Larger-scale disturbance tends to cause greater increase in annual streamflow. Hydrological response to fire is similar to the response to logging, but the severity of the impact varies with climate, fuel accumulation, fire intensity, overstory tree mortality, and climate. Fires often cause hydrophobic soils, with reduced soil infiltration and acceleration of surface runoff and soil erosion. In a recent national assessment of the contiguous United States, forest fires had the greatest increase in annual streamflow in semiarid regions, followed by warm temperate and humid continental climate regions, with insignificant responses in the subtropical Southeast (*6*). The hydrological impact of insect infestation is likely less pronounced than those of other disturbances. Large-scale beetle outbreaks in the western United States and British Columbia, Canada, over recent decades were predicted to increase streamflow, with reduced evapotranspiration because of the death of infested trees (*5*). However, further evidence showed negligible impacts of beetle infestation on annual streamflow, owing to increased evapotranspiration of surviving trees and understory vegetation (*7*).

Forestation can either reduce annual streamflow or increase it (*4*, *8*). Zhang *et al.* (*4*) found that 60% of the forestation watersheds had annual streamflow reduced by 0.7 to 65.1% with 0.7 to 100% forest cover gain, whereas 30% of them (mostly small watersheds) had annual streamflow increased by 7 to 167.7% with 12 to 100% forest cover gain. Variations in annual streamflow response to forestation are even greater than those caused by deforestation, possibly owing to site conditions prior to forestation and tree species selected. Planting with a single fast-growing exotic species can have greater reduction in annual streamflow than with native species (*8*). Streamflow reductions after forestation are more common in semiarid and arid regions than in the humid subtropics and tropics (*4*, *5*). Large-scale reforestation programs in the semiarid Loess Plateau in China caused substantial streamflow reductions that consequently approached water resource limits (*9*).

Dry-season low flow is critical for water supply, particularly in the face of more severe droughts under climate change. Low-flow response to forest change can be positive, neutral, or negative (*5*, *10*). The variable low-flow responses are mainly attributed to low-flow generation processes, forest characteristics (age, species, and regeneration), forestry practices (retention of riparian buffers, logging methods, and silviculture), changes in soil conditions, and choice of low-flow metrics (daily or 7-day minimum flow). Nevertheless, negative low-flow response is commonly expected if soil water storage and infiltration capacities are impaired by forest disturbances (soil compaction and erosion

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from logging, and soil water repellency following severe fires), and their recovery through reforestation could take much longer, because of the difficulty in restoring damaged soils (*10*).

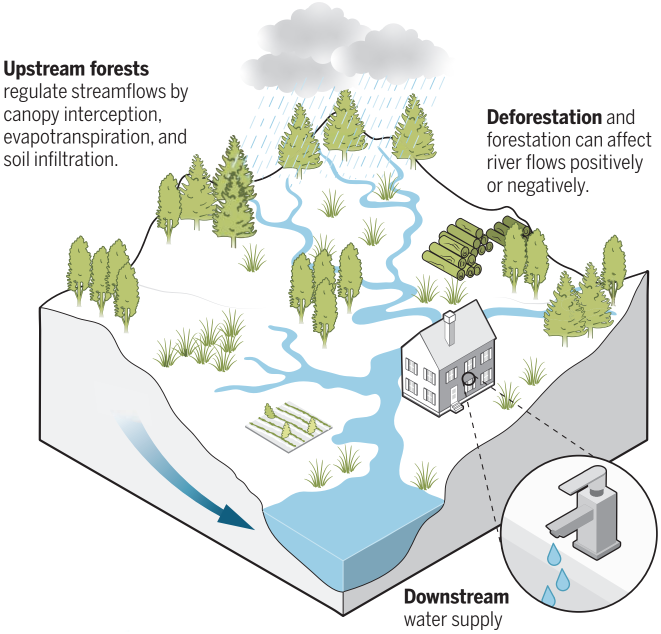
Generally, climate, watershed properties, forest characteristics, and their interactions are the major drivers for large variations in hydrological responses to forest change (*2*, *4*). Zhou *et al.* assessed global land-cover effects on annual streamflow, based on a general theoretical framework (*11*). They found that hydrological sensitivity to land-cover change was determined by watershed properties (watershed size, slope, configuration, and soil), climate (precipitation or potential evaporation), and their interactions, where land cover and watershed properties jointly indicate water retention ability. Land cover or forest change can cause greater hydrological responses in drier watersheds or those with low water retention capacity. Similarly, McDonnell *et al.* (*12*) recommended studying watershed storages and water movements in the vertical zone that includes forest canopy, soil, fresh bedrock, and the bottom of groundwater (*13*), to further reveal the mechanisms for variable hydrological response to forest change.

The feedback between forests and climate may also introduce complexity. Forests can supply atmospheric moisture through evapotranspiration and potentially increase precipitation (precipitation recycling) locally and in downwind directions. Therefore, forest change affects not only downstream river flow, but also precipitation and water supply downwind (*5*). Lawrence and Vandecar revealed variable rainfall responses to tropical deforestation across landscapes, depending on deforestation thresholds, such as reduced rainfall by large-scale deforestation and increased rainfall by small clearings (*14*). The effects of forest change on precipitation are likely related to topography, prevailing wind, and climate, because they affect moisture residence time, moisture transportation, and precipitation generation. The lack of observational evidence highlights the need for research on the feedback between climate and forest change at regional or continental scales.

Time scale is important for understanding these variations. Hydrological effects of forest change can vary with time as forests regrow. Coble *et al.* reviewed long-term responses of low flows to logging in 25 small catchments in North America (*10*). They identified dynamic

The complex influence of forests on water supply

Forests in watersheds play a critical role in regulating downstream water supply and associated ecosystem services.



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low-flow responses over three distinct time periods associated with the development of forest canopy leaf area index and corresponding evapotranspiration: consistent increase in the first 5 to 10 years, variable responses (increase, no change, or decline) during the next 10 to 20 years, and substantial decline in some (16 out of 25) watersheds multiple decades later. However, no decline in low flows was found in nine watersheds during the third period—likely dependent on similar factors previously identified for variations in low-flow response. The dynamic hydrological responses suggest that long-term studies are critical for fully capturing possible trends and variations in the effects of forest change on water supply (*5*).

The consistencies and large variations over space and time in streamflow responses to forest change call for a systematic perspective to elucidate both explanatory (factors affecting hydrological functions) and response (hydrological functions) variables in future studies (see the figure). In the systematic context, explanatory variables, including climate, forest, watershed properties, and their interactions and feedback across multiple spatial-temporal scales that jointly control streamflow responses, should all be assessed. To better clarify the response, a more complete spectrum of hydrological variables, including the magnitude, duration, timing, frequency, and variability of flows, which collectively determine river flow conditions, aquatic functions, and thus ecosystem services such as water supply, should be included in an assessment (*15*). Nonetheless, water-supply assessments often use limited hydrological variables (such as annual mean flows), which could underestimate total hydrological functions or even produce misleading conclusions resulting from different or contrasting responses of various flow variables.

A systematic assessment of the effects of deforestation and forestation on water supply requires multidisciplinary collaborations. The classic paired watershed experiment (PWE: one watershed as a control and the others as the treatment) (*12*), mainly designed to assess streamflow response to forest change, has limitations to evaluate interactions and feedback among water, forests, climate, and watershed properties. Future PWEs should systematically consider more variables and processes (flow pathways, water storage and retention, and hydrological sensitivity) with various approaches (isotopic tracing, telemetering, and modeling). With long-term in situ monitoring and growing remote-sensing data, the forest-water nexus at larger spatial scales should be explored using advanced analytical tools (machine learning, and coupled climatic-ecohydrological modeling) within a systematic context. Future assessment should also focus on watershed management tools such as payments for ecosystem services, with the inclusion of more representative water variables to support synergies or trade-offs between hydrological and other ecosystem services provided by forests in a changing environment. ■

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