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Infiltration on mountain slopes: a comparison of three environments

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Abstract

Water is well established as a major driver of the geomorphic change that eventually reduces mountains to lower relief landscapes. Nonetheless, within the altitudinal limits of continuous vegetation in humid climates, water is also an essential factor in slope stability. In this paper, we present results from field experiments to determine infiltration rates at forested sites in the Andes Mountains (Ecuador), the southern Appalachian Mountains (USA), and the Luquillo Mountains (Puerto Rico). Using a portable rainfall simulator–infiltrometer (all three areas), and a single ring infiltrometer (Andes), we determined infiltration rates, even on steep slopes. Based on these results, we examine the spatial variability of infiltration, the relationship of rainfall runoff and infiltration to landscape position, the influence of vegetation on infiltration rates on slopes, and the implications of this research for better understanding erosional processes and landscape change.

Infiltration rates ranged from 6 to 206 mm/h on lower slopes of the Andes, 16 to 117 mm/h in the southern Appalachians, and 0 to 106 mm/h in the Luquillo Mountains. These rates exceed those of most natural rain events, confirming that surface runoff is rare in montane forests with deep soil/regolith mantles. On well-drained forested slopes and ridges, apparent steady-state infiltration may be controlled by the near-surface downslope movement of infiltrated water rather than by characteristics of the full vertical soil profile. With only two exceptions, the local variability of infiltration rates at the scale of 10^{0} m overpowered other expected spatial relationships between infiltration, vegetation type, slope position, and soil factors. One exception was the significant difference between infiltration rates on alluvial versus upland soils in the Andean study area. The other exception was the significant difference between infiltration rates in topographic coves compared to other slope positions in the tabonuco forest of one watershed in the Luquillo Mountains. Our research provides additional evidence of the ability of forests and forest soils to preserve geomorphic features from denudation by surface erosion, documents the importance of subsurface flow in mountain forests, and supports the need for caution in extrapolating infiltration rates.

Keywords: Geomorphology; Infiltration; Denudation; Andes; Southern Appalachians

1. Introduction

Although the high peaks tend to capture our attention, they comprise only a small portion of mountain terrain. As three-dimensional features extending thousands of meters in height and thousands of kilometers in length, mountains encompass a variety of microenvironments. A major challenge to geomorphologists is to identify the ranges of values and scales of spatial variability of geomorphic processes and their controls on mountain slopes. In this

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paper, we focus on forested mountain slopes in humid temperate to tropical regions. Soils on these slopes comprise the "skin" of the mountains, and their biophysical characteristics exert important control on rates of degradational processes. We seek to better understand the role of water as an agent of erosion, and the characteristics of slope surfaces that partition rainwater into surface and subsurface flow paths.

Precipitation and gravity are well established as major drivers of the geomorphic change that eventually reduces mountains to lower relief landscapes. Rainfall and water from snowmelt promote denudation in three ways:

(i) Weathering: moisture serves as a reactant and a transport agent in weathering processes in which slopes lose strength and rocks become fragmented.
(ii) Erosion: the erosive energy of water striking and flowing across the land surface entrains and transports particles downslope.
(iii) Mass wasting: water entering pore spaces in slope surface materials contributes to the potential for mass movement by adding mass, increasing pore water pressure, and reducing strength.

At the same time, however, especially in non-arid mountain regions and within the altitudinal limits of continuous vegetation, water promotes slope stability:

(i) Soil: water contributes to the development of soil, which stores moisture and promotes low energy, non-erosive, subsurface water movement.
(ii) Vegetation: plentiful moisture supports the growth of continuous and luxuriant vegetation, which, in turn, alters the moisture regime of slopes through interception and evapotranspiration and alters soil biophysical characteristics to better retain and drain moisture.

The role of water as a driver of erosion has received considerable scientific study. The more complex and less direct roles of water in promoting slope stability through its effects on vegetation have received less attention than they merit in geomorphology. Understanding the balance that determines whether water has a stabilizing or destabilizing effect on mountain slopes at micro- to subregional scales requires better understanding the role of the solum in integrating climatic, biologic, and geological components of the hillslope environmental system. Recent attention to mountain regions recognizes that the world's largest rivers originate in mountains and that at least half of the world's population depends on water flowing in or from mountains (Price, 1999). The importance of mountains as sources of fresh water further underscores the need for better understanding the water cycle, including infiltration processes, on mountain slopes.

In this paper, we present results from field experiments of rainfall runoff and infiltration in the Andes Mountains (Ecuador), the southern Appalachian Mountains (USA), and the Luquillo Mountains (Puerto Rico). We hypothesized that mid-scale (hillslope to km) differences in geologic, edaphic, topographic, and biotic conditions control the spatial variability of infiltration rates in forested mountain regions; and we ex-

Table 1
Study area locations and characteristics

Study area	Jatun Sacha, Andes Mountains	Southern Appalachians	Luquillo Mountains
Country	Ecuador	USA	Puerto Rico
Latitude Longitude	01°S 78°W	36°N 84°W	18°N 66°W
Soil parent material	Sedimentary formations, alluvium (Tertiary)	Limestone, dolostone, and shale formations (Cambrian to Ordovician)	Volcanoclastic sediments, tuff units, and dioritic intrusions (Cretaceous, Tertiary)
Annual rainfall (mm)	4100	1360	2600–3600
Elevation of study sites (m)	350–450	250–350	250–1050
Vegetation type	Tropical rainforest	Mixed hardwood forest, except two sites in pines, one in grass, and one in disturbed site	Tropical forest vegetation; four main associations

pected relationships between infiltration rates and site factors to support a scientific basis for extrapolating infiltration rates, determined at points, to broader extents of montane forest. We also hypothesized that infiltration capacities (maximum rates) would be high enough to absorb rainfall and prohibit surface runoff during most rainfall events. Based on the results of our fieldwork in the three study areas, we examine the relationship of rainfall runoff and infiltration to landscape position, the spatial heterogeneity of infiltration, the influence of vegetation on infiltration, and the implications of this research for erosion and landscape change.

In the hydrologic cycle, rainwater returns to the atmosphere through evaporation and transpiration, remains on land (detention storage) and vegetation surfaces (as interception), or percolates into the soil. The movement of water into the soil, called infiltration (*I*), is generally measured indirectly. If evapotranspira-

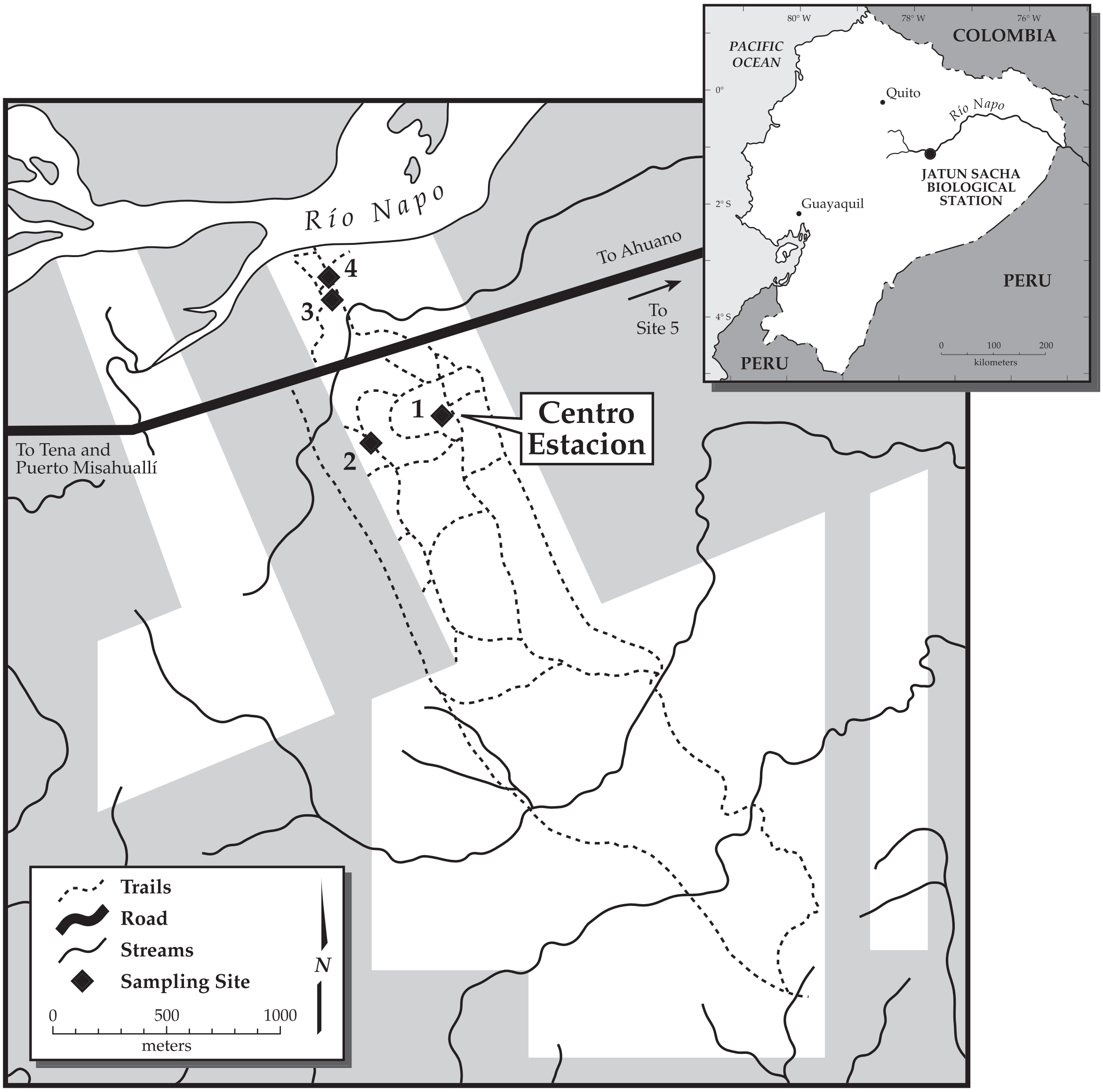

Fig. 1. Jatun Sacha Biological Reserve showing locations of groups of sites. The area of the reserve is unshaded.

tion, detention, and interception are minor or absent, infiltration (I) can be calculated as $I = R - \mathrm{RO}$, where R is rain and RO is a measure of runoff. Infiltration is not a single process but an assemblage of processes involving gravity and forces of molecular attraction between soil and water molecules. It integrates three independent processes: (i) entry through the soil surface, (ii) storage within the soil, and (iii) transmission through the soil (Dunne and Leopold, 1978). Infiltration rates are known to decline to a steady or quasi-steady state as a soil becomes increasingly moist over the period of a storm or experimental wetting. The widely used Philip equation (Philip, 1957) gives the infiltration rate (I) as a function of time t in the form

$$I = A + Bt^{-1/2} \quad (1)$$

where A and B are constants that depend on the soil and its initial moisture distribution. A mainly represents the steady rate of infiltration under gravitational potential, and B is a time-dependent term representing the hydraulic potential gradient at the advancing wetting front. Rates of infiltration are usually compared by comparing the A (steady-state) term (Whipkey and Kirkby, 1978).

Environmental factors that control infiltration rates are rainfall rates, soil properties (including texture, pore characteristics, organic matter content, and structure), vegetation, land use, depth of soil, and initial moisture (Betson, 1964; Dunne and Leopold, 1978). Most mountain slopes in humid regions are covered by forest, which contributes organic matter to the soil and increases soil drainage by promoting soil particle aggregation and supporting soil fauna. Organic litter protects the soil surface from compression and sealing by raindrop impact. Other environmental factors increasing infiltration rates in forests are those that create cracks and voids, such as earthworms and tree

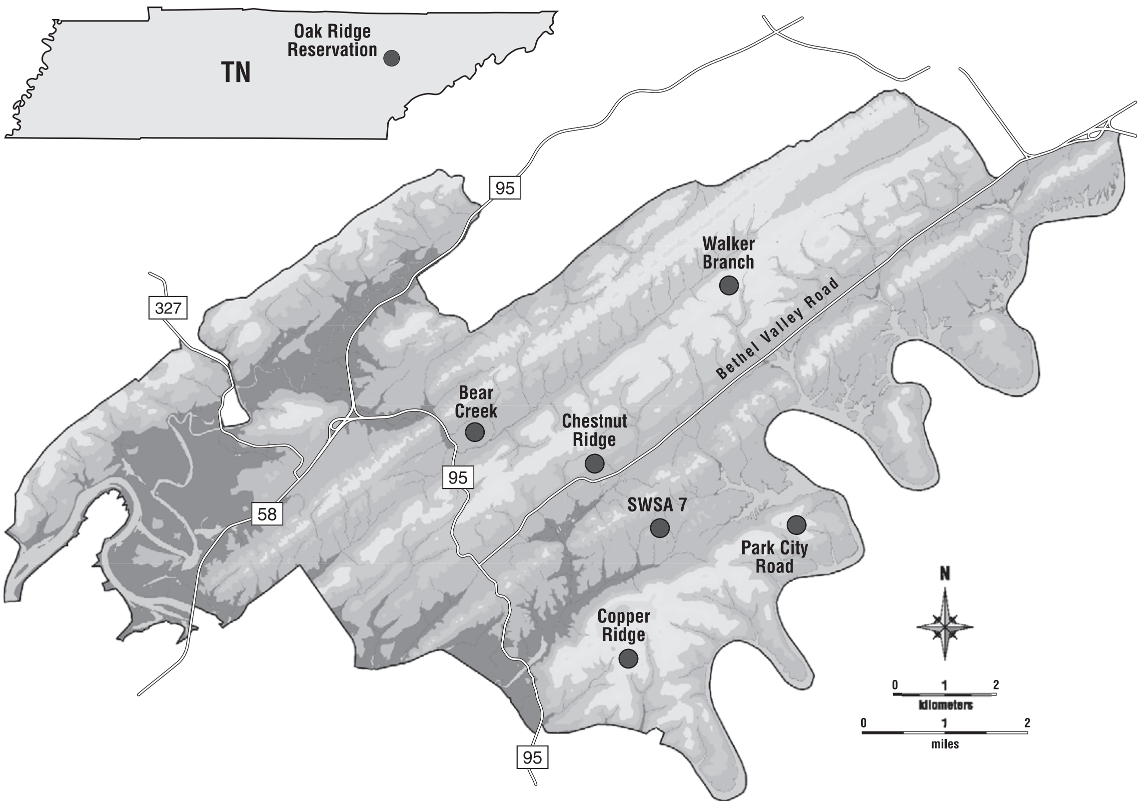

Fig. 2. The Oak Ridge Reservation showing locations of groups of sites.

roots (Knapp, 1978). The effects of these factors all vary spatially.

As interest in using geographic information systems and modeling environmental processes across broader spaces grows, so does recognition of the spatial variability of infiltration rates and the difference between the net hydrologic performance of a slope compared to that of discrete points within it (Hawkins and Cundy, 1987). Jetten et al. (1993) found the sample variance of infiltration rates for tropical rainforest soils to be so large that it was not possible to predict infiltration rate as a simple function of soil properties. Loague and Gander (1990) analyzed 247 infiltration rate measurements at 25-, 5-, and 2-m spacings from a grassland catchment in Oklahoma. They found that variations in infiltration rates were not explained by soil texture and suggested that animal activity, vegetation, and climate strongly affected the distribution of infiltration rates.

In mountain environments, slope position may contribute to the spatial variability of infiltration rates. Woods et al. (1997) identified slope position as a significant control on spatial variability of subsurface runoff. Infiltration capacity has been shown to change with topographic position, but the trend of the change is not always the same. Grah et al. (1983) found infiltration capacity to decrease downslope. In contrast, Dunne et al. (1991) found it to increase downslope. Because infiltration is defined as the vertical movement of water into soil (Hillel, 1971) and most commonly measured on horizontal surfaces, studying the relationship of infiltration to slope position in mountain regions poses significant research challenges.

Knowledge of hillslope hydrology has been hampered by the lack of measurements of soil hydraulic properties, especially in the humid tropics (Bonell and Balek, 1993). Our research was undertaken to better document and understand apparent infiltration rates in soils in tropical and temperate mountainous regions. Specific research objectives were to explore the relationships of infiltration rates with vegetation type, soils, and slope position as a step towards better understanding the spatial variability of infiltration rates in forested mountain environments.

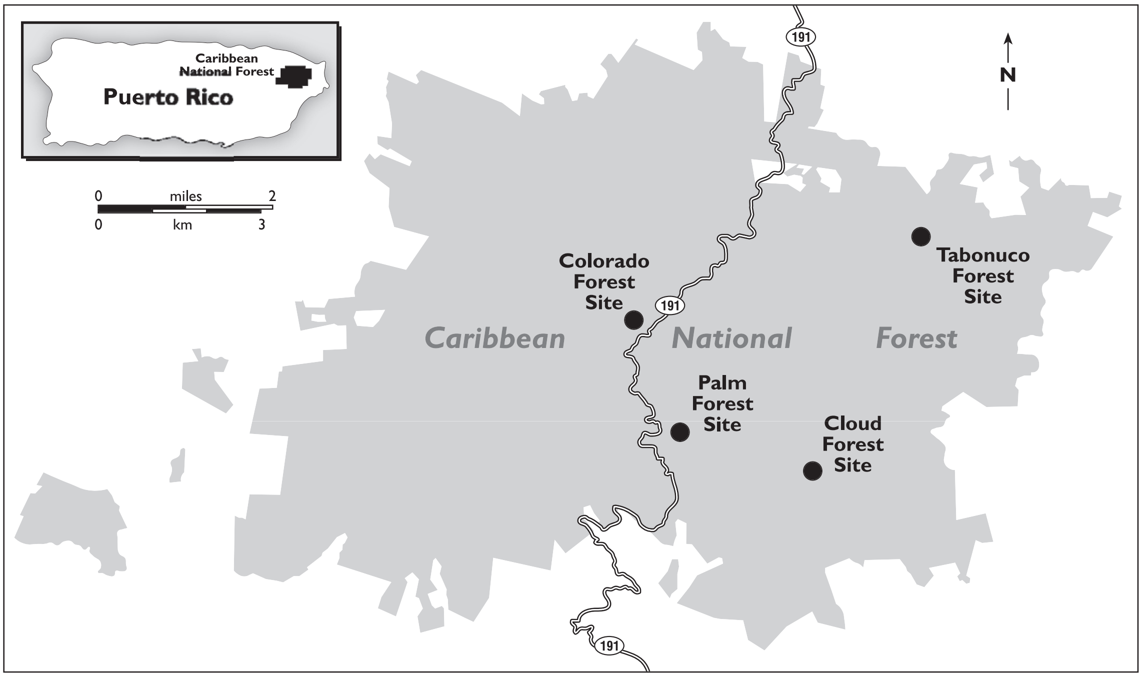

Fig. 3. The Luquillo Experimental Forest showing locations of groups of sites.

2. Study areas

The experiments and results come from three separate research projects: one on the lower eastern flank of the Andes Mountains in Ecuador, one in the southern Appalachian Mountains, and one in the Luquillo National Forest in Puerto Rico. General characteristics of the three research areas are given in Table 1. All are humid and forested; none are known to have been glaciated.

Field research at the Jatun Sacha Biological Reserve was conducted in June 1993 as part of a larger project investigating infiltration and hydrologic variability of soils in several different humid tropical environments (Buhi, 1997) and comparing runoff on- and off-trails (Wallin and Harden, 1996). The Biological Reserve covers a discontinuous area of about 750 ha in the steeply rolling foothills of the Andes and extends onto alluvial terraces and the flood plain of the Napo River (Fig. 1). Soil parent materials are Tertiary sedimentary rocks (shales and marls of Chalcana and Tena Formations) deformed by the Andes Mountains (Ecuador, 1982), and Andean-origin alluvium on terraces of the Napo River. Mean annual rainfall of ∼ 4100 mm is fairly distributed across the year, with a slightly drier December–February period (Jatun Sacha Foundation, 1992). Beneath the canopy of the tropical forest at Jatun Sacha, we compared infiltration rates of soils formed on recent alluvium to upland soils, principally Ultisols, to test the hypothesis that they would differ significantly. Surface soils of both groups were loamy in texture.

Fieldwork in the southern Appalachians was conducted in the summer of 1997 for the purpose of determining infiltration rates and investigating the spatial variability of infiltration on the Oak Ridge Reservation, located 28 km NW of Knoxville, TN (Fig. 2). We chose research sites on the ∼ 15,000 ha Oak Ridge Reservation to represent major differences in lithology, vegetation, topographic position, and land use history to begin to determine whether these factors could be used to extrapolate infiltration rates across the Reservation. The Oak Ridge Reservation covers a series of NE–SW-trending ridges and valleys, with bedrock geology of Early Cambrian to Mississippian sedimentary rocks. Structurally, the area is dominated by thrust faults that formed when the Blue Ridge thrust sheet pushed westward and deformed the Valley and Ridge sedimentary formations in front of it (Hatcher et al., 1992). Bedrock is predominantly carbonate (dolo-

Table 2
Comparison of research goals and methods

Study area	Jatun Sacha Reserve, Andes, Ecuador	Southern Appalachian Mountains, Oak Ridge, TN	Luquillo National Forest, Puerto Rico
Research goals	(1.) Compare runoff and infiltration rates on-and off-trails	(1.) Determine spatial variability of infiltration and runoff on Oak Ridge Reservation	(1.) Determine infiltration rates for Luquillo Forest
	(2.) Compare results of parallel research in Ecuadorian and Costa Rican sites	(2.) Examine relation of infiltration rates to other variables (soil, slope, geology, litter, topographic position)	(2.) Compare infiltration rates of different forest types and slope positions
Research method	Constant head single-ring infiltrometer and rainfall simulation	Rainfall simulation	Rainfall simulation
Number of trials	27 with ring infiltrometer, 21 with simulator	73	54
Antecedent moisture condition	Wet	Wet	Wet
Median intensity of simulated rainfall (mm/h)	36.4	87	91.8
Number of bulk density sample sites	15	73	54
Bulk density depth (cm)	0–10	0–10	0–10

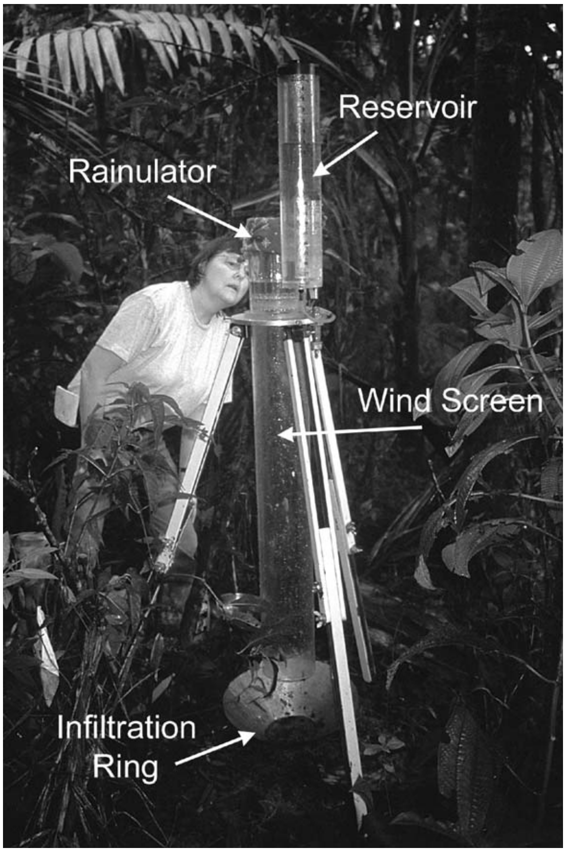

Fig. 4. Photograph of the McQueen rainfall simulator–infiltrometer in the Luquillo Mountains, Puerto Rico.

mite, limestone), much of which is weathered to saprolite (isovolumetrically chemically weathered bedrock), and shale (Hatcher et al., 1992). Soils are formed in colluvial residuum (weathering products lacking the isovolumetric characteristic of saprolite), with some of the carbonate ridge soils formed above 30 m or more of saprolite. Soils are predominantly Ultisols, Alfisols, and Inceptisols, and typically present a cherty, silt loam A horizon over a clayey to loamy B horizon (Lee et al., 1988). Present-day vegetation at most sites is second-growth, mixed hardwood forest. Settlers of European descent moved into the area in the mid-1880s and had extensively cleared and farmed the land by 1880 (SCS, 1936). In 1942, when the US government took over the land for the development of atomic weapons and energy, much of the land had been abandoned and had returned to forest (Lafon, 1995).

We conducted field research in the Luquillo Experimental Forest in Puerto Rico (Fig. 3) in January 1998 to develop a database of infiltration rates in support of water balance modelling for the forest and to begin to test the hypothesis that relationships between infiltration rates and vegetation association or slope position could provide a sound basis for extrapolating infiltration rates across the forest. The Luquillo Mountains in eastern Puerto Rico have steep slopes, with the highest point in the Luquillo Mountains, El Toro Peak (1975 m), only 9 km from the coast. Vegetation in the Luquillo Experimental Forest falls into four categories: tabonuco (*Dacryodes excelsa*) forest in the subtropical wet and subtropical rainforest life zones; Colorado (*Cyrilla racemiflora*) forest in the lower montane wet and rainforest life zones; palm (*Pretoea montana*) forest, which is associated with subtropical and lower montane wet and rainforest life zones, especially on steep and on poorly drained sites; and dwarf (cloud) forest, which occurs above 900 m (Wadsworth, 1951). Larsen et al. (1999) reported that much of the Luquillo area remained forested during the expansion of plantation and subsistence agriculture in Puerto Rico. Two catchments in the NE section of the experimental forest, the Bisley watersheds, have been the focus of long-term ecological and silvicultural research programs (Scatena, 1989).

Table 3
Characteristics and results of rainfall simulation experiments

Study area	Jatun Sacha Biological Reserve, Ecuador	Oak Ridge Reservation, USA	Luquillo Experimental Forest, Puerto Rico
Number of trials	21	72	54
Number with NO runoff	15	34	15
Median rainfall rate (mm/h)	36.4	87	91.8
Median infiltration rate (sites with infill < 100% rain) (mm/h)	31	69	38
Median runoff (% rain) for all trials	0	1	25
Range of infiltration rates (only from runoff-generating trials) (mm/h)	17–34	16–113	−2–99

Table 4
Runoff and infiltration results from Jatun Sacha, Ecuador

Site	Soil	Bulk density[a] (g/cc)	Runoff: rainfall simulator (mm/h)	Infiltration rate[b]: simulator (mm/h)	Infiltration rate[c]: ring (mm/h)	Infiltration range in site group min. – max. (mm/h)
1.3	Upland	0.72	0	>38	...	
1B	Upland	0.91	...	...	20	
1B	Upland	0.91	...	...	23	
1B	Upland	0.91	...	...	36	
1B	Upland	0.91	...	...	38	
1B	Upland	0.91	...	...	41	
1B	Upland	0.91	...	...	55	
1B	Upland	0.91	...	...	79	
1B	Upland	0.91	...	...	120	20–120
2.52	Upland	0.71	0	>47	...	
2.53	Upland	0.71	0	>36	...	
2.54	Upland	0.71	0	>32	...	
2.55	Upland	0.71	0	>48	...	
2.72	Upland	1.03	0	>18	...	
2.73	Upland	1.03	4	43	...	
2.92	Upland	0.89	0	>23	...	
2.93	Upland	0.89	0	>47	...	
2B	Upland	0.96	...	...	27	
2B	Upland	0.96	...	...	35	
2B	Upland	0.96	...	...	47	
2B	Upland	0.96	...	...	70	
2B	Upland	0.96	...	...	127	27–127
5.192	Upland	0.78	0	>45	...	
5.193	Upland	0.78	0	>11	...	
5.194	Upland	0.78	0	>30	...	
5B1	Upland	0.78	...	...	8	
5B2	Upland	0.78	...	...	88	
5B3	Upland	0.78	...	...	98	
5B4	Upland	0.78	...	...	59	8–98
3.112	Alluvial	0.77	10	17	...	
3.113	Alluvial	0.77	63	31	...	
3.131	Alluvial	0.63	0	>19	...	
3.132	Alluvial	0.63	0	>43	...	
3.142	Alluvial	0.63	Trace	>19	...	
3.143	Alluvial	0.63	7	34	...	
3.152	Alluvial	0.71	Trace	>22	...	
3.153	Alluvial	0.71	178	31	...	
3.154	Alluvial	0.71	119	25		
3B1	Alluvial	0.65	...	...	82	
3B2	Alluvial	0.65	...	...	125	
3B3	Alluvial	0.65	...	...	136	
3B4	Alluvial	0.87	...	...	156	
3B5	Alluvial	0.87	...	...	156	0–156
4B1	Alluvial	0.87	...	...	77	
4B2	Alluvial	0.87	...	...	86	
4B3	Alluvial	0.87	...	...	175	
4B4	Alluvial	0.87	...	...	206	77–206

[a] Mean bulk densities of top 5–10 cm of soil determined from constant volume auger samples.
[b] 35-min trials on wet soil, off-trail on forest floor.
[c] Steady rate from constant head in single ring on prewet soil.

Rainfall increases with elevation from about 2600 mm year^{-1} at the base to nearly 5000 mm year^{-1} at the summit (Brown et al., 1983). The clay-rich soils are principally Ultisols (50% of area) and Inceptisols (45%), with Entisols and Oxisols comprising the other 5% (Brown et al., 1983). We chose sampling sites to include as many combinations of the forest type and topographic position as possible; however, the dwarf (cloud) forest is limited to high ridges.

3. Research methods

Each of the three studies discussed in this paper had a slightly different set of research questions and research design; yet all three involved measuring rainfall runoff and infiltration rates and used identical or similar research methods. Research methods for the three sites are summarized in Table 2. In Puerto Rico, in Tennessee, and at 21 of the Ecuadorian sites, we used a McQueen (1963)-type rainfall simulator with a ring infiltrometer to determine the infiltration rate of wet soils on the forest floor. The McQueen rainfall simulator–infiltrometer is lightweight and can be hand carried to the field, allowing in situ measurements of runoff in remote and steep locations. The rainfall simulator–infiltrometer's plexiglass reservoir, rainulator, and windscreen are mounted on a standard surveyor's tripod (Fig. 4). From the reservoir, the water flows through a bubbler system that maintains a constant head in the rainulator to ensure uniform application of "rain" throughout the duration of the experiment. The rainulator forms 5-mm diameter drops on 91 pins inserted in precisely drilled holes, and the drops fall through the cylindrical windscreen to the soil surface. We placed the infiltrometer ring directly under the windscreen, penetrating the soil surface by 2–3 cm to define the 182.4-cm^2 sample plot and prevent lateral movement of the simulated rain water on the soil surface.

Most plots were wet to at least field capacity from recent and ongoing rainfall, or, in a few cases, we prewet them. We further prepared plots by removing twigs and undecomposed leaves so that simulated rain would not be blocked from reaching the soil surface. Rainfall intensity, determined by the head of water in the rainulator, was constant throughout each experiment. During the experiments, we noted incremental rainfall rates and measured runoff by extracting and

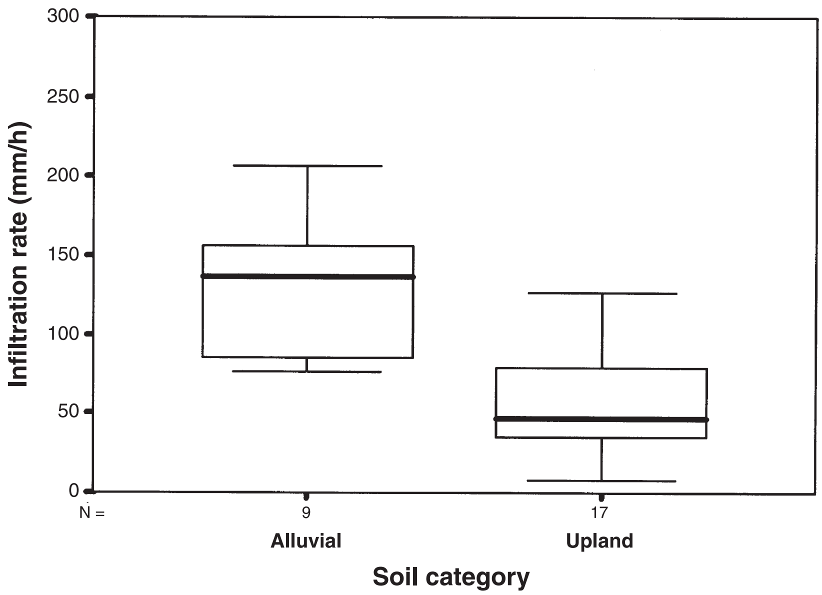

Fig. 5. Box plot showing infiltration rates at Jatun Sacha for sites on two different soils, as determined by single-ring infiltrometer. Horizontal line inside the box is the median value.

Table 5
Runoff and infiltration results from Oak Ridge Reservation, USA

Site	Slope position	Bulk density (g/cc)	Simulated rain (mm)	Runoff (ml)	Runoff ratio (ml/ml)	Duration of trial (min)	Infiltration rate (mm/h)	Infiltration range (mm/h)	Vegetation and geology
C12.11	Middle	2.18	21	0	0.00	30	>41	>36–98[a]	Under canopy,
C12.12	Middle	1.20	51	38	0.04	30	98		deciduous forest,
C12.13	Middle	1.08	44	208	0.25	30	66		on Eidson
C12.21	Middle	–	18	0	0.00	30	>36		member (shale)
C12.22	Middle	1.28	43	114	0.14	30	73		
C12.23	Middle	1.16	44	132	0.16	30	74		
C12.14	Bottom	0.96	51	244	0.25	30	76	59–109	Under canopy,
C12.15	Bottom	1.17	55	6	0.01	30	109		deciduous forest,
C12.24	Bottom	1.13	50	64	0.07	30	93		on Eidson
C12.25	Bottom	0.96	43	250	0.31	30	59		member (shale)
C17.11	Top	–	23	0	0.00	30	>45	no runoff	Under canopy,
C17.12	Top	–	40	0	0.00	30	>80	>32–>82	deciduous forest,
C17.21	Top	–	16	0	0.00	30	>32		on Copper Ridge
C17.22	Top	–	41	0	0.00	30	>82		formation (carbonate)
7.1.11	Bottom	0.92	44	0	0.00	30	>88	26–>91	Under canopy,
7.1.12	Bottom	1.18	54	606	0.59	30	44		deciduous forest,
7.1.13	Bottom	1.29	43	30	0.04	30	84		on Nolichucky
7.1.14	Bottom	1.03	46	0	0.00	30	>91		formation (shale)
7.1.21	Bottom	1.12	49	526	0.56	35	26		
7.1.22	Bottom	1.06	41	0	0.00	30	>81		
7.1.23	Bottom	1.15	36	7	0.01	35	61		
7.1.24	Bottom	1.27	28	3	0.01	30	56		
7.2.11	Top	1.26	43	13	0.02	30	84	>51–>91	Under canopy,
7.2.12	Top	1.05	46	0	0.00	30	>91		deciduous forest,
7.2.13	Top	1.04	40	0	0.00	30	>79		on Rogersville
7.2.21	Top	1.18	26	0	0.00	30	>52		formation (shale)
7.2.22	Top	0.85	26	0	0.00	30	>51		
7.2.23	Top	1.19	76	11	0.01	60	75		
7.3.11	Middle	1.10	97	77	0.04	60	89	27–89	Open, formerly
7.3.12	Middle	1.23	52	618	0.62	30	40		managed as grassland,
7.3.13	Middle	1.13	61	738	0.63	35	27		on Dismal Gap
7.3.21	Middle	1.22	52	0	0.00	50	>62		formation (shale)
7.3.22	Middle	1.13	44	380	0.46	35	33		
7.4.11	Top	1.17	55	35	0.03	30	107	68–107	Under canopy,
7.4.12	Top	1.01	50	48	0.05	30	95		deciduous forest,
7.4.21	Top	1.12	36	18	0.03	30	71		on Dismal Gap
7.4.22	Top	1.13	36	41	0.06	30	68		formation (shale)
wb1.11	Top	1.03	40	0	0.00	30	>79	>48–94[a]	Under canopy,
wb1.21	Top	1.27	35	0	0.00	30	>70		deciduous forest,
wb2.11	Top	1.10	48	14	0.02	30	94		on Copper Ridge
wb2.21	Top	1.11	24	0	0.00	30	>48		formation (carbonate)
wb3.11	Middle	1.21	99	82	0.04	55	97	>52–97[a]	Under canopy,
wb3.12	Middle	1.32	43	97	0.12	30	75		deciduous forest,
wb3.21	Middle	1.13	35	0	0.00	30	>69		on Kingsport
wb3.22	Middle	0.47	26	0	0.00	30	>52		formation (carbonate)
wb4.11	Top	0.87	45	0	0.00	30	>89	no runoff	Under canopy,
wb4.12	Top	1.17	46	0	0.00	30	>92	>92	deciduous forest,
wb4.21	Top	1.04	29	0	0.00	30	>58		on Kingsport
wb4.22	Top	0.70	33	0	0.00	30	>66		formation (carbonate)

Table 5 (*continued*)

Site	Slope position	Bulk density (g/cc)	Simulated rain (mm)	Runoff (ml)	Runoff ratio (ml/ml)	Duration of trial (min)	Infiltration rate (mm/h)	Infiltration range (mm/h)	Vegetation and geology
bc1.11	Top	0.90	58	0	0.00	40	>87	16–>87	Under young canopy, deciduous forest, on Dismal Gap formation (shale)
bc1.12	Top	1.07	41	473	0.80	30	16		
bc1.13	Top	1.12	41	190	0.25	30	61		
bc1.21	Top	1.05	46	0	0.00	40	>68		
bc1.22	Top	1.18	50	24	0.02	40	72		
bc1.23	Top	1.01	59	30	0.03	40	84		
bc2.11	Middle	1.71	50	723	0.76	30	24	23–56	In pine forest, over shale (Nolichucky)
bc2.12	Middle	1.20	48	695	0.76	30	23		
bc2.21	Middle	1.10	38	428	0.59	30	31		
bc2.22	Middle	1.21	45	134	0.15	40	56		
bc3.11	Middle	1.09	47	0	0.00	30	>94	48–>94	In pine forest, over shale (Dismal Gap)
bc3.12	Middle	1.13	47	0	0.00	30	>93		
bc3.21	Middle	1.24	36	12	0.02	30	72		
bc3.22	Middle	1.12	39	293	0.39	30	48		
bc4.21	Bottom	1.00	43	0	0.00	30	>86	>117	Under canopy, deciduous forest, on Rogersville formation (shale)
bc4.11	Bottom	1.28	58	0	0.00	30	>117	no runoff	
bc5.11	Middle	1.20	50	191	0.20	30	80	50–80	Open, disturbed by vehicles Dismal Gap formation (shale)
bc5.21	Middle	1.72	32	141	0.23	30	50		
pc1.11	Middle	0.91	43	0	0.00	30	>86	43–113[a]	Under canopy, deciduous forest, on Copper Ridge formation (carbonate)
pc1.12	Middle	1.07	77	36	0.02	40	113		
pc1.13	Middle	0.81	54	0	0.00	30	>109		
pc1.21	Middle	1.01	30	0	0.00	30	>60		
pc1.22	Middle	1.21	32	18	0.03	40	43		
pc1.23	Middle	0.90	18	0	0.00	30	>36		

[a] Maximum may be underestimated because runoff did not occur in all trials.

measuring all water ponded in the infiltrometer ring at 5-min intervals. For sites in which runoff was generated, we calculated the infiltration rate over each 5-min interval by subtracting runoff volume from rain volume. In Puerto Rico, we continued the experiments for 30 min or until the runoff rate became steady. The experiments in Ecuador and most in Tennessee were discontinued after 30–35 min. For rainfall simulation experiments in Tennessee and Puerto Rico, we used high rain intensities to deliberately exceed infiltration rates; but in the Ecuadorian study, we used lower intensities in order to compare runoff thresholds on- and off-trails. Only the off-trail results are reported in this paper.

The portability of the rainfall simulator–infiltrometer allowed us to conduct infiltration experiments at sites throughout the study areas. Site selection was designed to achieve reconnaissance-level comparisons between site factors: upland versus alluvial soils in Ecuador, different slope positions, lithology, and vegetation in the southern Appalachians, and slope position and forest type in the Luquillo Experimental Forest. We conducted multiple trials at groups of sites in each study area so that we could compare the variability of infiltration rates within and between site groups.

In Tennessee and Puerto Rico, we used a root auger (8 cm diameter) to extract soil cores at two depths (0–10 and 10–25 cm) before and after rainfall simulations. We oven dried and weighed the cores to quantify antecedent moisture and changes in moisture resulting from infiltration and to calculate bulk density. In the Ecuadorian study, we used a hammer-driven constant volume (8.5 cm long by 4.85 cm diameter) auger for bulk density samples.

An additional set of in situ measurements was made in the Ecuadorian study using a single-ring infiltrometer pressed 10 cm into the soil with a constant head of 4 cm. Although the research was completed during the wet season, we prewet the surrounding soil to minimize lateral seepage. The amount of water added to maintain a constant head was monitored, and the infiltration rate recorded when it reached a steady state (Buhi, 1997).

4. Results

At each study area, we found infiltration rates to vary considerably within site groups. Often, the full range of infiltration rates for a study area occurred within a single site. Table 3 summarizes the results of rainfall simulation experiments at all three study areas. At 34 of 72 sites in Tennessee, 15 of 54 in Puerto Rico, and 15 of 21 in Ecuador, the rate of rain applied was not enough to generate surface runoff. For those sites, we report that infiltration capacities exceed the rate of rainfall applied. Because the research goals, designs, and findings differed between study areas, we present the additional results from each area separately.

4.1. Jatun Sacha, Ecuadorian Andes

On the tropical forest floor at Jatun Sacha, the litter layer was typically just one leaf deep. Under natural rainfall, we observed that the larger leaves (e.g., *Cecropia*) block infiltration, causing rainfall runoff over short distances. With intact leaves removed from the soil surface for our experiments, apparent infiltration rates at Jatun Sacha ranged from 17 to 43 mm/h in the six (of 21) rainfall simulation experiments that produced runoff and from 6 to 206 mm/h in the constant head experiments (Table 4). Rainfall records for 1987–1992 at the research station indicated that the relatively light rainfall intensities used in these experiments occurred multiple times (eight estimated) per year (Wallin, 1995).

Infiltration rates determined with the constant head infiltration ring differed significantly ($\alpha = 0.05$, Mann Whitney *U*-test) between sites with alluvial and upland soils (Fig. 5). Alluvial surface soils had higher infiltration rates, with a mean of 134 ± 38 mm/h, compared to the mean of 57 ± 35 mm/h for the upland soils. Within-site trials demonstrated a high degree of very local variation of surface infiltration rates at the scale of ~ 1 m, on both alluvial and upland soils (Buhi, 1997).

4.2. Oak Ridge Reservation, southern Appalachian Mountains

At the southern Appalachian study area, apparent infiltration rates of runoff-producing trials varied from 16 to 117 mm/h (Table 5, Fig. 6A). A salient feature of these data is the within-site variability. Using only data from runoff-producing trials, a Kruskal–Wallis test indicated that median infiltration rates did not differ significantly ($\alpha = 0.05$) between trial locations. The high rate of rainfall application proved to be less than that required to generate runoff, even under moist soil conditions, at nearly half (34 of 72) of the trials. We obtained only one steady-state infiltration rate (94 mm/h) in 12 trials on carbonate ridge tops compared to 10 rates, ranging from 16 to 107 mm/h, from the 16 trials on shale ridges.

Infiltration rates of runoff-producing trials did not differ significantly (Kruskal–Wallis test, $\alpha = 0.05$) by topographic position (Fig. 6B), but more of the trials with no runoff were on ridgetops (55%) than mid- (29%) or low-slope (21%) positions. For the Oak Ridge Reservation, we found no significant linear relationships between infiltration rates and bulk density. Antecedent moisture contents of surface (0–10 cm) cores showed no relationship to topographic position or infiltration rate, but *subsurface* (10–20 cm) cores from ridgetop sites typically had slightly lower gravimetric moisture contents than those from slope bottom sites (median 23 g/g on ridge compared to 26 g/g on bottom, with one outlier removed in each case).

4.3. Luquillo Experimental Forest, Puerto Rico

Apparent infiltration rates in the Luquillo Experimental Forest ranged from 0 to >106 mm/h and varied considerably within vegetation zones (Table 6, Fig. 7A). We found no significant difference in infiltration rates between different forest types (Kruskal Wallis, $\alpha = 0.05$), although cloud forest soil conditions visibly differed from those at other montane sites. Antecedent moisture was higher in the cloud forest sites, and soil bulk density seemed lower, although it was also very low at occasional sites in the tabonuco and Colorado forests. Although we did not measure soil organic matter, we observed that cloud forest soils contained much more visible organic matter than soils in other types of forest. Across the experimental forest, we did

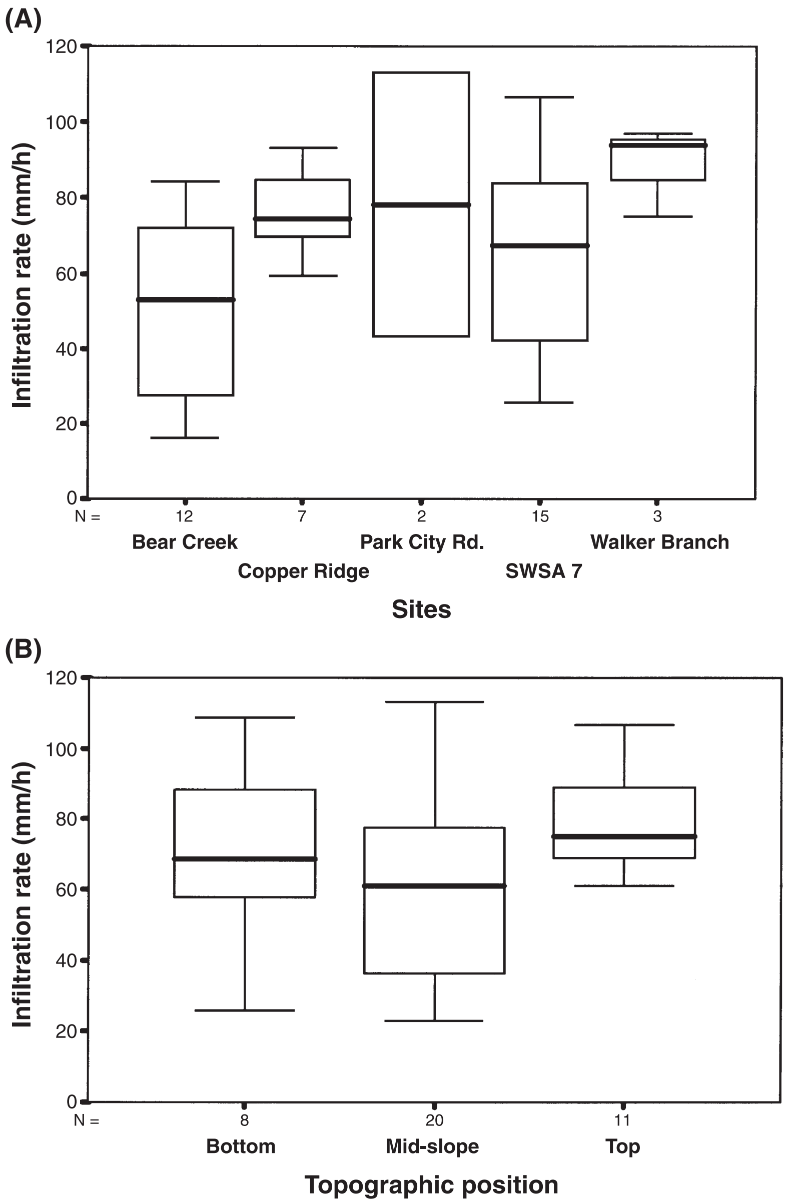

Fig. 6. Box plots of infiltration rates on the Oak Ridge Reservation, as determined from rainfall simulation experiments that produced surface runoff: (A) shows infiltration rates by site group; (B) shows infiltration rates for all runoff-producing trials plotted by topographic position.

not find a statistically significant relationship between antecedent moisture and infiltration rates or a significant relationship between apparent infiltration rate and soil bulk density.

An intriguing topographic pattern that emerged in the Bisley 1 watershed of the Luquillo Experimental Forest is that ridges and side slopes had significantly higher ($\alpha = 0.05$) infiltration rates than the coves they surrounded (Fig. 7B). Likewise, none of the 15 (of 54) sites with no runoff in the experimental forest were in cove positions. In the Bisley watersheds (tabonuco and palm forests), we observed that slopes drained efficiently without producing surface runoff in steady rain; but coves became much wetter and

Table 6
Infiltration data from Luquillo Experimental Forest, Puerto Rico

Forest type	Site	Bulk density (g/cc)	Topographic position[a]	Slope (°)	Simulated rain (mm/h)	Infiltration rate (mm/h)	Infiltration rate range (mm/h)
Colorado	C.1.01	0.58	R	9	107.2	83	1–>105
Colorado	C.2.01	1.17	S	15	69.4	1	
Colorado	C.1.02	0.50	R	15	105.0	>105	
Colorado	C.2.02	0.90	R	9	74.8	>75	
Colorado	C.1.03	0.58	S	27	101.2	82	
Colorado	C.2.03	0.55	S	18	77.4	29	
Colorado	C.1.04	0.41	S	36	113.2	8	
Colorado	C.2.04	0.45	S	34	68.6	51	
Colorado	C.2.05	0.80	C	7	55.6	− 2	
Cloud forest	EP.1.01	0.76	R	2	100.0	6	6–42
Cloud forest	EP.1.02	nd	R	22	105.0	21	
Cloud forest	EP.1.03	nd	R	21	124.6	7	
Cloud forest	EP.1.04	0.42	R	16	135.4	42	
Cloud forest	EP.1.05	nd	R	10	102.0	6	
Cloud forest	EP.1.06	0.30	R	20	109.2	32	
Cloud forest	EP.1.07	0.37	R	21	94.6	39	
Palm	P.1.02	0.67	S	25	96.6	83	18–83
Palm	P.1.03	0.71	S	21	115.6	18	
Palm	P.2.01	0.65	S	9	87.4	81	
Palm	P.2.02	0.64	S	25	74.6	60	
Palm	P.2.03	0.57	S	20	79.8	71	
Tabonuco	B.1.01	0.65	C	5	79.2	4	0–69
Tabonuco	B.2.01	0.78	C	10	71.4	0	
Tabonuco	B.1.05	0.56	C	5	106.0	69	
Tabonuco	B.1.11a	0.48	C	14	114.0	11	
Tabonuco	B.1.11b	0.60	C	12	107.8	41	
Tabonuco	B.1.02	0.65	W	3	68.0	5	3–5
Tabonuco	B.2.02	0.68	W	2	60.4	3	
Tabonuco	B.1.03	nd	R	40	77.6	>78	no runoff
Tabonuco	B.2.03	0.71	R	40	62.0	>62	>106
Tabonuco	B.1.04	0.62	R	23	106.0	>106	
Tabonuco	B.2.04	nd	R	32	81.0	>81	
Tabonuco	B.2.06	0.71	S	30	78.0	>78	76–>99
Tabonuco	B.1.07	0.56	S	3	98.6	>99	
Tabonuco	B.1.07b	0.60	S	36	82.2	76	
Tabonuco	B.2.07	0.64	S	20	69.2	>69	
Tabonuco	B.2.07b	0.66	S	46	101.8	77	
Tabonuco	B.1.08	0.59	S	20	81.6	21	10–94[b]
Tabonuco	B.2.08	0.64	S	13	88.0	>88	
Tabonuco	B.1.09	0.57	S	5	100.6	94	
Tabonuco	B.2.09	0.61	S	32	106.6	10	
Tabonuco	B.2.10A	0.28	S	30	98.0	83	
Tabonuco	B.2.10B	0.55	S	36	59.8	>60	
Tabonuco	B.1.12	0.59	R	4	83.2	>83	74–99[b]
Tabonuco	B.2.12	0.81	R	7	85.0	>85	
Tabonuco	B.1.13	0.24	R	53	102.2	99	
Tabonuco	B.2.13	0.73	R	30	81.4	74	
Tabonuco	B.1.14	0.43	R	4	96.2	>96	
Tabonuco	B.2.14	0.63	R	0	92.0	>92	

[a] C = cove, R = ridge, S = side slope, W = riparian.
[b] Maximum may be underestimated because runoff did not occur in all trials.

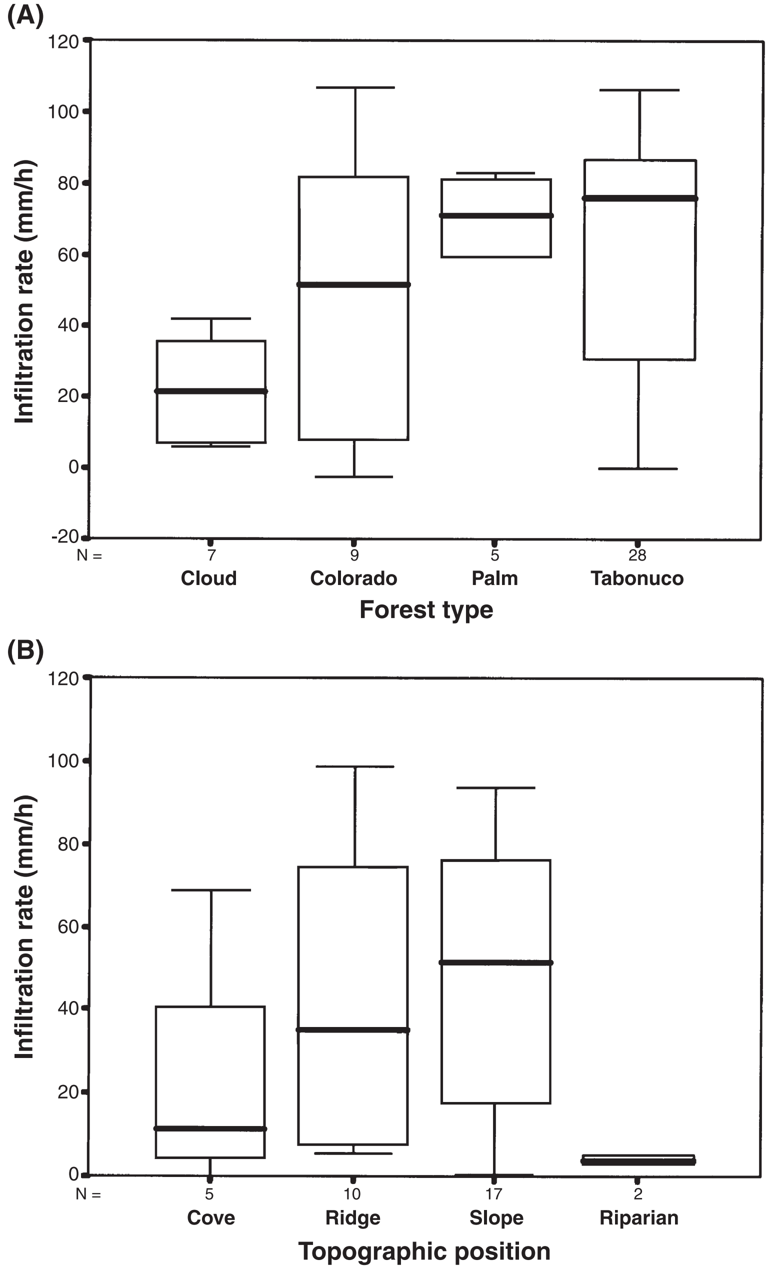

Fig. 7. Box plots of infiltration rates in the Luquillo Experimental Forest: (A) shows infiltration rates by forest type, using rainfall intensity as a minimum estimate for infiltration rate for 15 sites without runoff; (B) shows infiltration rates for all runoff-producing sites plotted by topographic position.

generated surface flow. During one sustained rainstorm, we climbed around in the Bisley 1 watershed with a soil auger to study the response to natural rain. We observed little to no runoff flowing across the surface but did observe a consistently wet zone in the top 3–5 cm of soil (sometimes as deep as 10 cm), where water was visibly draining downslope through a near-surface fine root zone. Soil below this depth was not saturated, in spite of the steady rain. Throughout our experiments in the Luquillo Experimental Forest, we found numerous earthworms in our samples. According to National Forest personnel, earthworms are considered to be the faunal species with greatest biomass in the Luquillo Experimental Forest.

5. Discussion

5.1. Jatun Sacha, Andes

Infiltration rates in the tropical rainforests at Jatun Sacha and Puerto Rico are comparable in magnitude and local variability to those of forested sites in Tennessee. The most notable trend we observed at Jatun Sacha was that the alluvial soils had higher apparent infiltration rates than the older upland soils. Even in the upland, the most intense rainstorms of a typical year would only generate runoff at a small proportion of the off-trail, forested sites tested if all of the rain reached the land surface. In this closed canopy forest, however, interception by trees makes surface runoff even less likely. Although only one of nine rainfall simulation trials at upland sites yielded runoff, rainfall simulation experiments using higher rainfall intensities were not undertaken because the Jatun Sacha research had different objectives.

As expected in the tropical forest, soil surface horizons at Jatun Sacha contained little visible organic matter. Although the research station calls much of the forest "bosque primario" (primary forest), the presence of potsherds at our study sites served as a reminder that this site, too, has a legacy of human use, which may have affected soil compaction and soil infiltration capacities.

5.2. Southern Appalachian Mountains

Infiltration rates exceeded the normal range of rainfall intensities across much of the Oak Ridge Reservation. The median intensity of applied rainfall (87 mm/h) approximated that of a 30-min rain with a 10-year recurrence interval in the region (Dunne and Leopold, 1978). Given that trees would intercept some of the natural rainfall, the likelihood of surface runoff occurring during the full leaf season at sites that produced no runoff in our experiments seems extremely low. At the US Forest Service's Coweeta Hydrological Laboratory in the southern Appalachians in NC, 13% of annual rainfall is lost through interception (Coweeta, 1984). Very high infiltration rates observed in many of our experiments at Oak Ridge are consistent with previous research on the reservation that documented the importance of subsurface flow during rain events. Wilson et al. (1990) found a perched saturated zone above the soil/saprolite interface (~ 2 m deep) during storms, and Mulholland et al. (1990) reported evidence that vadose zone and saturated soil zone flowpaths as well as bedrock zone flowpaths contributed to stream flow in the Walker Branch watershed at Oak Ridge.

For the 34 Oak Ridge sites with infiltration capacities exceeding the rate of rainfall application (87 mm/h median), we did not detect other site factors that could provide a sound basis for spatially extrapolating infiltration rates. Twelve of the sixteen site groups at Oak Ridge had at least one trial yielding no runoff, and 15 of 16 had at least one apparent infiltration rate in excess of 80 mm/h. Such local variability is consistent with findings by Loague and Gander (1990) and Robertson et al. (1997) for other locations in the US. On the Oak Ridge Reservation, infiltration processes at different slope positions may be affected by the geologic situation in which most of the ridges (deep saprolite from limestone and dolostone formations, and fractured carbonate bedrock) are very permeable, while the valleys are underlain by much less permeable shale formations. Further research seeking statistically significant differences in infiltration rates between soil types, topographic positions, or land use history at Oak Ridge or our other study areas would require a much larger set of samples with much more water applied. Even then, microscale differences may continue to dominate over broader-scale patterns, as occurred in the work by Jetten et al. (1993).

All of the reservation sites have a land use history involving forest clearing at some time prior to 1941, so some microscale differences in infiltration rates may reflect site-specific historic anthropogenic effects. The first Roane County soil survey (SCS, 1936) reported that unsustainable farming practices caused slopes in the area to be highly eroded by around 1900. Slopes across the reservation contain deep gullies, some of which are still active. Gullies are visible on an air photo taken in the late 1930s (Lafon, 1995); but the high infiltration rates determined in our study indicate that surface runoff is rare in the current landscape, and new gully formation would not be expected under present conditions.

The apparent erodibility, evident in gullying, of deeply weathered ridge sites in the southern Appalachian Mountains poses the interesting geomorphic problem of why such soft ridges have continued to exist in this humid environment. We suggest that a continuous presence of forest cover has protected these ridges from erosion over millennia. Settlers arriving in the area in the mid-1800s found an extensively forested region, which had been inhabited since about 11,000 years BP by small nomadic bands and later, by about 4500 years BP, by small, scattered Native American communities practicing subsistence agriculture (SAMAB, 1996). Pollen records indicate that this region was continuously forested, at times by more boreal species, even throughout the last glacial period (Delcourt and Delcourt, 1987). Thus, forest clearance in the mid-1800s may have been the first major forest-removing disturbance in >10 ky. Slopes in the Oak Ridge Reservation returned to forest when fields and pastures were abandoned, many in the first decades of the 1900s (SCS, 1936) and the rest in 1942 when the reservation was created. The fact that these erodible ridges have withstood millennia of rains in what is now a humid temperate environment highlights the important role of forests in preserving an otherwise more transient topographic form and leads us to a greater appreciation of the geomorphic role of forest ecosystems in slowing denudation on deep, well-drained soils in humid mountain environments.

5.3. Luquillo Experimental Forest

Our experiments and observations in the Luquillo Experimental Forest reinforced patterns observed in the Andes and southern Appalachians, confirming the near absence of surface runoff on forested slopes and the great spatial heterogeneity of infiltration rates. The likelihood of surface runoff is even lower than indicated by our infiltration results, which do not account for rainfall interception by the forest. Previous research in the Luquillo Experimental Forest revealed throughfall to be 59% and stemflow to be 2.3% of annual rainfall, and showed the forest to have a high frequency, low intensity rainfall regime (Scatena, 1990). The observed effectiveness of near-surface drainage during a heavy rain suggests that apparent steady-state infiltration rates of well-drained slopes are controlled by downslope subsurface drainage rather than soil profile characteristics alone. Thus, lateral subsurface flow, which is not considered to be a component of infiltration for horizontal sites (Hillel, 1971), is integral to infiltration processes on mountainsides, and strict definitions of horizontal infiltration (by matric suction) and vertical infiltration (suction and gravity) do not adequately describe infiltration phenomena on mountain slopes.

Lower infiltration rates in cove sites appear to be related to the relatively recent colluvial origin of their soil materials, probably from thin slope failures, and the reduced presence of roots and visible organic matter. As low points in the surrounding landscape, the coves are sites of topographic convergence of subsurface flow lines. We suggest that the fine colluvial deposits in the coves serve as reservoirs of moisture whose capacities are exceeded in wet times and from which moisture is supplied to streams via subsurface drainage in drier times. Further study of these cove-floor colluvial deposits would extend understanding of the hydrology of this forest and other mountain headwater regions as sources and regulators of fresh water.

5.4. Broader-scale patterns and implications

Beyond the noise of fine-scale spatial variability, we had hypothesized broader-scale controls of infiltration rates at the three study areas. Quantitative analyses were limited by the difficulty of quantifying infiltration rates that exceeded our rainfall application rates and by the resulting small number of trials that achieved steady or quasi-steady state rates. Only two broader trends were significant in our limited data. In Ecuador, infiltration rates differed significantly between alluvial and upland soils; and in Puerto Rico, within the tabonuco forest of the Bisley 1 watershed, apparent infiltration rates were lower in topographic coves than on slopes. The strong signal from these data and from our field observations is of microsite control of infiltration rates, presumably dominated by root and faunal macropores that exist in association with the forest ecosystem.

Although soil scientists have characterized infiltration rates of US soils for decades, such tests have not occurred in forests or on steep slopes because the commonly used double-ring infiltrometers are neither very portable nor suited for use on sloping surfaces or in soils containing roots. Thus, most knowledge about infiltration rates is based on flat land studies outside of forests. The portable sprinkling infiltrometers and single infiltration ring enabled us to extend our knowledge of infiltration to forested mountain slopes. On flat surfaces, the gravitational component of water movement in soil is limited to an area directly beneath the infiltration ring, even though water in tension also moves laterally. On mountainsides, however, the gravitational component of subsurface flow continued to drain water from the site throughout the experiments, as it would throughout natural storms. In a flat field, soil pores fill with water and the steady-state infiltration capacity becomes a function of the positive pressure of the hydraulic head and the hydraulic conductivity of the soil medium. On a long mountainside, the gravity-driven flow of water in the near subsurface can continue to freely drain water from the soil below the infiltration ring; and saturation may never be achieved, except in topographic settings where flow lines converge or at microsites where flow encounters a barrier. Downslope drainage was clearly demonstrated to us in the field where, in one case in the Luquillo Forest, extracting a surface soil core produced an audible suction 1 m downslope from the auger.

5.5. Infiltration rates and vegetation

Evidence from these studies suggests that forest vegetation is critically important to hillslope hydrology in humid mountain regions. The forest environment creates root macropores, including those of the fine root zone near the soil surface and those created by faunal activity. Low bulk densities of surface forest soils facilitate downslope drainage. Compared to the deep litter layer and distinct A horizon in the temperate mixed deciduous forest of the southern Appalachians, leaf litter in the tropical forests was very thin, but faunal (ant, termite, earthworm) activity was much more evident. Nonetheless, the end results of high and spatially heterogeneous infiltration rates were similar. Except at sites of subsurface flow path convergence and at which soils are very shallow or overlie an impermeable formation, surface runoff would be rare in a temperate or tropical mountainside forest. High local variability of infiltration rates on mountain slopes suggests that rainfall that reaches the ground but does not infiltrate into the soil at first would most likely be absorbed by higher infiltration capacity soil within a short distance as it flows downhill.

If litter, faunal activity, and the distribution of soil macropores are dominant controls of rainfall infiltration and subsurface flow in these mountain forests, land use conversions would be likely to reduce subsurface flow and decrease infiltration capacity. This was demonstrated by Spaans et al. (1990), who found saturated hydraulic conductivity of soil to drop from 1000 to 50 cm/day following conversion from a tropical rainforest to a 3-year-old pasture in Costa Rica. The potential for a similarly dramatic decrease in infiltration rates in our study areas was demonstrated by three rainfall simulation trials we conducted in a pasture outside the Luquillo National Forest in Puerto Rico. The pasture trials yielded infiltration rates of 19.5–44 mm/h, which are lower than those (92 mm/h median) in the montane forest.

Classic denudation studies described the relationship between sediment yield and mean annual precipitation (or runoff), noted the importance of vegetation in protecting the soil from erosion in humid regions (Langbein and Schumm, 1958; Douglas, 1967), and recognized the key role of soil in decreasing the conversion of rainfall to runoff, especially in arid environments (Yair and Anzel, 1987). Our studies broaden the geographic scope of local-scale data on infiltration rates and extend understanding of the geomorphic significance of infiltration and subsurface flow on mountain slopes. Well-drained, porous forest soils protect mountain slopes from denudation by surface water erosion, while forest disturbances, including fire, blow down, impairment by pests or contaminants, climate fluctuations, and clearing by humans, contribute to denudation and, if widespread, can initiate a cycle of positive feedback leading to lower infiltration and higher denudation rates.

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