

Negative Trade-offs Between Community Forest Use and Hydrological Benefits in the Forested Catchments of Nepal's Mid-hills

Authors: Badu, Manoj, Nuberg, Ian, Ghimire, Chandra Prasad, Bajracharya, Roshan Man, and Meyer, Wayne S.

Source: Mountain Research and Development, 39(3)

Published By: International Mountain Society

URL: <https://doi.org/10.1659/MRD-JOURNAL-D-18-00066.1>

BioOne Complete (complete.BioOne.org) is a full-text database of 200 subscribed and open-access titles in the biological, ecological, and environmental sciences published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Complete website, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at www.bioone.org/terms-of-use.

Usage of BioOne Complete content is strictly limited to personal, educational, and non - commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

BioOne sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.

Negative Trade-offs Between Community Forest Use and Hydrological Benefits in the Forested Catchments of Nepal's Mid-hills

Manoj Badu^{1*}, Ian Nuberg¹, Chandra Prasad Ghimire², Roshan Man Bajracharya³, and Wayne S. Meyer⁴

* Corresponding author: manoj.badu@hotmail.com

¹ School of Agriculture Food and Wine, University of Adelaide, South Australia, 5005, Australia

² AgResearch, Lincoln Research Centre, Private bag 4749, Christchurch 8140, New Zealand

³ Department of Environmental Science and Engineering, Kathmandu University, PO Box 6250, Nepal

⁴ Department of Ecology and Environmental Sciences, Faculty of Sciences, University of Adelaide, South Australia, 5005, Australia

© 2019 Badu et al. This open access article is licensed under a Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>). Please credit the authors and the full source.



Widespread community forestry practices in Nepal's mid-hills catchments involve removal of forest products—including firewood, litter, fodder, and medicinal herbs—by the local communities. Uncertainty is growing about how sustainable the management

of these catchments is and whether it can meet traditional needs and maintain ecosystem services, particularly water. As part of a broader study on the hydrological effects of community forestry practices, we measured selected soil properties, including saturated hydraulic conductivity (K_s), bulk density (BD), and soil organic carbon (SOC) across 4 depths (0–10, 10–20, 20–50 and 50–100 cm) in 3 types of community forest sites—broadleaf, pine-dominated, and mixed—in the Roshi Khola catchment of Kavre district. The same measurements were made at a minimally disturbed religious forest site in the catchment that had higher K_s values than the mixed and broadleaf sites,

signifying a lower degree of forest use-related disturbance. Likewise, SOC values for the religious forest were significantly higher ($P < 0.05$) and BD values significantly lower than the pine-dominated and mixed forest sites, particularly at shallower depths (0–50 cm). Importantly, comparison of the median K_s values (16–98 mm h^{-1}) with rainfall intensities measured at the catchment showed the less intensively used pine-dominated site to be conducive to vertical percolation with possible greater contributions to subsurface storage even during high-intensity rainfall events. These results highlight the critical role of forest use practices in landscape hydrology and have implications for the management of the forested catchments in the broader Himalayan region, particularly in relation to the negative local perceptions of the role of pine plantations on declining water resources.

Keywords: Community forest use; water; saturated hydraulic conductivity; forested catchments.

Peer-reviewed: April 2019 **Accepted:** July 2019

Introduction

During the early half of the 20th century, forest to farmland conversion and high local demand for forest products, including timber, firewood, livestock fodder, and compostable litter, caused significant loss of forest cover in Nepal's mid-hills and gave rise to the widely publicized but contested “theory of Himalayan environmental degradation” (Gilmour 1988; Ives 2004; Hofer and Messerli 2006). The alleged effects, mainly episodes of large-scale flooding and landslides (Eckholm 1976), prompted local and international initiatives to reforest the area as a remedial measure that concurrently fulfilled traditional forest needs. For example, a Nepal–Australia forestry project supported the planting of 20,000 ha of the central mid-hills during the early 1990s (Collett et al 1996), while the World Bank proposed planting at annual rates of 50,000 and 10,000 ha until 1990 and 2000, respectively (Sattaur 1987). The reforestation programs

largely used fast-growing species of pine, such as *Pinus roxburghii*, due to the species' high adaptability to the nutrient-poor soils of the mid-hills (Gilmour et al 1990). Importantly, forest development activities increased focus on community involvement, as customary forest policies systematically alienated local forest users (Acharya 2005; Springate-Baginski and Blaikie 2007) leading to the inception of Nepal's community forestry policy in the late 1970s (Cribb and AusAID 2006). At present, more than half (over 2.2 million ha) of the mid-hills catchments contain naturally grown or planted species of broadleaf and pine, more than two-thirds of which are managed by nearly 7 million local users organized as members of the Community Forest User Groups (hereafter CFUGs) (DFRS 2015).

Forestation is commonly associated with improved landscape stability and hydrological conditions through, for instance, improved soil infiltration (Buytaert et al 2007; Neary et al 2009; Archer et al 2013; Bonnesoeur et al 2019).

While the time taken for results to be apparent varies from years (Van Noordwijk et al 2003) to decades (Bonell et al 2010), the varied nature of forest management practices confounds the processes, including the ensuing hydrological regime (Farley et al 2004; Bonell and Bruijnzeel 2005; Wohl et al 2012; Julich et al 2015; Ochoa-Tocachi et al 2016; Marín et al 2018). In the lesser Himalayas, where communities rely heavily on local forests for food, fuel, and income (Breu et al 2017; Chakraborty et al 2018), forestry activities are known to affect many aspects of forest functioning. These activities commonly involve regular planting and harvesting of forest products by local communities. For instance, the persistent harvesting of forest litter and understory in southern China negatively affects the soil's structural complexity and supply of organic matter (Brown et al 1995), while cattle grazing diminished soil nutrient availability and soil hydraulic conductivity in forests in southern India (Mehta et al 2008). In the mid-hills of central Nepal, soil hydraulic conductivity was negatively affected by sustained forest use (Gilmour et al 1987; Ghimire, Bruijnzeel, Bonell et al 2014), consisting of collection of litter, firewood, fodder, and medicinal herbs that typically constitute CFUG activities in the region.

However, the likely hydrological effects of forest use are nonuniform across forested catchments because the intensity or regularity of CFUG activities is determined by varied community needs, as well as forest type and condition. For instance, pine forests are frequented less by CFUG members (oral communication, 2016, Rajendra KC.), because pine needles are not as suitable for composting or livestock fodder as broadleaf (Gautam and Edward 2001; KC et al 2015). Further, the evolving nature of forest ecosystems through successional change, for example broadleaf species integrating into pine plantations (Gilmour et al 1990), as reported from parts of the mid-hills (Gautam et al 2002; DFO Kavre 2014b), obscures the poorly understood forest–water relationships in the region. Clearer understanding of these relationships is critical given growing concerns about increased water shortages during the dry season in the mid-hills (CBS 2017; Poudel and Duex 2017) that are frequently attributed to pine plantations (Bhatta et al 2015; Sharma et al 2016). Additionally, the forested areas of the mid-hills catchments, managed mostly by local CFUGs (DFRS 2015), are vital for the local and regional water supply (Rasul 2016), which is significantly affected by the region's highly seasonal climate (~85% of the annual rainfall occurs during June–September; Merz et al 2003).

As part of a larger study to examine the hydrological effects of the community forestry practices in Nepal's mid-hills, this paper compares selected soil properties from 3 types of unequally used community forest (CF) sites—a broadleaf, a pine-dominated, and a mixed pine and broadleaf forest—with a minimally used religious mixed species forest in the central hill district of Kavre. The specific soil properties are texture, bulk density (BD), soil organic content (SOC), and saturated hydraulic conductivity (K_s). Further, the paper compares the K_s results with rainfall intensities measured at the research site to infer the possible hydrological pathways. Finally, the broad implications of the present findings for likely effects on dry season flows are discussed.

Methods

Study area

The study area was the northwestern part of Roshi Khola catchment of Kavre district, Nepal (Figure 1). The climate varies from subtropical to warm temperate with annual mean temperature of $17 \pm 0.21^\circ\text{C}$ and rainfall of 1330 ± 84 mm as shown by the 15-year (2001–2015) records of the Department of Hydrology and Meteorology of Nepal (DHM 2016). The rainfall patterns are highly seasonal, with 60–90% of the annual rainfall occurring during the monsoon period of June to September (Hannah et al 2005; Merz et al 2006). The elevation and aspect influence the microclimate such that the north-facing slopes are moister and cooler than the south-facing slopes (Gautam et al 2003). Typical of Nepal's mid-hills, the soils in the study area are weakly developed and relatively shallow (<100 cm). They are moderate to poorly drained with silt or silt-loam texture and are acidic (pH 4.0–4.3). Forests in the area encompass naturally grown or planted species of broadleaf and pine (mainly *Pinus roxburghii*), managed primarily by the CFUGs (DFRS 2015). The area under pine forest increased as a result of reforestation programs conducted primarily during the 1980s (Karki and Chalise 1995).

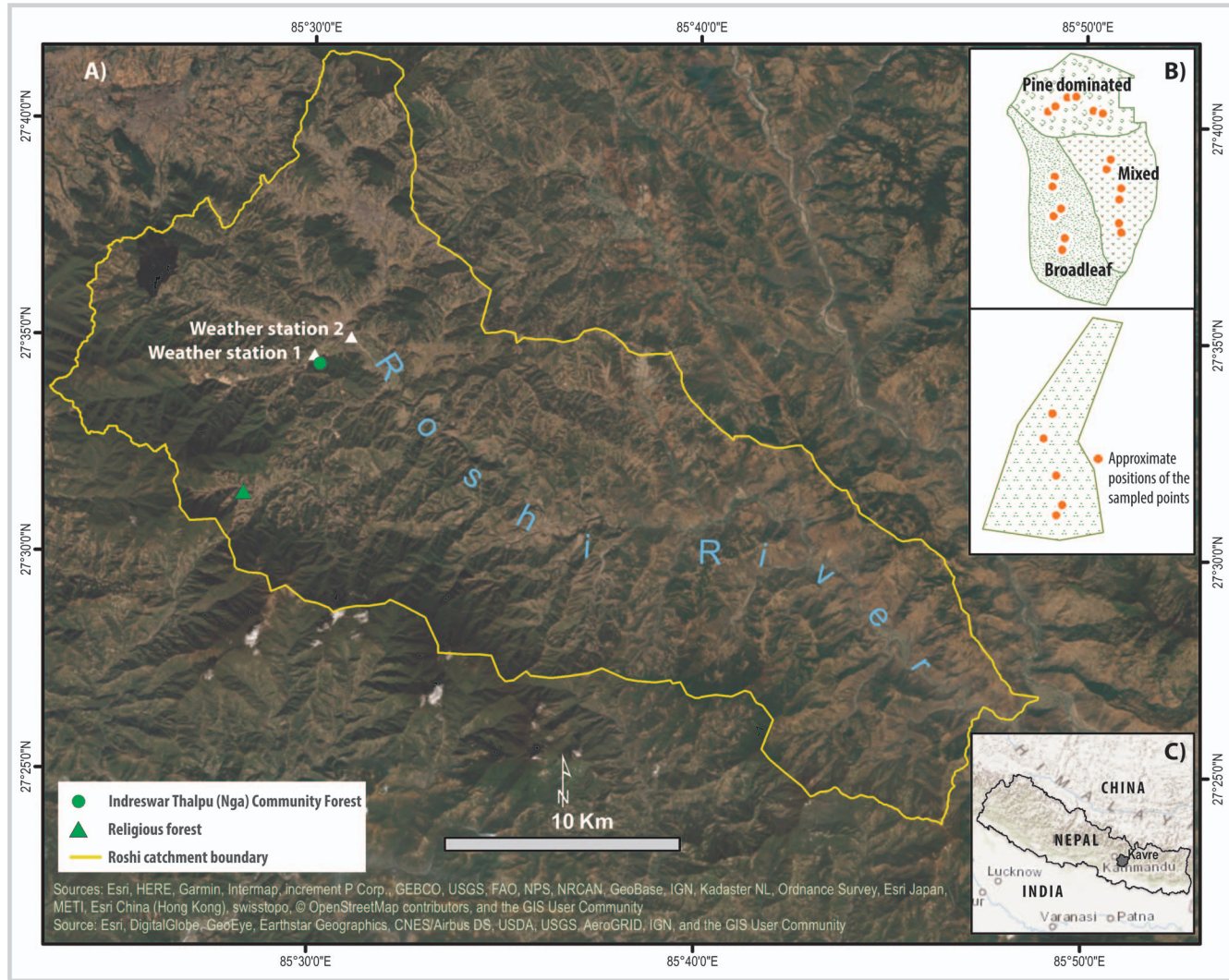
Current study sites were a forested catchment of Indreswar Thalpu (Nga) Community Forest (hereafter referred to as the experimental CF) located $27^\circ34'10''\text{N}$, $85^\circ30'15''\text{E}$ at an elevation of 1710 masl that encompassed stretches of planted pine, natural broadleaf, and mixed forests. After pervasive forest loss, the sites were revegetated naturally and through plantation during the late 1970s and early 1980s, mostly through the auspices of the Nepal–Australia forestry project. In the early 1990s, the forest management responsibilities were officially handed over to the local CFUG (*Indreswar Thalpu, Nga*) (DFO Kavre 2014a). Thus, organized CFUG activities in those sites have persisted for nearly 30 years (see Table 1).

The current Operational Plan (OP) document of the CFUG (2014/15 to 2024/25) shows that 174 households (total population 790) rely considerably on local forest products. In particular, there is a high annual demand for livestock fodder (>3200 tonnes) and compostable litter (>1600 tonnes), mainly from broadleaf species. However, the annual production levels of the forest are insufficient to meet these demands. This is mainly because of the predominantly agriculture-based lifestyle of the community as well as the significant presence of the pine species in the forest that have low use value for fodder and litter production. Nevertheless, the forest provides a surplus supply of firewood and timber that is occasionally sold in the local markets to earn additional income for the CFUG. This income contributes to funding community development activities, including the construction and maintenance of the local infrastructure, as well as employment (eg wages for the forest watcher).

A religious forest (Figure 1) with a similar forestry history and soil type was used as a control site that currently undergoes minimal community use because there is a much lower need to obtain forest products for religious purposes.

The individual sites are described in the next section based on the current OP documents, local community insights, and our field assessments, including a forest

FIGURE 1 Location of the study sites in Roshi Khola catchment of Kavre district, Nepal. (Map by M. Badu)



inventory conducted mostly during January to September 2015. An analysis of the soil profile for each of the forested sites showed the soils to be the fine to fine-loamy derivatives of weathered sandstone, schist, or phyllite of the order Inceptisol (Soil Survey Staff 1994) that transitioned to the parent material at a depth of about 50 to 60 cm. Further details about the location and topography of the sites are provided in Table 2.

Description of sites

Broadleaf forest site: This site was regenerated naturally through community initiatives that primarily involved fencing off the area to restrict traditional forest use. The dominant vegetation consists of *Schima wallichii*, *Castanopsis tribuloides*, and *Myrsine capitellata* along with shrub species, such as *Cleyera japonica*, *Eurya acuminata*, *Lyonia ovalifolia*, as well as *Rhododendron arboreum* in the higher elevations

TABLE 1 Forest management activities of the Indreswar Thalpu (Nga) CFUG, Kavre, Nepal (Based on the CFUG Operational Plan document, 2014/15–2024/2025).

| CFUG activities | Frequency | Time of year | No. of users involved |
|-----------------------------|---------------|--------------|-----------------------|
| Fodder and grass collection | 2 times/day | Oct–May | 1 user/household |
| Litter collection | 1 time/day | Oct–May | 1 user/household |
| Firewood collection | 1 time/month | Nov–May | As arranged |
| Weeding | Every 3 years | As arranged | 10–15 people |
| Thinning | Every 6 years | Nov–Feb | As arranged |
| Pruning | Every 3 years | Nov–Feb | As arranged |
| Plantation | Every 3 years | Nov–Feb | As arranged |

TABLE 2 Location of study sites.

| Site | Aspect | Area (ha) | Coordinates | Altitude (masl) | Mean slope |
|----------------|--------------------|-----------|--------------------------|-----------------|------------|
| Broadleaf | North | 1.2 | 27°34'18"N 85°30'17"E | 1615 | 22° |
| Pine dominated | South | 0.8 | 27°34'27"N 85°30'13"E | 1550 | 18° |
| Mixed | South to southwest | 0.9 | 27°34'21"N 85°30'17"E | 1585 | 19° |
| Religious | West to northwest | 1.5 | 27°31'03"N 85°28'42"E | 1955 | 21° |

(Figure 2A). This site undergoes high disturbance due to persistent community use, as the abundance of relatively low-lying (mean height ~9 m) broadleaf vegetation is collected for firewood, fodder, and litter (Figure 2E). There is minimal presence of ground cover on the site except in the less accessible, steeper sections that occasionally have a thin distribution of common grass species.

Pine-dominated forest site: This site is dominated by *P. roxburghii*, which was planted mostly during the late 1970s to early 1980s. However, due to the proximity to the broadleaf site, the broadleaf species appear randomly along with occasional patches of *Nephrolepis* fern as ground cover (Figure 2B). The low species diversity and dominance of pine species on the site has lower value for local users because the pine needles are less suitable as livestock fodder or compostable litter than broadleaf vegetation. Occasional signs of trampling are seen as some local residents visit the site for leisure and, seasonally, to collect wild berries and mushrooms. This level of forest-use intensity entails low to moderate disturbance on the site.

Mixed forest site: This site borders both the broadleaf and the pine-dominated site (Figure 2C). The broadleaf species, including *S. wallichii* and *C. tribuloides*, are mixed with *P. roxburghii*, although broadleaf species dominate the lower elevations closer to the broadleaf site. While local CFUG members use the site consistently, it also experiences disturbance due to occasional visits for leisure by commuters along the road on its northern boundary (Figure 2F). The road is unsealed and supports vehicles, mostly during the dry season (October–May). Minor signs of erosion are seen on the site.

Religious forest: The dominant vegetation in this site is a mix of planted and naturally propagated *Pinus wallichiana*, *Quercus semecarpifolia*, *P. roxburghii*, and *Alnus nepalensis* (Figure 2D). There is some regeneration and shrub species, including *Taxus wallichiana*, *E. acuminata*, and *R. arboreum*, along with the ground cover of common grass species in steeper sections. Based on the current OP document (2014–2024), the age of the vegetation varies from 5 to 30 years. Although this site is part of the historically degraded national forest, the local community has used the forest for religious purpose since the mid-1980s, until the government formally handed over management duties to the Mukteswar Mahadev religious committee in 2014. Current forest management activities include tree planting, restricted access, and occasional removal of forest products for religious events.

Soil sampling and analysis

Multiple field visits and meetings with the local forest users were held to obtain an in-depth understanding of the forested sites. Samples were collected during March to mid-April 2015 from 6 (5 for the religious forest) representative points located approximately 20–30 m apart in each site along an approximate “S” shape (Figure 1B). As applied in other parts of the mid-hills, the sampling strategy ensured that the sampling sites were not clustered and were distributed evenly (Shrestha et al 2007). The sampling equipment (Eijkelkamp Agrisearch Equipment, the Netherlands) comprised chromium-plated stainless steel rings (100 cm³) fitted to an Edelman auger. This was used to draw minimally disturbed core samples from 4 depths (0–10, 10–20, 20–50, and 50–100 cm) at each of the representative points, resulting in a total of 92 samples. Similar soil-depth categories have been used by other studies in the mid-hills (Gilmour et al 1987; Ghimire et al 2013, Ghimire, Bruijnzeel, Bonell et al 2014), and core samples from similar numbers of representative locations have been used to describe the soil hydrological properties globally, including in Brazil (Lozano-Baez et al 2018), the UK (Archer et al 2016), and Switzerland (Amrein et al 2005). Importantly, obtaining representative measures of K_s is difficult because it is naturally highly variable (Zimmermann et al 2006) and is affected by the methods of measurement (Paige and Hillel 1993; Reynolds et al 2000; Hangen and Vieten 2018; Zhang et al 2019). As such, our sample size may not be sufficiently large to account for such variations, so the K_s data presented here need careful interpretation.

The samples were drawn from the midrange of each depth, except for the deepest layer (50–100 cm), where the depth to the parent material affected the sampling decision. The samples were analyzed at the laboratory facilities of the Kathmandu University, located approximately 5 km from the experimental CF. Texture was determined by the soil hydrometer method (Gee and Bauder 1986), BD by the core method (Blake and Hartge 1986), SOC by the dry combustion method (Nelson and Sommers 1982), and pH using a glass calomel electrode probe in a soil water ratio of 1:1 (McLean 1982).

Saturated hydraulic conductivity (K_s) was determined using the constant head method based on the Darcy equation given as

$$K_s = VL/[At(H_2 - H_1)],$$

where V = volume of water flowing through the soil sample, L = sample length, A = cross-sectional area of the sample, t = time taken, and $H_2 - H_1$ = hydraulic head difference.

FIGURE 2 (A) Broadleaf forest; (B) pine-dominated forest; (C) mixed forest; (D) religious forest; (E) litter from the broadleaf forest site piled up at the catchment for composting; (F) unsealed road on the northern boundary of the mixed forest site. (Photos B, D, and F taken by M. Badu; C and E by B. Mijar; and A by R. Bhandari)



The K_s measurements and apparatus design are based on procedures described by Klute and Dirksen (1986: 694–696). The apparatus comprised a rack to hold 4 core samples that incorporated a constant head maintained by a common water supply. Water was siphoned individually to the soil

cores, and the percolated volume was recorded every 10 minutes until 3 constant measurements were obtained. The core method used here is relatively simple, cost-effective, and reliable, particularly in complex landscapes (Ilek and Kucza 2014) such as these.

Rainfall intensity

The rainfall data used to infer the dominant hillslope hydrological pathways were recorded at a nearby location (about 270 m from the experimental CF; Figure 1A, Weather station 1) during the respective monsoon periods of 2015 and 2016. Rainfall was recorded using a tipping-bucket rain gauge (Onset Computer Corporation, USA) at 30-minute intervals.

A rainfall event was categorized as an event that measured a minimum of 5 mm in total and occurred after a dry period of at least 3 hours from the preceding event (Negishi et al 2006). For each event, the maximum 30-minute ($I_{30\max}$) and 60-minute ($I_{60\max}$) rainfall intensities (expressed as equivalent hourly rainfall intensities) were determined by computing the maximum rainfall over the corresponding periods (Ghimire et al 2013).

Data analysis

A nonparametric Kruskal–Wallis test (Kruskal and Wallis 1952) for nonnormal data was used in R (version 3.4.0) to statistically compare the results of the selected soil properties (BD, SOC, and K_s) of the various forest types. Dunn's multiple comparison test (Dunn 1964) with Bonferroni correction was further used to compare the results across 4 depths. A difference was considered significant when $P < 0.05$.

The K_s values obtained were used to infer the likely hydrological pathways with respect to rainfall intensities based on the daily rainfall data collected as described. In doing so, median surface and subsurface K_s values for each forest type were compared with the selected percentiles of maximum rainfall intensities (eg over 30 minutes, $I_{30\max}$) to estimate the rainfall at the soil surface (Gilmour et al 1987; Bonell et al 2010; Ghimire et al 2013). This is important because the K_s distribution and rainfall intensities strongly influence the hydrological pathways in areas with concentrated rainfall such as these (Zimmermann et al 2006; Germer et al 2010).

Results and discussion

BD and SOC measurements as influenced by the intensity of forest use

The BD measurements, as expected, generally increased with depth for all sites (Figure 3D). In particular, median values for the mixed forest site were significantly higher than those of the religious forest at the 3 upper depths ($P < 0.007$, 0.01, and 0.003 at 0–10, 10–20, and 20–50 cm, respectively). While site attributes could account for this difference, the higher values for the mixed forest suggests increased foot traffic–related compaction that occurs due to the site's proximity to the road (Figure 2F). Although the contribution of increased foot traffic is difficult to categorize here, BD as a measure of compaction increases with increased frequency and intensity of forest management activities (Osman 2013), including thinning (Tarpey et al 2008) and harvesting (Whitford and Mellican 2011). Thus, the generally higher median values for the broadleaf site compared with the religious forest could reflect the degree of community use.

The median values of SOC (Figure 3C) ranged from approximately 2% to 8%. The maximum, 11%, was obtained from the religious forest and the minimum, 1%, for the pine-dominated site. As expected, SOC decreased with depth. The

values for the religious forest were significantly higher than those for the pine-dominated site at all corresponding depths, suggesting the reduced contribution of pine needles to SOC compared with that of accumulated litter in the religious forest. The SOC levels for the pine-dominated site are consistent with those in other parts of the mid-hills (Shrestha and Singh 2008; Aryal et al 2013), including China (Yang et al 2010) and India (Sharma et al 2011).

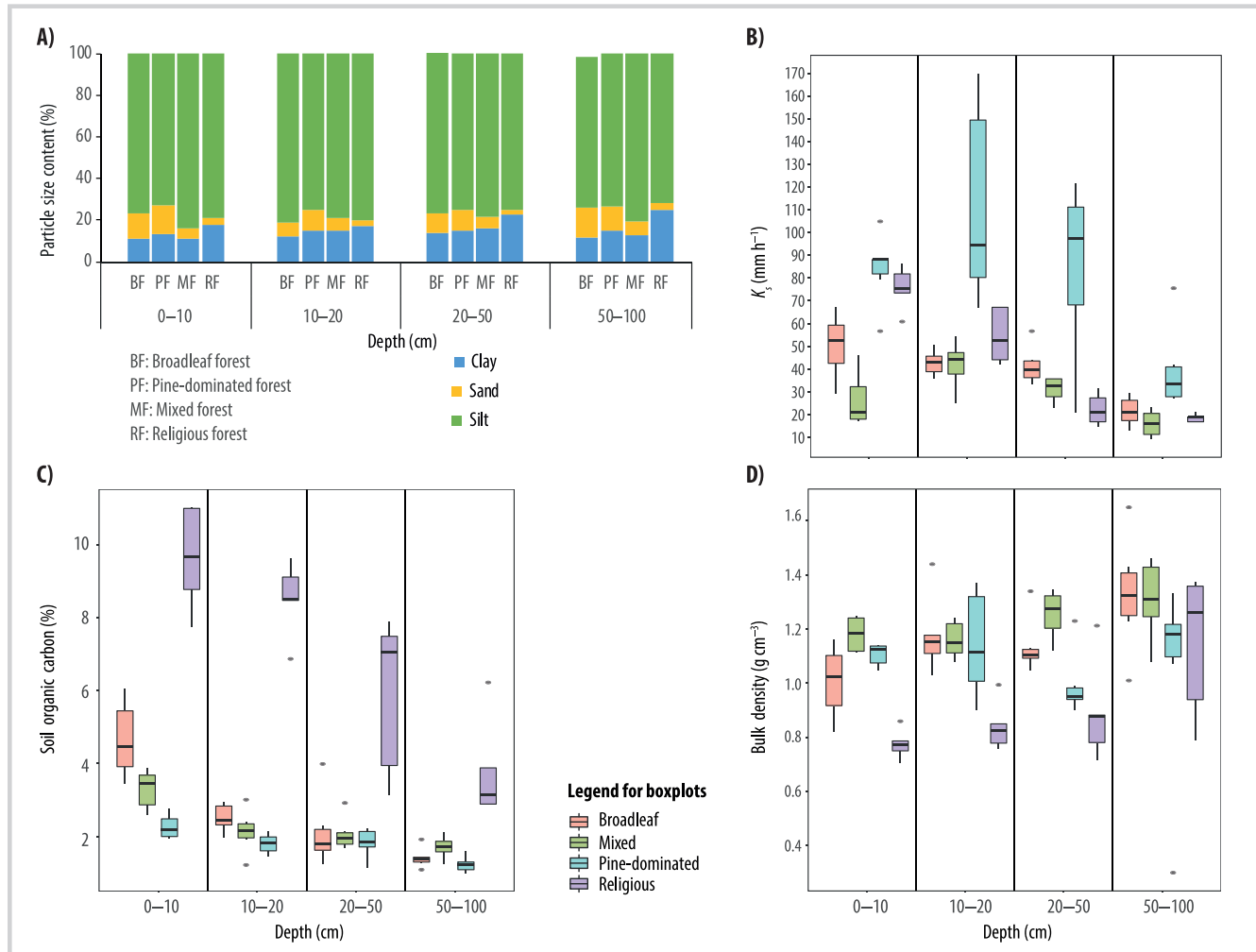
In Nepal's mid-hills, inherent factors affecting the SOC levels include forest type, climate, and topography (Bajracharya and Sherchan 2009). These are further affected by community forestry practices, including removal of biomass. The higher SOC levels for the religious forest compared with other sites indicate reduced removal of litter, fodder, or firewood, allowing higher biomass accumulation and decomposition. Similar effects, such as increased SOC levels and associated nutrient availability due to prolonged length of litter retention, have been reported in other parts of the mid-hills (Schmidt et al 1993) and globally, including parts of South and North America. In these cases, the persistent removal of aboveground organic matter reduced soil carbon (Hofstede et al 2002; Powers et al 2005). Conversely, the retention of harvesting residue conserved organic matter and improved site quality and productivity in south Australia (Hopmans and Elms 2009) and Spain (Merino et al 2004).

K_s measurements and inferred hillslope hydrological pathways

The median K_s values generally remained higher for the pine-dominated and religious forest (in the shallower depths), likely indicating the lower degree of anthropogenic disturbance related to forest use in these sites (Ziegler et al 2004; Zimmermann et al 2006). The median values ranged from approximately 16–98 mm h⁻¹ with maximum for the pine-dominated and minimum for the mixed forest sites (Figure 3B). While the values were generally lower for more intensively used sites, that is, the broadleaf and mixed forests, the consistently higher median values for the pine-dominated site were significant at 3 depths ($P < 0.001$, 0.004, and 0.003 at 0–10, 10–20, and 50–100 cm, respectively) compared with the mixed forest site. Similar results showing an inverse relationship between K_s and disturbance have been reported in other tropical landscapes (Zwartendijk et al 2017) and in parts of the mid-hills, using in situ methods comprising a constant head well permeameter combined with ring infiltrometers (Gilmour et al 1987) and disc permeameter (Ghimire, Bruijnzeel, Bonell et al 2014). The mid-hills studies showed that forestation improved soil infiltration, particularly in the less-disturbed natural forests. This is believed to improve hydrological outcomes in tropical landscapes (Ilstedt et al 2007) through reduced compaction and increased macroporosity due, for instance, to increased SOC levels (Lal 1988; Neary et al 2009). Notably, however, the mixed and broadleaf forest sites of the present study had lower K_s values, despite the higher SOC levels, compared with the pine-dominated site (Table 3). This underlines the critical role of anthropogenic disturbance on soil hydraulic conductivity, as has been found in other parts of the lesser Himalayas (Bonell et al 2010).

As Figure 3B shows, the median K_s values did not vary significantly among sites at the deepest layer (50–100 cm) but varied widely at the shallower depths (0–50 cm). This is

FIGURE 3 (A) Particle size distribution; (B) K_s ; (C) SOC; and (D) BD at various depths at each of the study sites.



probably a function of the vegetation cover and forest use rather than inherent site qualities, such as soil type. Interestingly, a comprehensive analysis of the global database on these relationships (Jarvis et al 2013) reported that soil texture has only a weak effect on soil hydraulic conductivity, particularly at shallower depths (<30 cm), compared with SOC, BD, and land use. Thus, due to those variations, as well as the presence of an impeding layer, the shallower depths largely govern hydrological pathways causing water to pond or flow laterally, depending on rainfall intensity (Figure 4A). For instance, overland flow or ponding is probable in the mixed forest site with maximum 30-minute ($I_{30\max}$) or 60-minute ($I_{60\max}$) rainfall intensities of 47.8 mm h^{-1} and 34.6 mm h^{-1} , respectively. The intensities were derived from a total of 103 rainfall events recorded during the monsoon periods of 2015 and 2016 that highlight the significant contribution of monsoonal rainfall to the annual totals (Figure 4B). Specifically, the monsoonal totals were 874 mm (97% of the June–December rainfall) in 2015 and 1030.9 mm (82% of the annual rainfall) in 2016. These values are comparable to the long-term measurements of 944 mm (76% of the annual totals) recorded close to the present study area (Weather station 2, Figure 1A). The frequency and distribution of the maximum 30-minute ($I_{30\max}$) and 60-minute ($I_{60\max}$) rainfall intensities are presented in Figure 4C.

However, the observed patterns at the mixed forest site are unlikely to be the dominant flow path because the median values of $I_{30\max}$ (11.2 mm h^{-1}) and $I_{60\max}$ (7.6 mm h^{-1}) suggest vertical percolation with overland flow or ponding probable only beyond the 80% percentile (21.8 mm h^{-1}) of $I_{30\max}$. In fact, percolation to varying depths occurs at all other sites, even under the maximum of $I_{30\max}$, until ponding or lateral flow occurs (Figure 4A), with the pine-dominated site allowing percolation to the deepest layer (20–50 cm).

Even though higher rainfall intensities for shorter intervals, for example a maximum hourly equivalent of 88.8 mm h^{-1} to 130 mm h^{-1} for 5-minute intervals, have been used to infer the hydrological pathways in other parts of the mid-hills (Gilmour et al 1987; Ghimire et al 2013; Ghimire, Bruijnzeel, Bonell et al 2014), studies have recognized such rainfall patterns to be less dominant in the region.

Hydrological implications of the sustained community forestry practices

Forest-use practices strongly influence the hydrological outcomes of many tropical and subtropical landscapes (Ilstedt et al 2007), which often support the traditional lifestyle of many local communities. In Nepal's mid-hills, the

TABLE 3 Descriptive statistics of the soil parameters for the study sites: broadleaf forest (BF), pine-dominated forest (PF), mixed forest (MF), and religious forest (RF).

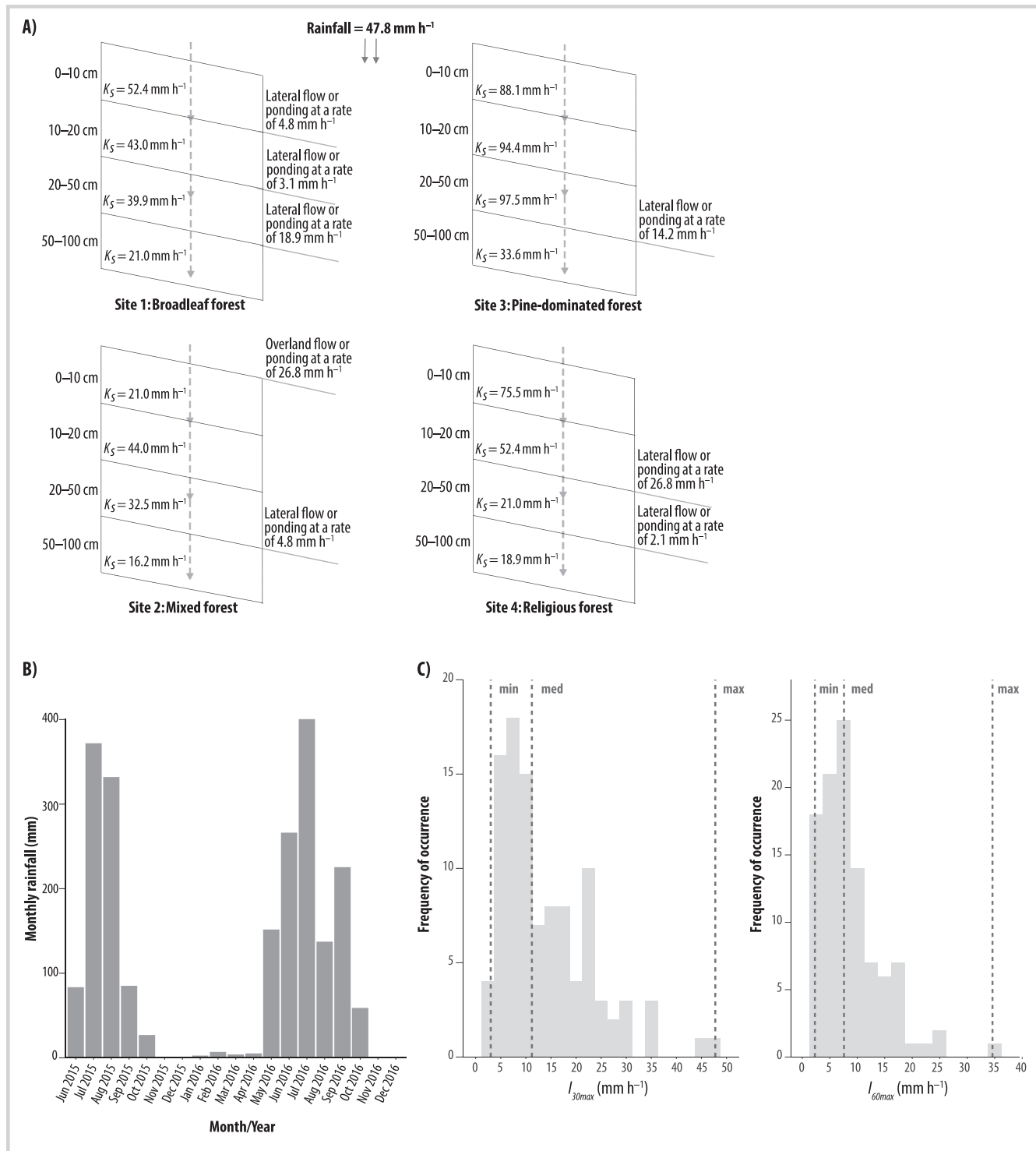
| Depth (cm) | K_s (mm h ⁻¹) | | | | SOC (%) | | | | BD (g cm ⁻³) | | | |
|---------------|-----------------------------|-----|----|----|---------|-----|-----|------|--------------------------|------|------|------|
| | BF | PF | MF | RF | BF | PF | MF | RF | BF | PF | MF | RF |
| 0–10 | | | | | | | | | | | | |
| Mean | 50 | 84 | 26 | 76 | 4.7 | 2.3 | 3.3 | 9.6 | 1.01 | 1.11 | 1.18 | 0.78 |
| Median | 52 | 88 | 21 | 76 | 4.5 | 2.2 | 3.5 | 9.7 | 1.03 | 1.13 | 1.18 | 0.77 |
| SD | 14 | 16 | 12 | 10 | 1.0 | 0.3 | 0.5 | 1.4 | 0.13 | 0.04 | 0.07 | 0.06 |
| Minimum | 29 | 57 | 17 | 61 | 3.5 | 1.9 | 2.6 | 7.7 | 0.82 | 1.05 | 1.11 | 0.71 |
| Maximum | 67 | 105 | 46 | 86 | 6.1 | 2.8 | 3.9 | 11.0 | 1.16 | 1.14 | 1.25 | 0.86 |
| 10–20 | | | | | | | | | | | | |
| Mean | 43 | 112 | 42 | 55 | 2.5 | 1.8 | 2.1 | 8.5 | 1.18 | 1.14 | 1.16 | 0.84 |
| Median | 43 | 94 | 44 | 52 | 2.4 | 1.8 | 2.2 | 8.5 | 1.16 | 1.12 | 1.15 | 0.82 |
| SD | 5 | 45 | 10 | 12 | 0.4 | 0.3 | 0.6 | 1.0 | 0.14 | 0.2 | 0.07 | 0.09 |
| Minimum | 36 | 67 | 25 | 42 | 2.0 | 1.5 | 1.2 | 6.9 | 1.03 | 0.9 | 1.08 | 0.76 |
| Maximum | 50 | 170 | 55 | 67 | 3.0 | 2.1 | 3.0 | 9.6 | 1.44 | 1.37 | 1.24 | 0.99 |
| 20–50 | | | | | | | | | | | | |
| Mean | 42 | 85 | 31 | 22 | 2.1 | 1.8 | 2.1 | 5.9 | 1.14 | 0.99 | 1.26 | 0.89 |
| Median | 40 | 98 | 33 | 21 | 1.8 | 1.8 | 2.0 | 7.1 | 1.11 | 0.95 | 1.28 | 0.88 |
| SD | 8 | 38 | 5 | 7 | 1.0 | 0.4 | 0.4 | 2.2 | 0.1 | 0.12 | 0.09 | 0.19 |
| Minimum | 34 | 21 | 23 | 15 | 1.3 | 1.2 | 1.7 | 3.1 | 1.05 | 0.9 | 1.12 | 0.72 |
| Maximum | 57 | 122 | 36 | 31 | 4.0 | 2.2 | 2.9 | 7.9 | 1.34 | 1.23 | 1.35 | 1.21 |
| 50–100 | | | | | | | | | | | | |
| Mean | 21 | 40 | 16 | 18 | 1.4 | 1.2 | 1.7 | 3.8 | 1.33 | 1.05 | 1.31 | 1.14 |
| Median | 21 | 34 | 16 | 19 | 1.4 | 1.2 | 1.7 | 3.2 | 1.33 | 1.18 | 1.31 | 1.26 |
| SD | 6 | 18 | 6 | 2 | 0.3 | 0.2 | 0.3 | 1.4 | 0.21 | 0.38 | 0.15 | 0.26 |
| Minimum | 13 | 27 | 9 | 17 | 1.1 | 1.0 | 1.3 | 2.9 | 1.01 | 0.3 | 1.08 | 0.79 |
| Maximum | 29 | 76 | 23 | 21 | 1.9 | 1.6 | 2.1 | 6.2 | 1.65 | 1.33 | 1.46 | 1.37 |

forest fodder and litter are mixed with animal dung, which constitutes the primary source of soil enrichment (Pilbeam et al 2005; Giri and Katzensteiner 2013), including improvement of N, P and K levels (Balla et al 2014). While all forest types of the mid-hills (national, private, or community forests) supply these products, community forests alone contribute more than 50% of the litter supplied (Adhikari et al 2007).

Yet, the hydrological effects of the sustained removal of these forest products are uncertain, even though the resulting reductions in soil microbial activity (Ding Ming et al 1992) and SOC levels are known to reduce rainfall infiltration (Franzluebbers 2002). Further, the corresponding increase in compaction, resulting from higher foot traffic and trampling, exacerbates the situation because it impedes soil hydraulic conductivity (Startsev and McNabb 2000). The lower K_s values of the broadleaf forest site are indicative of this effect as it undergoes higher foot traffic due to the greater use value of the forest products, while the mixed forest site has higher foot traffic due to its

proximity to the road and has correspondingly low K_s values. This could hamper the replenishment of soil and groundwater reserves, contributing to reduced dry-season flows in the area, even though water use by vegetation is an important consideration in evaluating these effects (Ghimire, Bruijnzeel, Lubczynski et al 2014; Ghimire, Lubczynski et al 2014). Indeed, removal of litter and woody debris has been found to cause increased soil loss and runoff (Hartanto et al 2003), while the compaction related to forest use accelerates erosion, shallow landslides (Sidle et al 2006), and floods (Alaoui et al 2018). Moreover, a recent study (Upadhyay et al 2018) showed that community forestry practices induce higher sediment loss, than that lost from agricultural land in Nepal's mid-hills catchments. Such a situation confounds reported land use-related social and environmental consequences in the region (Gardner and Gerrard 2003; Jaquet et al 2016) and is ironic because much of the forest in the mid-hills was established to curb sediment loss.

FIGURE 4 (A) Potential hydrological pathways for the various study sites after a 30-minute rainfall intensity of 47.8 mm h^{-1} ; (B) monthly rainfall distribution during the study period; (C) frequency distribution of maximum 30-minute (left) and 60-minute (right) rainfall intensities recorded at the study sites in the Roshi Khola catchment of Kavre, Nepal.



Conclusion

Increased forestation is widely believed to improve hydrological conditions, particularly in tropical and subtropical environments. However, land-use history and prevalent management regimes, such as community forestry practices, might have a greater effect on forest–water relationships, as shown by the results of this study.

Specifically, broadleaf and mixed forest sites showed higher compaction (BD) and lower hydraulic conductivities (K_s) than the minimally used religious forest, which is likely the result of the higher foot traffic and increased trampling associated with greater use of the sites by CFUG members. The K_s values of the broadleaf and mixed forest sites were lower, despite their higher SOC values, than the pine-dominated site, even though higher levels of SOC improve

soil infiltration of forested sites. With growing debate about the role of pine plantations on reduced dry season streamflows in parts of the mid-hills of Nepal, this preliminary study suggests that a more nuanced understanding of the impact of community forestry on catchment hydrology is needed. It also highlights the need for increased research, particularly in view of the prevailing community forestry practices in the broader mid-hills region.

ACKNOWLEDGMENTS

We are grateful to the members of the Indreswar Thalpu CFUG and the Mukteswar Mahadev religious committee for their help in our work; we received invaluable support to conduct our field activities as well as background information about the local landscape. We thank the people of Malpi and Dhungkharka community for their support, especially Bharat Mijar, Hari KC, Balan Mahat, and Prem Timilsina for the logistic help during the fieldwork. We thank the District Forest Office of Kavre for the valuable information about the community forestry practices in the research area and the overall support of our project. We thank the anonymous reviewers for the constructive comments on the paper.

REFERENCES

- Acharya K.** 2005. Private, collective, and centralized institutional arrangements for managing forest "commons" in Nepal. *Mountain Research and Development* 25(3):269–277.
- Adhikari B, Williams F, Lovett J.** 2007. Local benefits from community forests in the middle hills of Nepal. *Forest Policy and Economics* 9(5):464–478.
- Alaoui A, Rogger M, Peth S, Blöschl G.** 2018. Does soil compaction increase floods? A review. *Journal of Hydrology* 557:631–642. <https://doi.org/10.1016/j.jhydrol.2017.12.052>.
- Amrein D, Rusterholz H-P, Baur B.** 2005. Disturbance of suburban Fagus forests by recreational activities: Effects on soil characteristics, above-ground vegetation and seed bank. *Applied Vegetation Science* 8(2):175–182.
- Archer NAL, Bonell M, Coles N, MacDonald AM, Auton CA, Stevenson R.** 2013. Soil characteristics and landcover relationships on soil hydraulic conductivity at a hillslope scale: A view towards local food management. *Journal of Hydrology* 497:208–222. <https://doi.org/10.1016/j.jhydrol.2013.05.043>.
- Archer NAL, Otten W, Schmidt S, Bengough AG, Shah N, Bonell M.** 2016. Rainfall infiltration and soil hydrological characteristics below ancient forest, planted forest and grassland in a temperate northern climate. *Ecohydrology* 9(4):585–600.
- Aryal S, Bhattarai DR, Devkota RP.** 2013. Comparison of carbon stocks between mixed and pine-dominated forest stands within the Gwalinidaha community forest in Lalitpur district, Nepal. *Small-scale Forestry* 12(4):659–666.
- Bajracharya R, Sherchan D.** 2009. Fertility status and dynamics of soils in the Nepal Himalaya: A review and analysis. In: Lucero D, Boggis J, editors. *Soil Fertility*. Hauppauge, NY: Nova Science Publishers, pp 111–135.
- Balla M, Tiwari K, Kafle G, Gautam S, Thapa S, Basnet B.** 2014. Farmers' dependency on forests for nutrients transfer to farmlands in mid-hills and high mountain regions in Nepal (case studies in Hemja, Kaski, Lete and Kunjo, Mustang district). *International Journal of Biodiversity and Conservation* 6(3):222–229.
- Bhatta LD, van Oort BEH, Stork NE, Baral H.** 2015. Ecosystem services and livelihoods in a changing climate: Understanding local adaptations in the Upper Koshi, Nepal. *International Journal of Biodiversity Science, Ecosystem Services & Management* 11(2):145–155.
- Blake G, Hartge K.** 1986. Bulk density. In: Klute A, editor. *Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods*. 2nd edition. Madison, WI: American Society of Agronomy, Soil Science Society of America, pp 363–375.
- Bonell M, Bruijnzeel L, editors.** 2005. *Forest, Water and People in the Humid Tropics Past, Present and Future Hydrological Research for Integrated Land and Water Management*. (International Hydrology Series). Cambridge, United Kingdom: Cambridge University Press. doi:10.1017/CB09780511535666.
- Bonell M, Purandara BK, Venkatesh B, Krishnaswamy J, Acharya HAK, Singh UV, Jayakumar R, Chappell N.** 2010. The impact of forest use and reforestation on soil hydraulic conductivity in the Western Ghats of India: Implications for surface and sub-surface hydrology. *Journal of Hydrology* 391(1):47–62.
- Bonnesoeur V, Locatelli B, Guariguata MR, Ochoa-Tocachi BF, Vanacker V, Mao Z, Stokes A, Mathez-Stiefel S-L.** 2019. Impacts of forests and reforestation on hydrological services in the Andes: A systematic review. *Forest Ecology and Management* 433:569–584.
- Breu T, Molden D, von Dach SW, Zimmermann AB, Mathez-Stiefel S-L.** 2017. Focus issue: Mountain forests and the SDGs. *Mountain Research and Development* 37(3):245–245.
- Brown S, Lenart M, Mo J, Kong G.** 1995. Structure and organic matter dynamics of a human-impacted pine forest in a mab reserve of subtropical China. *Biotropica* 27(3):276–289.
- Buytaert W, Iniguez V, Bièvre BD.** 2007. The effects of afforestation and cultivation on water yield in the Andean páramo. *Forest Ecology and Management* 251(1):22–30.
- CBS [Central Bureau of Statistics].** 2017. *National Climate Change Impact Survey 2016: A Statistical Report*. Kathmandu, Nepal: Central Bureau of Statistics.
- Chakraborty A, Joshi PK, Sachdeva K.** 2018. Capturing forest dependency in the central Himalayan region: Variations between oak (*Quercus* spp.) and pine (*Pinus* spp.) dominated forest landscapes. *Ambio* 47:504–522.
- Collett G, Chhetri R, Jackson WJ, Shepherd KR.** 1996. *Nepal Australia Community Forestry Project: Socio-economic Impact Study*. Technical Note: Nepal Australia Community Forestry Project No.1/96. Canberra, ACT, Australia: ANUTECH Pty Ltd.
- Cribb J, AusAID [Australian Agency of International Development]** 2006. *Recovering Shangri La: The Partnership in Community Forestry Between Nepal and Australia 1966-2005*. Canberra, Australia: AusAID.
- DFO [District Forest Office] Kavre.** 2014a. *Community Forest Operational Plan of the Indreswar Thalpu (Nga) Community Forest User Group, Fiscal Year 2014/15–2024/25*. Kavre, Nepal: District Forest Office, Kavre.
- DFO [District Forest Office] Kavre.** 2014b. *Monitoring and Evaluation Report of the Community Forest Development Program: Fiscal Year 2013/14* [in Nepali]. Kavre, Nepal: District Forest Office, Kavre.
- DFRS [Department of Forest Research and Survey].** 2015. *Middle Mountains Forests of Nepal*. Kathmandu, Nepal: FRA [Forest Resource Assessment] Nepal, DFRS.
- DHM [Department of Hydrology and Meteorology].** 2016. Precipitation and temperature records of Dhulikhel station, Kavre district. Unpublished data. Available from corresponding author of this article.
- Ding Ming M, Yi Wei M, Liao Lan Y, Martens R, Insam H.** 1992. Effect of afforestation on microbial biomass and activity in soils of tropical China. *Soil Biology and Biochemistry* 24(9):865–872.
- Dunn OJ.** 1964. Multiple comparisons using rank sums. *Technometrics* 6(3):241–252.
- Eckholm E.** 1976. *Losing Ground: Environmental Stress and World Food Prospects*. New York, NY: Norton.
- Farley KA, Kelly EF, Hofstede RGM.** 2004. Soil organic carbon and water retention after conversion of grasslands to pine plantations in the Ecuadorian Andes. *Ecosystems* 7(7):729–739.
- Franzuebbers AJ.** 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. *Soil and Tillage Research* 66(2):197–205.
- Gardner RAM, Gerrard AJ.** 2003. Runoff and soil erosion on cultivated rainfed terraces in the Middle Hills of Nepal. *Applied Geography* 23(1):23–45.
- Gautam A, Edward W.** 2001. Species diversity and forest structure of pine plantations in the middle hills of Nepal. *Banko Janakari* 11(2):13–21.
- Gautam A, Webb E, Eiumnoh A.** 2002. Gis assessment of land use/land cover changes associated with community forestry implementation in the middle hills of Nepal. *Mountain Research and Development* 22(1):63–69.
- Gautam A, Webb E, Shivakoti G, Zoebiech M.** 2003. Landuse dynamics and landuse change patterns in a mountain watershed in Nepal. *Agriculture, Ecosystems and Environment* 99:83–96.
- Gee G, Bauder J.** 1986. Particle-size analysis. In: Klute A, editor. *Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods*. 2nd edition. Madison, WI: American Society of Agronomy, Soil Science Society of America, pp 363–375.
- Germer S, Neill C, Krusche A, Eisenbeer H.** 2010. Influence of land-use change on near-surface hydrological processes: Undisturbed forest to pasture. *Journal of Hydrology* 380(3):473–480.
- Ghimire C, Bruijnzeel L, Bonell M, Coles N, Lubczynski M, Gilmour D.** 2014. The effects of sustained forest use on hillslope soil hydraulic conductivity in the middle mountains of central Nepal. *Ecohydrology* 7(2):478–495.
- Ghimire CP, Bonell M, Bruijnzeel LA, Coles NA, Lubczynski MW.** 2013. Reforesting severely degraded grassland in the lesser Himalaya of Nepal: Effects on soil hydraulic conductivity and overland flow production. *Journal of Geophysical Research: Earth Surface* 118(4):2528–2545.
- Ghimire CP, Bruijnzeel LA, Lubczynski MW, Bonell M.** 2014. Negative trade-off between changes in vegetation water use and infiltration recovery after reforesting degraded pasture land in the Nepalese lesser Himalaya. *Hydrology and Earth System Sciences* 18(12):4933–4949.
- Ghimire CP, Lubczynski MW, Bruijnzeel LA, Chavarro-Rincón D.** 2014. Transpiration and canopy conductance of two contrasting forest types in the lesser Himalaya of central Nepal. *Agricultural and Forest Meteorology* 197(Supplement C):76–90.
- Gilmour D, King G, Applegate G, Mohns B.** 1990. Silviculture of plantation forest in central Nepal to maximise community benefits. *Forest Ecology and Management* 32(2):173–186.
- Gilmour D.** 1988. Not seeing the trees for the forest: A re-appraisal of the deforestation crisis in two hill districts of Nepal. *Mountain Research and Development* 8(4):343–350.
- Gilmour DA, Bonell M, Cassells DS.** 1987. The effects of forestation on soil hydraulic properties in the middle hills of Nepal: A preliminary assessment. *Mountain Research and Development* 7(3):239–249.
- Giri A, Katzensteiner K.** 2013. Carbon and nitrogen flow in the traditional land use system of the Himalaya region, Nepal. *Mountain Research and Development* 33(4):381–390.
- Hangen E, Vieten F.** 2018. A comparison of five different techniques to determine hydraulic conductivity of a riparian soil in north Bavaria, Germany. *Pedosphere* 28(3):443–450.
- Hannah DM, Kansakar SR, Gerrard AJ, Rees G.** 2005. Flow regimes of Himalayan rivers of Nepal: Nature and spatial patterns. *Journal of Hydrology* 308(1–4):18–32.

- Hartanto H, Prabhu R, Widayat ASE, Asdak C.** 2003. Factors affecting runoff and soil erosion: Plot-level soil loss monitoring for assessing sustainability of forest management. *Forest Ecology and Management* 180(1):361–374.
- Hofer T, Messerli B.** 2006. *Floods in Bangladesh : History, Dynamics and Rethinking the Role of the Himalayas*. Tokyo, Japan: United Nations University Press.
- Hofstede R, Groenendijk J, Coppus R, Fehse J, Sevink J.** 2002. Impact of pine plantations on soils and vegetation in the Ecuadorian high Andes. *Mountain Research and Development* 22(2):159–167.
- Hopmans P, Elms SR.** 2009. Changes in total carbon and nutrients in soil profiles and accumulation in biomass after a 30-year rotation of *Pinus radiata* on podzolized sands: Impacts of intensive harvesting on soil resources. *Forest Ecology and Management* 258(10):2183–2193.
- Ilek A, Kucza J.** 2014. A laboratory method to determine the hydraulic conductivity of mountain forest soils using undisturbed soil samples. *Journal of Hydrology* 519:1649–1659.
- Istedt U, Malmer A, Verbeeten E, Muryarso D.** 2007. The effect of afforestation on water infiltration in the tropics: A systematic review and meta-analysis. *Forest Ecology and Management* 251(1):45–51.
- Ives J.** 2004. *Himalayan Perceptions : Environmental Change and the Well-Being of Mountain Peoples*. London, United Kingdom: Routledge.
- Jaquet S, Shrestha G, Kohler T, Schwilch G.** 2016. The effects of migration on livelihoods, land management, and vulnerability to natural disasters in the harpan watershed in western Nepal. *Mountain Research and Development* 36(4):494–505.
- Jarvis N, Koestel J, Messing I, Moeys J, Lindahl A.** 2013. Influence of soil, land use and climatic factors on the hydraulic conductivity of soil. *Hydrology and Earth System Sciences* 17(12):5185–5195.
- Julich S, Mwangi M, Feger KH.** 2015. Forest hydrology. In: Köhl M., Pancel L, editors. *Tropical Forestry Handbook*. Berlin, Germany: Springer.
- Karki S, Chalise S.** 1995. Local forest user groups and rehabilitation of degraded forest lands. In: Schreier H, Shah PB, Brown S, editors. *Challenges in Mountain Resources Management in Nepal: Processes, Trends, and Dynamics in Middle Mountain Watershed*. Kathmandu, Nepal: ICIMOD [International Centre for Integrated Mountain Development], IDRC [International Development Research Centre], pp 88–95.
- KC B, Stainback GA, Rayens K.** 2015. Comparison of three major forest types of mid hills region of Nepal for conservation and local benefits. *Small-scale Forestry* 14(4):479–491.
- Klute A, Dirksen C.** 1986. Hydraulic conductivity and diffusivity: Laboratory methods. In: Klute A, editor. *Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods*. 2nd edition. Madison, WI: American Society of Agronomy, Soil Science Society of America, pp 687–734.
- Kruskal W, Wallis W.** 1952. Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association* 47(260):583–621.
- Lal R.** 1988. *Tropical Ecology and Physical Edaphology*. Chichester, United Kingdom: John Wiley & Sons.
- Lozano-Baez S, Cooper M, Ferraz S, Ribeiro Rodrigues R, Pirastru M, Di Prima S.** 2018. Previous land use affects the recovery of soil hydraulic properties after forest restoration. *Water* 10(4):453.
- Marin F, Dahik CQ, Mosquera GM, Feyen J, Cisneros P, Crespo P.** 2018. Changes in soil hydro-physical properties and SOM due to pine afforestation and grazing in Andean environments cannot be generalized. *Forests* 10(1):17.
- McLean E.** 1982. Soil pH and lime requirement. In: Page AL, Miller, RH, Keeney DR, editors. *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*. 2nd edition. Madison, WI: American Society of Agronomy, Soil Science Society of America, pp 199–224.
- Mehta VK, Sullivan PJ, Walter MT, Krishnaswamy J, DeGloria SD.** 2008. Impacts of disturbance on soil properties in a dry tropical forest in southern India. *Ecohydrology* 1(2):161–175.
- Merino An, Fernández-López A, Solla-Gullón F, Edeso JM.** 2004. Soil changes and tree growth in intensively managed *Pinus radiata* in northern Spain. *Forest Ecology and Management* 196(2):393–404.
- Merz J, Dangol PM, Dhakal MP, Dongol BS, Nakarmi G, Weingartner R.** 2006. Rainfall-runoff events in a middle mountain catchment of Nepal. *Journal of Hydrology* 331(3):446–458.
- Merz J, Nakarmi G, Shrestha SK, Dahal BM, Dangol PM, Dhakal MP, Dongol BS, Sharma S, Shah PB, Weingartner R.** 2003. Water: A scarce resource in rural watersheds of Nepal's middle mountains. *Mountain Research and Development* 23(1):41–49.
- Neary DG, Ice GG, Jackson CR.** 2009. Linkages between forest soils and water quality and quantity. *Forest Ecology and Management* 258(10):2269–2281.
- Negishi JN, Sidle RC, Noguchi S, Nik AR, Stanforth R.** 2006. Ecological roles of roadside fern (*Dicranopteris curranii*) on logging road recovery in peninsular Malaysia: Preliminary results. *Forest Ecology and Management* 224(1):176–186.
- Nelson D, Sommers L.** 1982. Total carbon, organic carbon and organic matter. In: Page AL, Miller RH, Keeney DR, editors. *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*. 2nd edition. Madison, WI: American Society of Agronomy, Soil Science Society of America, pp 539–579.
- Ochoa-Tocachi BF, Buytaert W, De Bièvre B, Céleri R, Crespo P, Villacís M, Llerena CA, Acosta L, Villazón M, Gualipa M, et al.** 2016. Impacts of land use on the hydrological response of tropical Andean catchments. *Hydrological Processes* 30(22):4074–4089.
- Osman KT.** 2013. Forest disturbances and soil degradation. In: *Forest Soils: Properties and Management*. Cham, Switzerland: Springer, pp 157–171.
- Paige G, Hillel D.** 1993. Comparison of three methods for assessing soil hydraulic properties. *Soil Science* 155(3):175–189.
- Pilbeam CJ, Mathema SB, Gregory PJ, Shakya PB.** 2005. Soil fertility management in the mid-hills of Nepal: Practices and perceptions. *Agriculture and Human Values* 22(2):243–258.
- Poudel DD, Duex TW.** 2017. Vanishing springs in Nepalese mountains: Assessment of water sources, farmers' perceptions, and climate change adaptation. *Mountain Research and Development* 37(1):35–46.
- Powers RF, Andrew Scott D, Sanchez FG, Voldseth RA, Page-Dumroese D, Elioff JD, Stone DM.** 2005. The North American long-term soil productivity experiment: Findings from the first decade of research. *Forest Ecology and Management* 220(1):31–50.
- Rasul G.** 2016. Managing the food, water, and energy nexus for achieving the Sustainable Development Goals in South Asia. *Environmental Development* 18:14–25.
- Reynolds WD, Bowman BT, Brunke RR, Drury CF, Tan CS.** 2000. Comparison of tension infiltrometer, pressure infiltrometer, and soil core estimates of saturated hydraulic conductivity. *Soil Science Society of America Journal* 64:478–484.
- Sattaur O.** 1987. Trees for the people. *New Scientist* 115(1577):58–62.
- Schmidt M, Schreier H, Shah P.** 1993. Factors affecting the nutrient status of forest sites in a mountain watershed in Nepal. *Journal of Soil Science* 44(3):417–425.
- Sharma B, Nepal S, Gyawali D, Pokharel G, Wahid S, Mukherji A, Acharya S, Shrestha A.** 2016. *Springs, Storage Towers, and Water Conservation in the Midhills of Nepal*. Kathmandu, Nepal: ICIMOD [International Centre for Integrated Mountain Development].
- Sharma CM, Gairola S, Baduni NP, Ghildiyal SK, Suyal S.** 2011. Variation in carbon stocks on different slope aspects in seven major forest types of temperate region of Garhwal Himalaya, India. *Journal of Biosciences* 36(4):701–708.
- Shrestha B, Singh B, Sitaula B, Lal R, Bajracharya R.** 2007. Soil aggregate and particle associated organic carbon under different land uses in Nepal. *Soil Science Society of America Journal* 71(4):1194–1203.
- Shrestha BM, Singh BR.** 2008. Soil and vegetation carbon pools in a mountainous watershed of Nepal. *Nutrient Cycling in Agroecosystems* 81(2):179–191.
- Sidle RC, Ziegler AD, Negishi JN, Nik AR, Siew R, Turkelboom F.** 2006. Erosion processes in steep terrain: Truths, myths, and uncertainties related to forest management in Southeast Asia. *Forest Ecology and Management* 224(1):199–225.
- Soil Survey Staff SS.** 1994. *Keys to Soil Taxonomy*. Washington, DC: US Department of Agriculture.
- Springate-Baginski O, Blaikie P, editors.** 2007. *Forests, People and Power: Political Ecology of Reform in South Asia*. London, United Kingdom: Earthscan.
- Startsev AD, McNabb DH.** 2000. Effects of skidding on forest soil infiltration in west-central Alberta. *Canadian Journal of Soil Science* 80(4):617–624.
- Tarpey RA, Jurgensen MF, Palik BJ, Kolka RK.** 2008. The long-term effects of silvicultural thinning and partial cutting on soil compaction in red pine (*Pinus resinosa* Ait.) and northern hardwood stands in the northern great lakes region of the United States. *Canadian Journal of Soil Science* 88(5):849–857.
- Upadhyay HR, Smith HG, Griepentrog M, Bodé S, Bajracharya RM, Blake W, Cornelis W, Boeckx P.** 2018. Community managed forests dominate the catchment sediment cascade in the mid-hills of Nepal: A compound-specific stable isotope analysis. *Science of the Total Environment* 637–638:306–317.
- Van Noordwijk M, Farida A, Verbist B, Tomich T.** 2003. Agroforestry and watershed functions of tropical land use mosaics. In: Van Noordwijk M, editor. *2nd Asia Pacific Training Workshop on Ecohydrology Proceedings: Integrating Ecohydrology and Phytotechnology into Workplans of Government, Private and Multinational Companies, Cibinong, West Java, Indonesia, 21–26 July 2003*. <http://old.worldagroforestry.org/downloads/Publications/PDFs/PP03061.pdf>; accessed on 27 January 2020.
- Whitford KR, Mellican AE.** 2011. Intensity, extent and persistence of soil disturbance caused by timber harvesting in jarrah (*Eucalyptus marginata*) forest on FORESTCHECK monitoring sites. *Australian Forestry* 74(4):266–275.
- Wohl E, Barros A, Brunzell N, Chappell NA, Coe M, Giambelluca T, Goldsmith S, Harmon R, Hendrickx JMH, Juvik J, et al.** 2012. The hydrology of the humid tropics. *Nature Climate Change* 2:655–662.
- Yang K, Zhu J, Zhang M, Yan Q, Sun OJ.** 2010. Soil microbial biomass carbon and nitrogen in forest ecosystems of Northeast China: A comparison between natural secondary forest and larch plantation. *Journal of Plant Ecology* 3(3):175–182.
- Zhang J, Bruijnzeel LA, Quiñones CM, Tripoli R, Asio VB, van Meerveld HJ.** 2019. Soil physical characteristics of a degraded tropical grassland and a 'reforest': Implications for runoff generation. *Geoderma* 333:163–177.
- Ziegler AD, Giambelluca TW, Tran LT, Vana TT, Nullet MA, Fox J, Vien TD, Pinthong J, Maxwell JF, Evett S.** 2004. Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: Evidence of accelerated overland flow generation. *Journal of Hydrology* 287(1):124–146.
- Zimmermann B, Eisenbecker H, De Moraes JM.** 2006. The influence of land-use changes on soil hydraulic properties: Implications for runoff generation. *Forest Ecology and Management* 222(1):29–38.
- Zwartendijk BW, van Meerveld HJ, Ghimire CP, Bruijnzeel LA, Ravelona M, Jones JPG.** 2017. Rebuilding soil hydrological functioning after swidden agriculture in eastern Madagascar. *Agriculture, Ecosystems & Environment* 239:101–111.