*hydrology*

*Article*

# Effects of Hillslope Trenching on Surface Water Infiltration in Subalpine Forested Catchments

**Matthew C. LaFevor [1,*] and Carlos E. Ramos-Scharrón [2]**

[1] Department of Geography, The University of Alabama, Tuscaloosa, AL 35487, USA
[2] Department of Geography and The Environment & LLILAS-Benson, The University of Texas at Austin, Austin, TX 78748, USA; cramos@austin.utexas.edu
* Correspondence: mclafevor@ua.edu

**Abstract:** Concerns over freshwater scarcity for agriculture, ecosystems, and human consumption are driving the construction of infiltration trenches in many mountain protected areas. This study examines the effectiveness of infiltration trenches in a subalpine forested catchment in central Mexico, where public and private organizations have been constructing trenches for ~60 years. We rely on empirical data to develop rainfall-runoff models for two scenarios: a baseline (no trenches) and a trenched scenario. Field measurements of infiltration capacities in forested and trenched soils (n = 56) and two years of meteorological data are integrated into a semi-distributed runoff model of 28 trenched sub-catchments. Sensitivity analysis and hydrographs are used to evaluate differences in total runoff and infiltration between the two scenarios. Multiple logistic regression is used to evaluate the effects of environmental and management variables on the likelihood of runoff response and trench overtopping. The findings show that soil infiltration capacity and rainfall intensity are primary drivers of runoff and trench overtopping. However, trenches provided only a 1.2% increase in total infiltration over the two-year period. This marginal benefit is discussed in relation to the potential adverse environmental impacts of trench construction. Overall, our study finds that as a means of runoff harvesting in these forested catchments, trenches provide negligible infiltration benefits. As a result, this study cautions against further construction of infiltration trenches in forested catchments without careful ex ante assessment of rainfall-runoff relationships. The results of this study have important implications for forest water management in Mexico and elsewhere, where similar earthworks are employed to enhance runoff harvesting and surface water infiltration.

**Keywords:** water harvesting; conservation; infiltration excess overland flow; mountain protected areas; runoff mitigation

check for updates

**Citation:** LaFevor, M.C.; Ramos-Scharrón, C.E. Effects of Hillslope Trenching on Surface Water Infiltration in Subalpine Forested Catchments. *Hydrology* **2021**, *8*, 147. https://doi.org/10.3390/hydrology8040147

Academic Editor: Michael Piasecki

Received: 6 September 2021
Accepted: 28 September 2021
Published: 30 September 2021



## 1. Introduction

A wide variety of approaches to water resource management have been implemented in mountain protected areas [1]. Presently, these approaches are largely driven by concern over growing freshwater demand and the impacts of hydroclimatic change on water resource supply [2]. Mountain protected areas are considered as 'water towers' or essential landscape elements that facilitate the capture and temporary storage of water for agriculture, ecosystems, and human consumption [3]. New forest management strategies in mountainous areas focus less on comprehensive ecosystem function and more on the provision of water services [4]. This shift reflects a growing need to balance forest resilience and integrity with the increasing global demand for water resources [5].

Traditionally, forest water management has focused on altering groundcover through afforestation, species management, and ecosystem restoration or repair [6–8]. Increased groundcover is generally associated with enhanced water retention and quality, infiltration, and groundwater recharge, though the direction and strength of the effects depend critically on relationships between soils, vegetation type, and climatic factors [9,10]. Such nature-based solutions have proven highly effective at mitigating the impacts of runoff in forests [11] and on agricultural lands [12]. The use of 'natural' vegetation, whether as hedgerows [13], grass strips [14], other herbaceous cover [15], and trees generally provide more sustainable and cost-effective strategies for surface water management [16,17].

While insights from research into vegetation- and nature-based solutions continue to propel advances in forest water management [18], a more direct form of management has gained popularity in highland forests of Latin America—the construction of earthen infiltration trenches [19]. Infiltration trench construction in subalpine forests represents a significant shift from nature-based or restorative approaches to water management to a more direct, engineered approach.

Infiltration trenches belong to a class of engineered landforms that have roots in the technologies of intensive agriculture. In their simplest form, infiltration trenches resemble cross-slope earthworks that are excavated along hillslope contours. Trenches are designed to capture overland flow and allow it to slowly infiltrate into the subsoil—instead of allowing it to continue downslope as stormflow. For millennia, farmers have used trenches to protect crops from overland flow, reduce soil erosion, and enhance root-zone soil moisture in arid and semi-arid environments [20]. Research has long shown the practice can be effective if the spatial distribution, design, and management of trenches is carefully tailored to environmental conditions and management goals [21].

The integration of infiltration trenching practices into modern conservation contexts is relatively new. In Mexico, trenching programs in subalpine forests began during the mid-twentieth century and expanded over several decades [22,23], resulting in public and private investments of billions of pesos (hundreds of millions of USD) in mountain protected areas [24]. The core justification for trenching rests on the assumption that trenches enhance the efficiency of a given landscape in converting precipitation into exploitable water resources. This is achieved through the capture of overland flow and enhancement of infiltration and groundwater recharge, which ultimately helps mitigate freshwater scarcity due to climatic change, environmental degradation, and overconsumption [4,24]. However, estimates of the effects of trenches on infiltration tend to be based on proxy measures of their water storage capacity (i.e., the presumed amount of water capture is typically set to equal the volumetric water storage capacity of the trenches), rather than on a process-based assessment of their effectiveness [25,26]. Critically needed are scientific assessments of trench effectiveness that include spatially distributed empirical modeling of soils surface hydrology, precipitation, infiltration, and runoff response relationships.

The global distribution of infiltration trenching is poorly understood. In Latin America, trenching programs have been reported in highland protected areas of Peru, Chile, Bolivia, Ecuador, and Mexico [19,27], though scientific studies of these efforts are limited. The primary exception is Somers et al. (2018), who devised an empirical model to examine the infiltration benefits of trenches in alpine grasslands in the Peruvian Andes. The study found that trenches in this environment enhanced surface water infiltration over a baseline (no trenches) scenario, by only 3.7% [28]. It is unclear whether findings in the Peruvian Andes apply to subalpine forest catchments, where rainfall intensities, environmental characteristics, and overland flow dynamics are quite different. In Mexico alone, government-led trenching programs in natural protected areas represent one of the largest deliberate efforts at landscape engineering in recent history [23,26,29].

To address this knowledge gap, this paper assesses the effectiveness of infiltration trenches in subalpine forests of Mexico's Matlalcuéyatl (La Malinche) Natural Protected Area and National Park (MNPAP). Here, a distributed infiltration and runoff model is developed from primary field data and experiments in 28 trenched sites over a two-year period (2018–2019). The model compares two general scenarios: a baseline (no trenches) and a trenched scenario. The model uses two forms of analysis. First, a sensitivity analysis examines how infiltration and runoff are affected by variations in environmental factors such as rainfall and infiltration rates, and by trench design (i.e., spacing and size). Comparison of the results from each scenario provides general measures of trench effectiveness. Next, to provide greater resolution to the trenched scenario, multiple logistic regression models are used to examine the marginal effects of environmental and trench design factors on the probability of runoff generation and trench overtopping—two primary indicators of trench effectiveness. Understanding the effects of individual factors on runoff and overtopping is a crucial element in optimizing trench design and management. Finally, the cumulative amount of infiltration under both scenarios is compared using rainfall intensities registered in the area over a two-year period (2011–2013). The findings are discussed in the context of the potential infiltration benefits and adverse environmental impacts of trenching, and how results can inform future trenching practices.

## 2. Materials and Methods

### *2.1. Study Area*

This study was conducted in a subalpine forested catchment (5.3 km$^2$) of the MNPAP. The MNPAP is representative of mountain protected areas in the central trans-Mexican volcanic belt region, which includes most forest and alpine grasslands above ~2800 m above sea level (masl) [30]. Throughout the late 20th and early 21st centuries, the MNPAP has been the target of extensive infiltration trenching programs [22,29,31]. The MNPAP is comprised of 46,112 ha of subalpine forests and grasslands that range in elevation from 2400 masl to the summit of the Malinche volcano (4461 masl) [32]. The territory of the MNPAP forms a radial pattern around the slopes of the volcano, a semi-active stratovolcano and Mexico's 6th highest peak, and a prominent feature on the country's eastern trans-volcanic belt [33].

The MNPAP represents a critical source area for surface and groundwater for the metropolitan Puebla-Tlaxcala region, home to approximately 3 million inhabitants. The MNPAP forms part of the upper Atoyac-Zahuapan River Drainage Basin, which belongs to the larger Balsas hydrological region in central Mexico [34]. The river provides freshwater for urban, industrial, and agricultural use in communities extending from highland Mexico to the Pacific Coast [32].

The lower regions of the MNPAP (~2400–3000 masl) are characterized by conifer forest fragments (*P. hartwegii, P. montezumae, P. patula*), some oak remnants (*Quercus rugosa*) and forest grasslands (*Festuca tolucensis*) that result from intermittent agriculture, livestock grazing, logging, and fires [35,36]. Above 3000 masl, pine forests thicken and dense grasses persist through the understory and into the lower alpine regions (~3900–4400 masl) [23]. The climate of the MNPAP is predominantly temperate subhumid, with an annual mean temperature of 15.3 °C and a summer rainy season from May to November. Annual precipitation ranges from ~400 to 1200 mm y$^{-1}$ (mean = 827 mm y$^{-1}$) [34,36,37]. Most soils are of recent volcanic origin (regosols, fluvisols, cambisols) and exhibit high permeability in forested areas [38].

Infiltration trenching in the MNPAP began in the mid-twentieth century through the work of the Malinche Commission, a joint federal and state program focused on soil and water conservation [22]. In 1996, trench construction and management became the responsibilities of the state governments of Tlaxcala and Puebla, which now manage 70% and 30% of the MNPAP territory, respectively [39]. Trench construction expanded rapidly during the late 20th century and now covers the greater part of the MNPAP forest floor and portions of the alpine grasslands [29], though precise estimates of the total surface coverage are unavailable, as are any firm estimates of the benefits of the trenches [40].

### *2.2. Data Collection*

In this study, we examined a representative sample of trenches and forest catchments in the MNPAP at elevations ranging from 3000–4000 masl. Field characterization and experiments in the study area were conducted during July of 2018 and 2019.

Soils were sampled at 28 sites along six transects (Figure 1B). At each site the saturated hydraulic conductivity ($K_{sat}$) and sorptivity ($S$) (capillary suction) of soils were measured with a Guelph permeameter [41]. Under field capacity conditions, 30-cm deep boreholes were made with an auger in each trench and adjacent forest soil. Soil samples from the first (0–15 cm) and second (15–30 cm) halves of the borehole fills were taken for laboratory analysis.

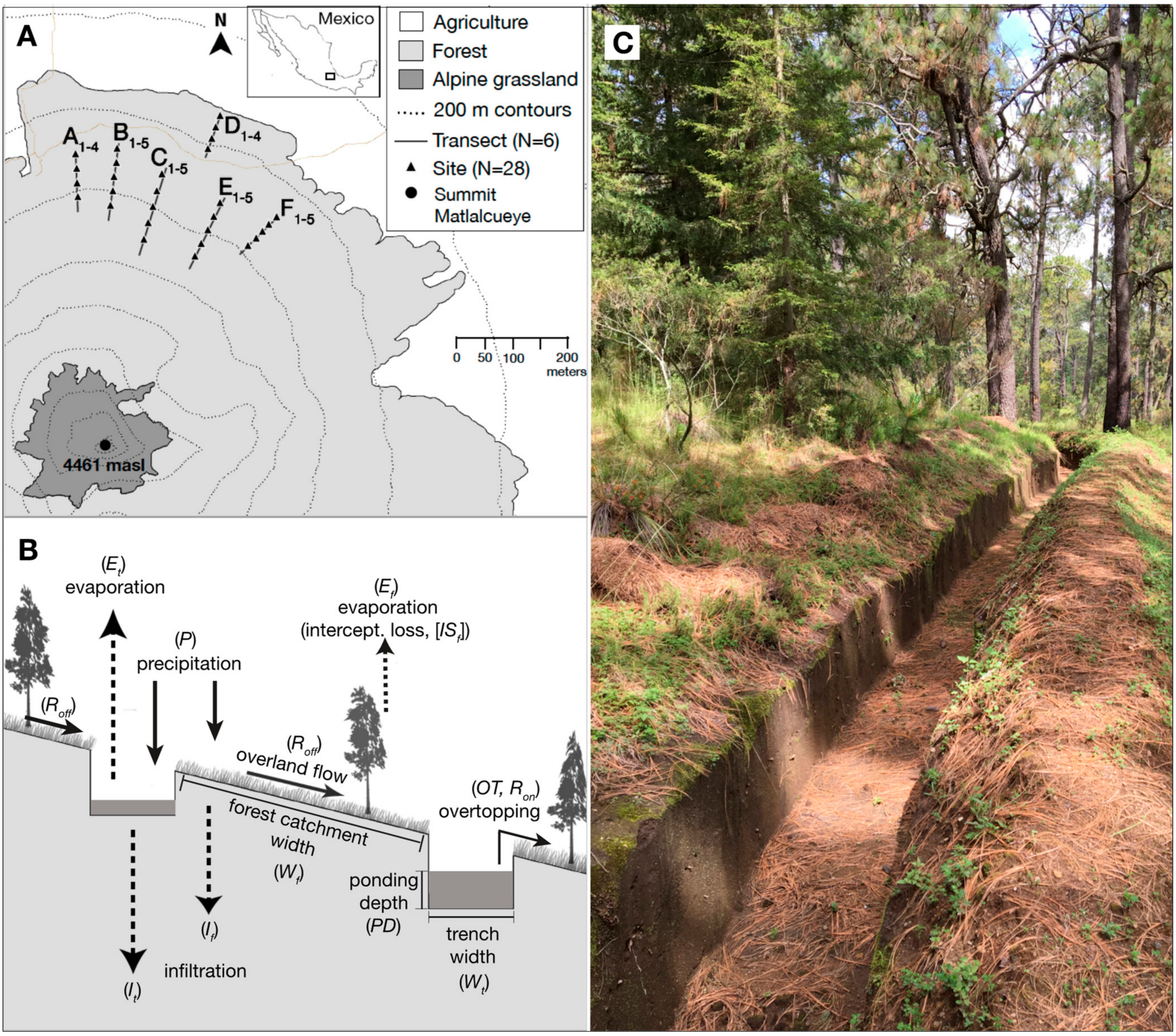


**Figure 1.** (**A**). Map of study are in northwestern quadrant of La Malinche Natural Protected Area showing the six transects and 28 sample sites. (**B**). Profile view of infiltration trenches and primary surface processes. (**C**). Photo of infiltration trench.

Permeameter measurements followed the 'two-head' procedure for improved accuracy [42]. The first steady-state hydraulic head was established using a 5 cm water column and the second was established with a 10 cm column. These depths were chosen so steady state could be reached in under 30 min [43]. Hourly meteorological data (precipitation intensity, air temperature, barometric pressure, wind speed, relative humidity) were obtained from March 2011 to March 2013 from a tandem weather station and rain gauge (Hobo U30 with PAR sensor and Hobo RG30-M, Onset Computer Corporation) positioned 3.8 km and 300 m elevation below the midpoint of where soil sampling and testing took place. A temperature correction of −3 °C was used to represent the study area following the dry adiabatic lapse rate [44]. Field measurements are shown in Table 1.

**Table 1.** Measures of site dimensions and forest and trench soils in the 28 study sites. Within each transect, the first site (1) is furthest upslope and the last site (4 or 5) is furthest downslope.

| | | Forest Catchments | | | | Trenches | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Dimensions | | Permeameter Results | | Dimensions | | Permeameter Results | |
| Transect | Site | Width (m) | Slope (m $m^{-1}$) | $K_{sat}$ (mm $hr^{-1}$) | Sorptivity (mm $hr^{-1/2}$) | Width (m) | Height (m) | $K_{sat}$ (mm $hr^{-1}$) | Sorptivity (mm $hr^{-1/2}$) |
| A | 1 | 44.0 | 0.12 | 7.0 | 7.4 | 0.37 | 0.35 | 31.3 | 3.47 |
| | 2 | 39.5 | 0.01 | 51.5 | 4.0 | 0.39 | 0.38 | 35.8 | 0.98 |
| | 3 | 44.3 | 0.09 | 2.6 | 9.2 | 0.43 | 0.41 | 51.6 | 7.20 |
| | 4 | 51.6 | 0.07 | 49.4 | 7.6 | 0.41 | 0.40 | 15.8 | 5.74 |
| B | 1 | 38.9 | 0.14 | 54.0 | 9.1 | 0.42 | 0.38 | 42.5 | 1.50 |
| | 2 | 44.5 | 0.14 | 62.6 | 2.5 | 0.50 | 0.45 | 13.9 | 9.6 |
| | 3 | 41.4 | 0.14 | 52.4 | 6.4 | 0.45 | 0.39 | 5.4 | 13.7 |
| | 4 | 43.4 | 0.14 | 62.4 | 4.9 | 0.39 | 0.37 | 76.0 | 3.0 |
| | 5 | 44.6 | 0.12 | 51.6 | 7.2 | 0.45 | 0.43 | 2.5 | 7.0 |
| C | 1 | 62.2 | 0.11 | 54.1 | 10.0 | 0.45 | 0.43 | 4.8 | 7.8 |
| | 2 | 67.2 | 0.09 | 85.2 | 7.7 | 0.43 | 0.41 | 71.5 | 1.4 |
| | 3 | 54.8 | 0.10 | 65.7 | 9.3 | 0.38 | 0.38 | 7.1 | 9.6 |
| | 4 | 66.2 | 0.10 | 49.8 | 11.4 | 0.42 | 0.40 | 53.9 | 8.0 |
| | 5 | 72.6 | 0.07 | 74.1 | 8.3 | 0.52 | 0.49 | 6.9 | 6.1 |
| D | 1 | 24.5 | 0.07 | 51.7 | 8.4 | 0.39 | 0.32 | 40.7 | 9.9 |
| | 2 | 38.0 | 0.10 | 40.5 | 7.9 | 0.37 | 0.35 | 61.2 | 6.8 |
| | 3 | 53.9 | 0.09 | 20.2 | 4.7 | 0.39 | 0.34 | 51.6 | 5.8 |
| | 4 | 42.8 | 0.07 | 35.8 | 7.6 | 0.38 | 0.34 | 114.8 | 7.2 |
| E | 1 | 55.3 | 0.09 | 7.3 | 11.3 | 0.57 | 0.56 | 96.3 | 7.0 |
| | 2 | 43.2 | 0.06 | 33.8 | 7.8 | 0.62 | 0.57 | 7.3 | 11.3 |
| | 3 | 41.5 | 0.06 | 53.8 | 5.3 | 0.58 | 0.49 | 3.0 | 12.5 |
| | 4 | 56.1 | 0.09 | 78.2 | 1.8 | 0.56 | 0.52 | 17.9 | 3.1 |
| | 5 | 52.9 | 0.12 | 66.9 | 9.2 | 0.61 | 0.58 | 29.1 | 4.2 |
| F | 1 | 14.4 | 0.12 | 71.5 | 1.4 | 0.67 | 0.58 | 40.8 | 10.8 |
| | 2 | 14.7 | 0.09 | 33.7 | 6.5 | 0.66 | 0.61 | 5.3 | 13.0 |
| | 3 | 15.3 | 0.08 | 93.8 | 0.5 | 0.72 | 0.67 | 9.6 | 11.8 |
| | 4 | 12.3 | 0.12 | 22.4 | 4.0 | 0.75 | 0.67 | 92.2 | 10.7 |
| | 5 | 20.1 | 0.13 | 44.3 | 8.0 | 0.73 | 0.68 | 33.6 | 2.6 |
| | | | Mean | 49.15 | 6.75 | | Mean | 36.51 | 7.19 |
| | | | SD | 23.01 | 2.87 | | SD | 31.03 | 3.66 |

### 2.3. Models

A one-dimensional infiltration-runoff model was developed and applied to each of the 28 sites, incorporating the forest catchment and trench dimensions of each transect described in Table 1. The model was applied for each scenario (baseline and trenched) following Somers et al. (2018) [28]. The model is based on a water balance concept with two main components: a forest infiltration component and a trench infiltration component (omitted in baseline scenario). The forest component followed the form:

$$I_f = P + R_{on} - IS_f - R_{off} \tag{1}$$

where $I_f$ is infiltration through the forest floor, $P$ is precipitation, $R_{on}$ is infiltration excess overland flow (i.e., Horton overland flow; hereafter, runoff/on) from site above, $IS_f$ is interception loss, and $R_{off}$ is runoff. All variables are represented as water depth (mm) per unit area of the forest catchment. In the baseline scenario, any runoff leaving the catchment is incorporated as run-on into the catchment immediately downslope. $R_{off}$ is considered as a loss to the forest catchment where it is generated (i.e., rainfall that was not intercepted by vegetation or infiltrated by forest soils) and a gain to the catchment immediately below. In the trenched scenario, $R_{off}$ is harvested in the trench immediately downslope, where it may infiltrate, pond and evaporate, or overtop the trench. Any overtopping is then incorporated as runon into the forest catchment immediately downslope. The trench component of the model followed the form:

$$I_t = P + R_{off} - PD - E_t - OT \quad (2)$$

where $I_t$ is infiltration in the bottom of the trench, $P$ is precipitation, $R_{off}$ is runoff from the forest catchment above, $PD$ is the depth of ponded water in the trench (per unit trench area), $E_t$ is evaporation from the ponded water surface, and $OT$ is trench overtopping. Potential evaporation from the ponded water was estimated using a Dalton equation for open water evaporation [45], and potential evaporation of precipitation intercepted by forest vegetation was estimated using a Penman–Monteith formula [46]. Interception storage capacity (fixed at 3 mm) was estimated from studies of similar forest canopies and grasslands in central Mexico [47,48] and from similar coniferous forests [49,50].

The baseline and trenched scenario models were run at one-hour time steps over the two-year period (2011–2013) for which meteorological data were available. This one-hour time step aligned with: (1) the one-hour meteorological data time step, and (2) the maximum times for Guelph permeameter tests to reach steady state ($T_{st}$) and the maximum runoff response times of concentration ($T_c$) for each simulated transect. For each transect catchment site, $T_{st}$ + $T_c$ < 1 hr. In other words, a one-hour time step was sufficient at each catchment site to reach soil saturation and to model runoff response travel time to the adjacent catchment below (baseline scenario) or to the downslope trench (trenched scenario). Overland flow velocities were estimated using Manning's equation (forest cover with heavy brush/litter) and were used to calculate $T_c$ for each catchment site (Appendix A Table A1). Because the mean length of catchments was greater than 100 ft (30.48 m) (Table 1), shallow concentrated flow velocity curves were used to estimate $T_c$, following USDA (2010, Eqs. 15.7–15.8) [51].

### *2.4. Comparing Baseline and Trenched Scenarios (Objective 2)*

Two forms of analysis were used to compare baseline and trenched scenarios. First, a sensitivity analysis was performed to quantify the sensitivity of infiltration and runoff to changes in trench spacing and design and environmental factors. Second, multiple logistic regression was performed to examine the importance of these factors in controlling runoff generation and trench overtopping. Logistic regression quantified the marginal effects of trench design and environmental factors on the probabilities of runoff generation and trench overtopping occurring.

#### 2.4.1. Sensitivity Analysis

First, one-at-a-time (OAT) sensitivity analysis was used [28,52]. In this analysis, a range of three plausible values for environmental and trench design parameters was selected and the models were run for each scenario using each of the three values. For each OAT parameter change, all other parameter values were held constant at their means. The infiltration and runoff sensitivity results for baseline and trenched scenarios were illustrated as percent of precipitation (%I = $\Sigma$I $[\Sigma P]^{-1}$, %R = $\Sigma$R $[\Sigma P]^{-1}$). The differences between the baseline and trenched scenarios were considered as measures of trench effectiveness (e.g., infiltration enhancement = $\%I_{\text{trenched}} - \%I_{\text{baseline}}$).

#### 2.4.2. Multiple Logistic Regression

Next, multiple logistic regression was used to better understand the effects of environmental and trench design factors on the likelihood of runoff and trench overtopping occurring, two key indicators of trench effectiveness. Logistic regression is a widely used approach to modeling relationships between one or more independent variables and one or more binary dependent variables [53]. Here, the above factors were used as independent variables to develop two separate logistic models, each predicting the combined parameter effects on the probability that runoff (Model 1) and overtopping (Model 2) occur. Each binary dependent variable was modeled as the target outcome of either *R* or *OT* occurring (Yes = 1, No = 0). Each model used the maximum likelihood estimation following:

$$\log\left(\frac{P}{1-P}\right) = b_0 + b_1X_1 + b_2X_2 + \cdots + b_nX_n \quad (3)$$

where $P$ is the response probability that the target outcome (Y = 1) of *R* or *OT* occurred, $X_1$ through $X_n$ are the model parameters, and $b_0$ though $b_n$ are the regression coefficients.

In logistic regression the coefficients show the change in the expected log odds per one-unit increase in $X_i$, while holding other variables constant at their means. To facilitate interpretation, the log odds were plotted as the marginal effects of incremental changes in each variable on the probability of Y = 1 (i.e., runoff or trench overtopping occurring), over the entire value range of each variable. These plots allowed the identification of the threshold values at which incremental changes in variables resulted in changes in the probability that *R* and *OT* occurred. Finally, the efficiency of each of the 28 trench sites was evaluated based on comparing the modeled cumulative amount of infiltration between scenarios derived from rainfall intensities registered from March 2011 to March 2013.

## 3. Results

### 3.1. Data Collection

The width of forest catchments (i.e., spacing between trenches; Figure 1) ranged from 20.1 (F5) to 72.6 m (C5) (Table 1). Forest catchment slope ranged from 0.01 to 0.14 m m$^{-1}$. The mean $K_{sat}$ value for forest catchments was higher than for the bottom of trenches (49.2 and 36.5 mm hr$^{-1}$, respectively), though a two-sample T test found that the difference was not statistically significant ($\alpha < 0.05$) (Figure 2). Forest $K_{sat}$ values fell within the range of those found for conifer forests in Mexico (35 mm hr$^{-1}$) [54] and elsewhere: 63 mm hr$^{-1}$) [55], 77–81 mm hr$^{-1}$ [56], and 28 mm hr$^{-1}$ [57].

The sorptivity and time to steady state values for forest catchments and trenches also showed no statistically significant differences. Trench soils were generally coarser than forest soils, with higher shares of gravel and sand particles and lower shares of silt and clay (Figure 2). All time to steady state values (the mean of the one- and two-head procedures) were below 27 min and within the 30-min experimental period. All time to concentration values were below 6.6 min, meaning that runoff travel time in each catchment to the downslope catchment (baseline) or to the downslope trench took less than 6.6 min (Appendix A Table A1). Therefore, because $T_{st} + Tc < 1$ hr at each site, the one-hour time step was confirmed as being appropriate for modeling the baseline and trench scenarios.

Mean annual temperature was 14.8 °C during the two-year period (March 2011–March 2013), which was only slightly above the 20-year average of 14.4 °C derived from the CLImate COMputing database at the website (http://clicom-mex.cicese.mx/, accessed on 13 August 2021) [58]. Mean annual precipitation was 764.4 mm in Year 1 and 724.4 mm in Year 2 (Figure 3). Both years were above the 20-year mean of 650.1 mm y$^{-1}$ [58]. Rainfall intensities ranged from 0.2 mm hr$^{-1}$ to 40.2 mm hr$^{-1}$ (mean = 1.8 mm hr$^{-1}$). The mean potential evaporation from forest interception was 4.1 mm day$^{-1}$. This rate is comparable to previous studies in coniferous forests, which range from 2.4 to 4.8 mm day$^{-1}$, depending on environmental and climate factors [59]. Mean potential surface evaporation from ponded water in trenches was 2.7 mm day$^{-1}$. This value was higher than Somers et al., 2018 (0.8 mm day$^{-1}$) for the Peruvian Andes [28] and more in line with other studies of highland shallow water body evaporation [60].

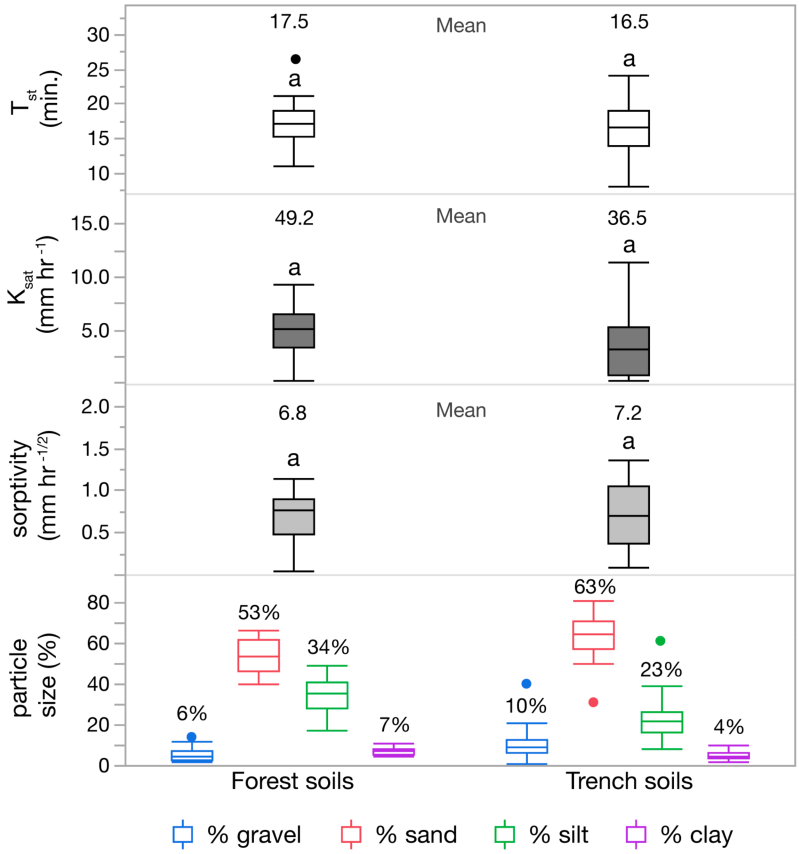


**Figure 2.** Outlier box plots of the time to reach steady state ($T_{st}$), saturated hydraulic conductivity ($K_{sat}$), sorptivity ($S$), and particle size distribution for forest and trench soils.

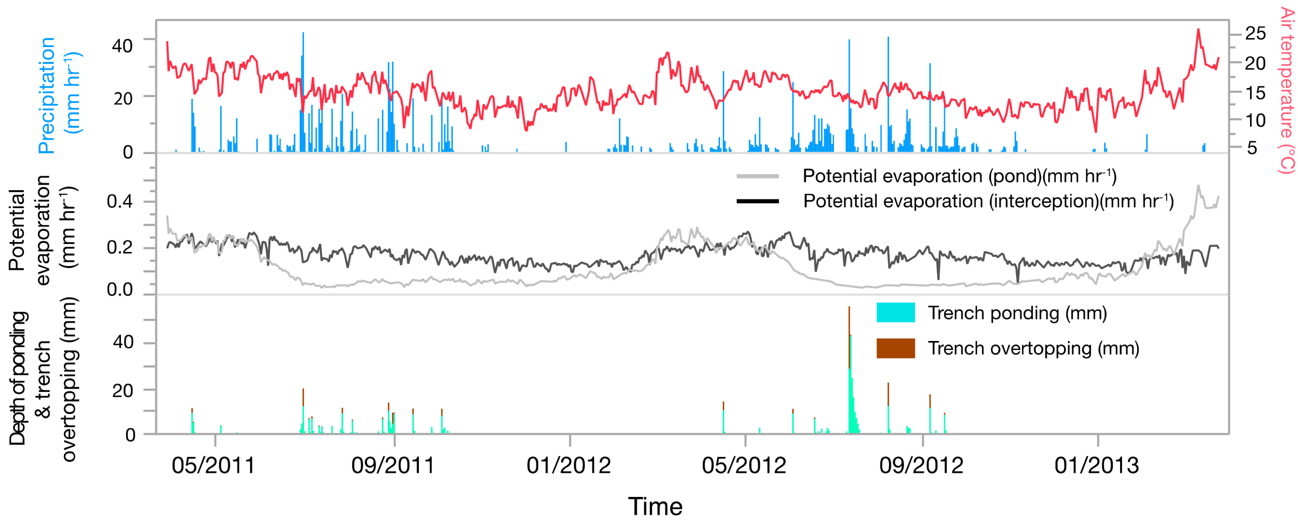


**Figure 3.** Other input parameters for the infiltration model (all sites). Precipitation (mm hr$^{-1}$) and air temperature (°C). Potential evaporation from pond surface (mm hr$^{-1}$) and from interception (mm hr$^{-1}$). Trench ponding (mm) and overtopping (mm).

### 3.2. Sensitivity Analysis

Two types of sensitivity analysis were performed. First, is the sensitivity of the amount of infiltration and runoff to the input variables in both baseline and trenched scenarios (results found in the 'difference' columns; Table 2). Second, the sensitivity of the difference in both net infiltration and runoff loss between the baseline and trenched scenarios to the input variables. These values are derived from the difference between the two range value results in each scenario.

**Table 2.** Sensitivity of infiltration (*I*) and runoff (*R*) to environmental variables for baseline (no trenches) and trenched scenarios. Outputs for the baseline scenario were derived using ′0′ values for trench-related parameters.

| | | Infiltration (% Total Precipitation) | | | Runoff (% Total Precipitation) | | |
|---|---|---|---|---|---|---|---|
| **Sensitivity Variable (Mean)** | **Range** | **Baseline** | **Trenched** | **Difference** | **Baseline** | **Trenched** | **Difference** |
| Unperturbed (all at means) | | 55.9 | 57.1 | 1.2 | 0.0 | 0.00 | 0.0 |
| Infiltration capacity of forest | 93.8 | 55.9 | 57.1 | 1.2 | 0.0 | 0.00 | 0.0 |
| (49.15 mm $hr^{-1}$) | 2.6 | 27.4 | 30.5 | 3.1 | 29.6 | 27.7 | −1.9 |
| Infiltration capacity of trench | 114.8 | 55.9 | 57.1 | 1.2 | 0.00 | 0.0 | 0.0 |
| (36.43 mm $hr^{-1}$) | 2.5 | 55.9 | 56.6 | 0.7 | 0.00 | 0.5 | 0.5 |
| Interception storage | 3.5 | 53.3 | 54.5 | 1.2 | 0.00 | 0.0 | 0.0 |
| (3 mm) | 2.5 | 59.2 | 60.3 | 1.2 | 0.00 | 0.0 | 0.0 |
| Trench width | 0.75 | 55.9 | 57.7 | 1.8 | 0.00 | 0.0 | 0.0 |
| (0.50 m) | 0.37 | 55.9 | 56.8 | 0.9 | 0.00 | 0.0 | 0.0 |
| Depth of trenches | 0.68 | 55.9 | 57.1 | 1.2 | 0.00 | 0.00 | 0.00 |
| (0.46 m) | 0.32 | 55.9 | 57.1 | 1.2 | 0.00 | 0.00 | 0.00 |
| Forest width | 72.6 | 94.8 | 95.9 | 1.2 | 0.00 | 0.00 | 0.00 |
| (42.86 m) | 12.3 | 16.0 | 17.2 | 1.2 | 0.00 | 0.00 | 0.00 |
| Potential Evap. (interception) | +10% | 55.2 | 56.4 | 1.2 | 0.00 | 0.00 | 0.00 |
| (4.08 mm $day^{-1}$) | −10% | 56.9 | 58.1 | 1.2 | 0.00 | 0.00 | 0.00 |
| Potential Evap. (trench pond) | +10% | 55.9 | 57.1 | 1.2 | 0.00 | 0.00 | 0.00 |
| (2.74 mm $day^{-1}$) | −10% | 55.9 | 57.1 | 1.2 | 0.00 | 0.00 | 0.00 |

For example, the sensitivity analysis shows that when all parameters are at their means (unperturbed), 55.9% of total precipitation will infiltrate in a baseline scenario and 57.1% in the trenched scenario. This 1.2% difference is smaller than the 3.7% difference (79.6% and 83.3%, respectively) found by Somers et al. (2018) [28]. However, when forest infiltration capacity was at the lower of the two range values (2.6 mm $hr^{-1}$), the sensitivity of infiltration increased to a 3.1% difference. Overall, trenches provided greater infiltration when forest infiltration capacity is at the lower end of the range (also a 1.2% difference).

Over the range of parameter values, infiltration in the baseline scenario was most sensitive to forest width (Δ = 94.8 − 16.0 = 78.8%), forest infiltration capacity (25.5%), and interception storage (5.9%). Infiltration in the trenched scenario was most sensitive to the same parameters: forest width (78.6%), forest infiltration capacity (26.6%), and interception storage (5.9%).

The sensitivity of infiltration to the differences between baseline and trenched scenarios was much smaller. Infiltration differences were most sensitive to forest infiltration capacity (Δ = 3.1% − 1.2% = 1.9%), followed by trench width (0.9%) and trench infiltration capacity (0.5%). Between scenarios, infiltration was not sensitive to changes in forest interception storage capacity, depth of trenches, forest width, or evaporation of interception storage or ponded water.

In the baseline scenario, runoff was only sensitive to forest infiltration capacity (Δ = 29.6 − 0.0 = 29.6%). In the trenched scenario, runoff was sensitive to forest infiltration capacity (27.7%) and trench infiltration capacity (0.5%). Between scenarios, differences in runoff were sensitive to forest infiltration capacity (1.9%) and trench infiltration capacity (0.5%). In sum, the sensitivity of infiltration to parameter changes were generally aligned with those of Somers et al. (2018) [28], though the total sensitivity of infiltration between scenarios in the current case was smaller. Overall, total infiltration was most sensitive to the infiltration capacity of the forest floor and forest catchment width.

### *3.3. Logistic Regression Models*

While sensitivity analysis provided estimates of the impacts of OAT parameter changes on total infiltration and runoff, only three values for each parameter were used. For the trenched scenario, multiple logistic regression allowed a closer look at the marginal effects of incremental changes in parameter values.

Two considerations that play critical roles in how trenches are designed and managed are the frequency of runoff generation and trench overtopping. In environments where the frequency and magnitude of runoff is high, conventional wisdom suggests constructing more or larger trenches (e.g., reducing forest catchment width or increasing trench storage volume). Understanding the determinants of runoff generation and trench overtopping is therefore key to the effective design, planning, and management of infiltration trenches.

For this analysis, key assumptions of multiple logistic regression were met. Independence of parameters was established with all variable inflation factors $\leq$1.5. Absence of collinearity was established based on the diagonal values in a covariance matrix (all between $-0.2$ and 1.3). Whole effects in both models were statistically significant (likelihood ratio chi-square test, $\alpha < 0.05$) and produced pseudo Rsquare (McFadden) values of 0.9 and 0.9, respectively (Table 3). The results show that the infiltration capacities of forests and trenches, precipitation intensity, and widths of forest catchments were statistically significant determinants of forest runoff and trench overtopping.

**Table 3.** Logistic regression results for forest runoff and trench overtopping models. Significance tests performed using the likelihood-ratio, chi-square statistic ($\alpha < 0.05$).

| | **Forest Runoff** | | | **Trench Overtopping** | | |
|---|---|---|---|---|---|---|
| **Term** | **Estimate** | **SE** | ***p*** | **Estimate** | **SE** | ***p*** |
| Inf. cap. forest (mm hr$^{-1}$) | $-1.0$ | 0.1 | <0.001 | $-0.5$ | 0.1 | <0.001 |
| Precipitation (mm hr$^{-1}$) | 1.2 | 0.1 | <0.001 | 0.7 | 0.1 | <0.001 |
| Inf. cap. trench (mm hr$^{-1}$) | $-0.1$ | 0.0 | <0.001 | $-0.1$ | 0.0 | 0.01 |
| Forest width (m) | 0.1 | 0.0 | <0.001 | 0.2 | 0.0 | <0.001 |
| Trench width (cm) | 0.2 | 0.0 | <0.001 | $-0.1$ | 0.0 | 0.23 |
| Evap. ponding (mm day$^{-1}$) | $-3.3$ | 1.0 | 0.09 | $-4.6$ | 1.7 | 0.21 |
| Evap. forest (mm day$^{-1}$) | $-0.5$ | 0.2 | 0.04 | $-0.1$ | 0.3 | 0.80 |
| *Pseudo Rsquare (U) (McFadden)* | | *0.9* | *<0.001* | | *0.9* | *<0.001* |

Interpretation of coefficients in logistic regression is complicated by the log-likelihood transformation used in the analysis. Therefore, interpretation of parameter effects is usually made by examining log-odds ratios or marginal plots [53]. Here, marginal plots are used to examine the effects of incremental changes in parameters on the probabilities (Y = 1) of runoff or trench overtopping. Figure 4 shows that forest infiltration capacity had the largest effect. As forest infiltration capacity increased, the probabilities of runoff or trench overtopping dropped precipitously from ~70% when infiltration capacities are ~15 mm hr$^{-1}$ to ~0% when capacities are >45 mm hr$^{-1}$. Trench infiltration capacity also was negatively associated with runoff and trench overtopping, but the effects were smaller (more gradual slope). Precipitation intensity also had a strong effect on the probability of runoff and overtopping; though, when other parameters were at their means, even the most intense periods (30–40 mm hr$^{-1}$) resulted in only a ~50% chance of runoff or overtopping. The spatial distribution and design of trenches (i.e., forest catchment width and width of trenches) and evaporation factors (both interception loss and ponding loss) had little effect on the probability of runoff or trench overtopping.

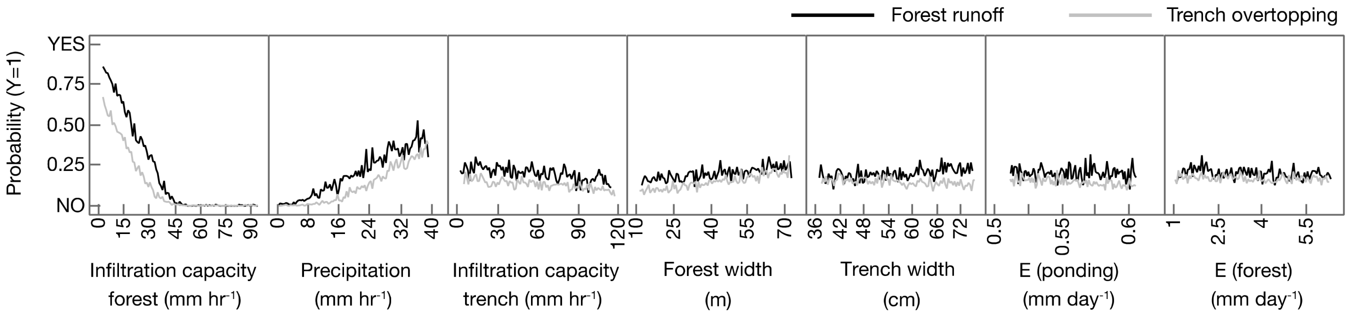


**Figure 4.** Marginal plots of entire range of parameter effects on response probability (*p*) that forest runoff and trench overtopping occur (for both, Yes = 1 and No = 0). Lines represent marginal effects of each parameter when others are held at means (see Table 3).

Only when probabilities of Y = 1 are >50%, were runoff and overtopping more likely than not to occur. When all variables were at their means, only forest infiltration capacities <~20 mm hr$^{-1}$ were likely to generate runoff, while for trench overtopping, only forest infiltration capacities less than ~10 mm hr$^{-1}$ were likely to generate overtopping. These associations are illustrated at the site level in Figure 5.

### 3.4. Cumulative Infiltration and Runoff

Stacked graphs of cumulative precipitation, runoff, and infiltration display the net differences between the baseline and trenched scenarios for each of the seven transects (Figure 5). The top row in each transect (A1–F1) illustrates the forest catchments furthest upslope. The second row (A2–F2) shows the catchment immediately downslope. The pattern continues throughout the transect until the terminal downslope site (4 or 5) is reached. For reference, forest infiltration capacity—the strongest determinant of runoff generation—is illustrated in the upper-left corners of the boxes for each site.

Runoff was predicted to occur only on forest catchments with relatively low infiltration capacities (~2.6–7.3 mm hr$^{-1}$; sites A1, A3, and E1). These infiltration capacities correspond with the ~20 mm hr$^{-1}$ value for runoff generation identified in Figure 4. However, as illustrated in Figure 5, any runoff generated at these three sites flowed into the catchments below (A2, A4, and E2) where infiltration capacities were much higher (51.5, 49.4, and 33.8 mm hr$^{-1}$, respectively) and where all runoff (now run-on) infiltrated within the 1 hr time step (see Tables 1 and A1).

Therefore, no runoff was predicted to have exited a transect or was 'lost' under baseline conditions. Regarding the infiltration of runoff, the wide variation in forest infiltration capacities meant that areas of relatively high infiltration capacity compensated for areas with low infiltration capacity. The same pattern was repeated in the trenched scenario, where all ponded water that overtopped the trenches (also sites A1, A3, and E1) was then infiltrated in the forested catchment immediately downslope (Appendix A, Figure A1).

The cumulative infiltration totals for the baseline and trenched scenarios are shown in Table 4. These totals reflect the modeled results from the 28 sites, which include the infiltration derived from run-on (i.e., from runoff and upslope trench overtopping). The percent increase in infiltration (1.2%) matches that derived from the sensitivity analysis.

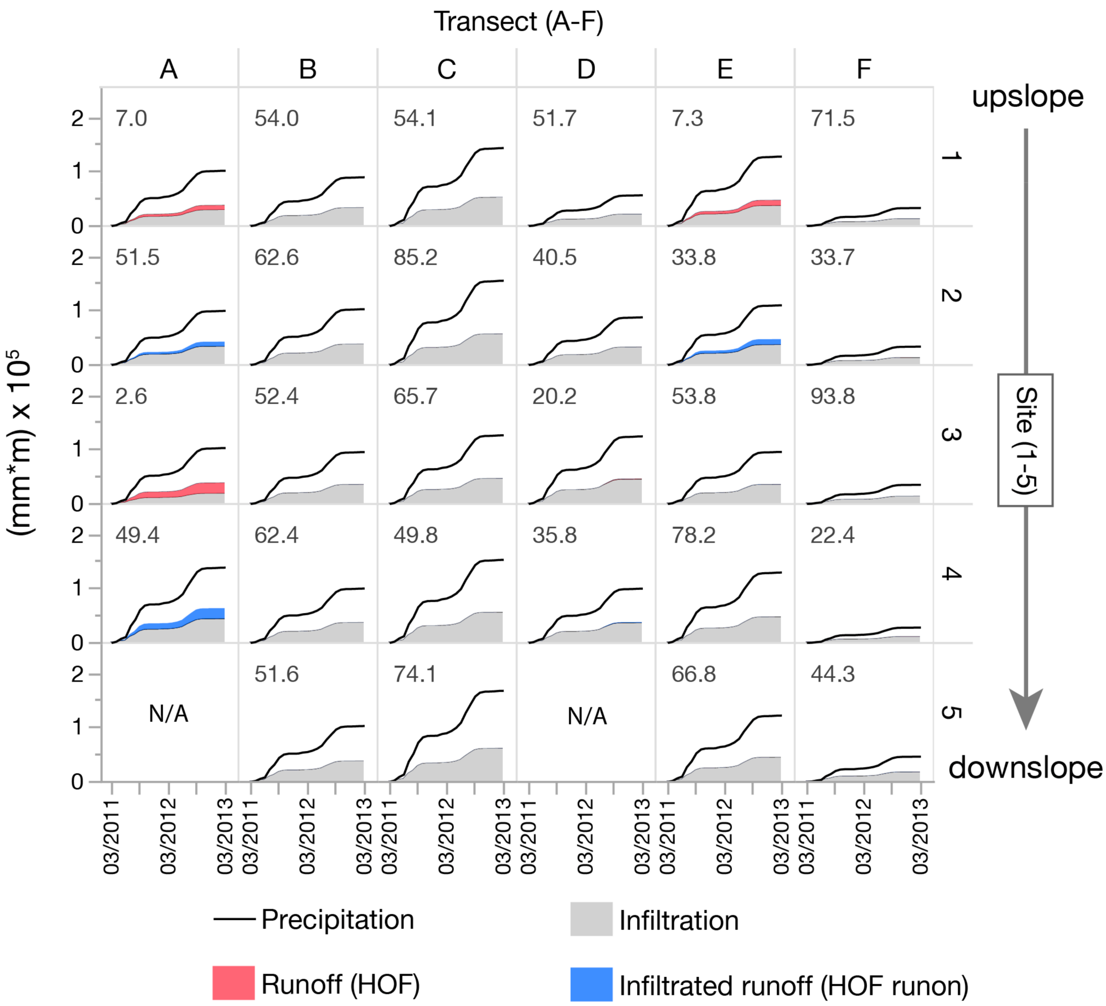


**Figure 5.** Stacked cumulative totals for each transect and site over the two-year study period for the baseline scenario (no trenches). Forest infiltration capacity (mm $hr^{-1}$) is shown in upper-left corners of each box (site). Runoff occurred at only three sites (A1, A3, and E1), but then infiltrated immediately downslope as run-on. No runoff/on escaped any transect due to the high infiltration capacities of downslope sites. The trenched scenario shows a similar pattern, where overtopping occurs in the same three sites and then infiltrates further downslope (Appendix A, Figure A1).

**Table 4.** Cumulative infiltration as a percent of total precipitation under baseline (no trenches) and trenched scenarios. In each scenario, water derived from runoff and overtopping of trenches infiltrates immediately downslope (Figure 5) and is included in total infiltration.

| | | Cumulative Infiltration (% of Total Precipitation) | | |
|---|---|---|---|---|
| **Type** | **Stage** | **No Trenches (Baseline)** | **Trenches (T)** | **Difference** |
| Infiltration | Initial | 56.6 | 57.9 | 1.3 |
| Runoff/on (baseline) and overtopping/run-on (T) | Subsequent | 2.2 | 2.1 | −0.1 |
| Infiltration (total) | Final | 58.8 | 60.0 | 1.2 |

## 4. Discussion

### *4.1. Effectiveness of Infiltration Trenches*

During the two-year study period trenches only provided 1.2% greater infiltration (as proportion of total precipitation) than a baseline (no trenches) scenario. This increase in infiltration is about 68% less than the increase found in alpine grasslands (3.7%) in a similar study [28]. This relatively small 1.2% increase can be explained in the context of two observations.

First, to be effective, trenches must capture water that would otherwise leave the catchment as runoff, allowing it to slowly infiltrate in place. Therefore, hillslopes that do not generate runoff would receive no added benefit from trenching [28]. Indeed, the increased infiltration from trenches observed in alpine grasslands resulted from the capture of runoff only during times of high precipitation intensity. In the current study, precipitation intensities were relatively low compared with soil infiltration capacities, and runoff occurred in only three of the 28 sites. This corresponds with previous studies showing that infiltration excess overland flow in forested areas with low precipitation intensities tends to be infrequent and low magnitude [9], except in local patches, on roads, or in otherwise disturbed areas [61,62]. Catchment-level studies on the threshold precipitation required to generate runoff in forests generally shows infiltration excess overland flow occurs only once infiltration capacities have been reached [63]. Furthermore, in areas where forest runoff occurs locally, it is subjected to infiltration in adjacent soils [8]. The current study confirms this observation. All baseline scenario runoff infiltrated in the forest catchment immediately downslope, before leaving the transect. Therefore, as a means of runoff harvesting, trenches provided no additional benefit in the study area.

A second key observation made by Somers et al. (2018) is that trenches enhance infiltration due to the lack of rainfall interception [28]. Rainfall and run-off fall directly onto exposed trench soils instead of being intercepted by grasses (alpine case) or forest canopy and grasses (subalpine forest case). In other words, the precipitation lost to interception and subsequent evaporation in forested areas of the catchments was received directly as throughfall in trenched areas of the catchments. This difference was shown in the sensitivity analysis (Table 3, ′unperturbed′ row) where no runoff was generated, but where trenches provided 1.2% greater infiltration. Without interception in the trenches, small storms of less than 3 mm (forest interception storage capacity) reached trench soils and infiltrated directly (assuming no ponding). However, in forested areas this precipitation was held in storage (assuming open storage capacity) and subjected to evaporation loss. Forest interception storage was 66% greater than the mean hourly storm total (3 mm/1.8 mm). For an estimate of the additional rainfall available in trenches attributable to the lack of interception, this 1.7% can be multiplied by the % surface area of the catchment occupied by trenches ($W_t * W_f^{\ -1} = 1.1\%$), which equals an available ~1.7% of total precipitation. After adjusting for pond evaporation (~0.5%), this result approximates the 1.2% infiltration benefit we believe is largely due to the lack of interception storage in trenches—even when no runoff is generated.

### *4.2. Environmental Concerns*

The lack of groundcover in trenches introduces an added dimension of concern for the planning, construction, and management of infiltration trenches: the potential for environmental degradation. Trench construction involves the excavation of soils and carbon, potentially exposing plant roots to frost, bacteria, and rot and degrading local ground cover over time [31,64]. The excavated soil is usually piled downslope as unconsolidated fill, where it is susceptible to erosion. Once entrained, these soils often collect in the downslope trenches as alluvium [21,65]. Over time, the silting and clogging of soil pores in trenches can result in lost infiltration capacity and water storage capacity [66]. Unable to store as much runoff, trench overtopping becomes more likely. Overtopping, in turn, often results in concentrated flow around the trench edges, potentially causing localized erosion and damaging the structural integrity of trenches [21,65].

On a broader scale, the increased foot and vehicular traffic associated to trench construction and maintenance can lead to soil compaction and other disturbance effects on runoff generation. In the MNPA, unpaved roads have developed in part to facilitate access to trenches by workers tasked with cleaning trench litter and accumulated sediments. Unpaved roads in forests often lead to lower soil infiltration capacity, increased runoff, and enhanced surface connectivity between runoff source and depositional areas [67,68]. Additional research is needed to assess the potential for these and other environmental impacts (direct and indirect) to result from trenching in the MNPA. Ultimately, careful tradeoff analysis is required to weigh the potential environmental costs of trenching against, in the current case, a 1.2% increase in total infiltration. The results from such analyses should then be weighed against the benefits of nature-based or vegetative approaches to runoff mitigation and management [11–17].

### 4.3. Generalizability, Assumptions, and Limitations

This study suggests that infiltration trenching in mountain protected areas first requires careful assessment of environmental factors and precipitation-runoff relationships to ensure trenches are necessary. In Mexico, precise estimates of the extent of trenching in forested areas are unavailable, though several studies have examined the effects of other cross-slope earthworks on soil conservation in individual forests [64] and broader regions [69,70]. In general, these studies highlight the limitations of mechanical soil conservation measures and the need for careful assessment of environmental factors before designing and implementing them. In the context of forest water management in Mexico, this study provides additional justification for such assessments.

The findings from this study also highlight the key role that the spatial variability of soil infiltration capacity plays in driving rainfall-runoff responses in forested catchments. This variability is a fundamental characteristic of forest environments, though it is seldom incorporated adequately into runoff models, which often rely instead on statistical approximations [71]. In this study, illustrating the impacts of this variability on runoff generation was key to evaluating the effectiveness of trenches as runoff harvesting structures. Because variable infiltration capacity is a fundamental characteristic of most forest environments, the central findings of this study are relevant to any forest hillslope environment where trenching is being considered as a means of enhancing infiltration.

This study has several limitations. Though we measured soil infiltration capacity in 56 soils (28 forest, 28 trench) and assigned each to the runoff calculations of individual forest catchments, better understanding of the variability of soil infiltration capacity is needed to improve our estimates. In addition, better understanding of the spatial variability of other environmental factors is needed. Though notoriously difficult to measure, interception storage and loss is highly variable in forest catchments [47,72–74]. For modeling purposes, we assumed a uniform rate of forest canopy and grassland (3 mm) and trench (0 mm) interception storage based on previous studies in similar environments. However, this discounted the potential impacts of breaks in forest cover or the periodic accumulation of litter in trenches. Similarly, better understanding of the variable impacts of meteorological parameters would help improve model accuracy, though measuring the hydroclimatic heterogeneity of mountain weather remains a fundamental challenge to watershed science [75]. Finally, our models did not account for the potential impacts of unpaved roads on catchment hydrology. Unpaved roads play important roles in both runoff generation and in the interception of run-on from catchments above. The potential for trenches to provide benefits to runoff management around road drainage points requires additional study.

## 5. Conclusions

This study examined the effectiveness of infiltration trenches in a subalpine forested catchment in Mexico. Sensitivity analysis and multiple logistic regression were used to model two scenarios: a baseline (no trenches) scenario and a trenched scenario. Findings show that trenches provided a 1.2% increase in infiltration relative to precipitation over the two-year study period. This is ~68% less than the increase found in alpine grasslands, which comprises the only available comparison. Forest infiltration capacity was an important determinant of runoff generation, which occurred in only three of the 28 sub-catchments. However, in this study infiltration excess runoff generated on soils with relatively low infiltration capacities was infiltrated immediately downslope in forest catchments with higher infiltration capacities. Therefore, no water loss due to runoff occurred. As a result, infiltration trenches provided no additional benefit for runoff harvesting in the study area. The small infiltration benefit we found likely derived instead from the lack of vegetation interception associated with the groundcover disturbance of the trenches. In sum, this study cautions against the construction of infiltration trenches in forested environments with low precipitation intensities relative to infiltration capacities without first carefully assessing the precipitation–runoff response relationships at the sub-catchment level to determine if trenches are justified. Yet, even in these contexts, natural vegetation-based approaches are likely to be more effective, efficient, and sustainable than the large-scale excavation of earthen trenches.

**Author Contributions:** Conceptualization, M.C.L. and C.E.R.-S.; methodology, M.C.L. and C.E.R.-S.; fieldwork, M.C.L. and C.E.R.-S.; formal analysis, M.C.L. and C.E.R.-S.; investigation, M.C.L. and C.E.R.-S.; resources, M.C.L.; data curation, M.C.L.; writing—original draft preparation, M.C.L.; writing—review and editing, M.C.L. and C.E.R.-S.; visualization, M.C.L. and C.E.R.-S.; funding acquisition, M.C.L. Both authors have read and agreed to the published version of the manuscript.

**Funding:** This research received funding from the Research Grants Committee of the University of Alabama.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** All primary data not provided in the study are available upon request.

**Acknowledgments:** We thank Sandra Nashif for insightful comments on this paper, and Jordan Cissell and James Misfeldt for assistance in fieldsite identification.

**Conflicts of Interest:** The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

## Appendix A

**Table A1.** Runoff velocity ($V$) and time of concentration ($T_c$) estimates for each transect and site. Because the mean width of forest catchments was over 100 ft (Table 1), Manning's calculations were made using shallow concentrated flow estimates (USDA, 2010, 15–7) [44]. Velocity and time of concentration for each site is shown using roughness coefficients for forests with heavy ground litter as outlined by USDA (2010, Figure 15–4, Equations 15–1) [44].

| Transect | A | | B | | C | | D | | E | | F | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Site** | **V (m min$^{-1}$)** | **$T_C$ (min)** | **V (m min$^{-1}$)** | **$T_C$ (min)** | **V (m min$^{-1}$)** | **$T_C$ (min)** | **V (m min$^{-1}$)** | **$T_C$ (min)** | **V (m min$^{-1}$)** | **$T_C$ (min)** | **V (m min$^{-1}$)** | **$T_C$ (min)** |
| 1 | 14.6 | 3.0 | 16.5 | 2.4 | 14.6 | 4.3 | 11.0 | 2.2 | 14.6 | 3.8 | 14.6 | 1.0 |
| 2 | 14.6 | 2.7 | 16.5 | 2.7 | 12.8 | 5.2 | 14.6 | 2.6 | 11.0 | 3.9 | 12.8 | 1.1 |
| 3 | 12.8 | 3.5 | 16.5 | 2.5 | 14.6 | 3.7 | 12.8 | 4.2 | 11.0 | 3.8 | 12.8 | 1.2 |
| 4 | 11.0 | 4.7 | 16.5 | 2.6 | 14.6 | 4.5 | 11.0 | 3.9 | 14.6 | 3.8 | 14.6 | 0.8 |
| 5 | na | na | 14.6 | 3.0 | 11.0 | 6.6 | na | na | 14.6 | 3.6 | 15.5 | 1.3 |
| Tot. (min) | | 13.9 | | 13.3 | | 24.4 | | 12.9 | | 18.9 | | 5.5 |

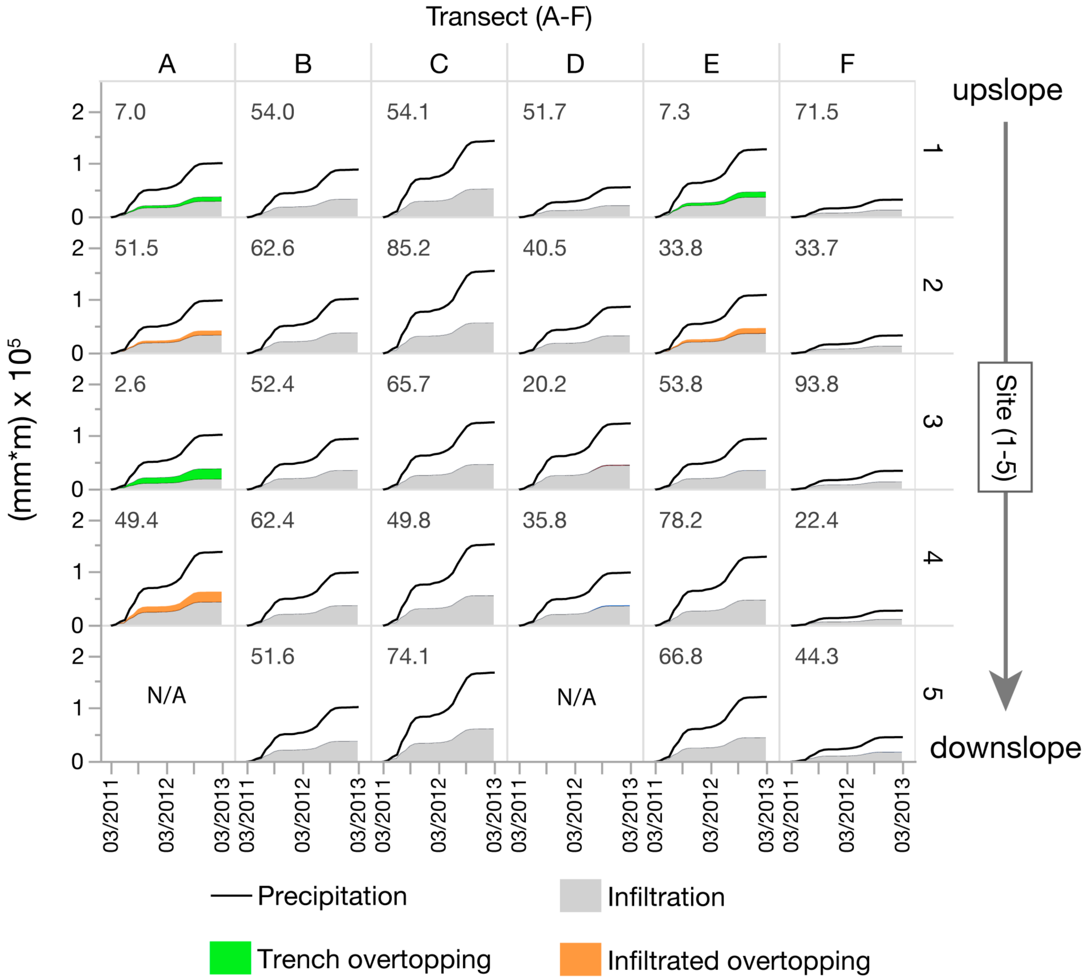


**Figure A1.** Stacked cumulative totals for each transect and site over the two-year study period for the trenched scenario. Forest infiltration capacity (mm hr$^{-1}$) shown in upper-left corners of each box (site). Trench overtopping occurred at only three sites (A1, A3, and E1). However, all overtopping infiltrated in the site immediately downslope. No overtopping escaped any terminal (downslope) site due to sites with high forest infiltration capacity.

## References


1. González, H.F.; Porras, J.L.C.; de Gutiérrez, I.B.; LaMoreaux, J.W. (Eds.) *Management of Water Resources in Protected Areas*; Environmental Earth Sciences; Springer: Berlin/Heidelberg, Germany, 2013; ISBN 978-3-642-16329-6.
2. Viviroli, D.; Kummu, M.; Meybeck, M.; Kallio, M.; Wada, Y. Increasing Dependence of Lowland Populations on Mountain Water Resources. *Nat. Sustain.* **2020**, *3*, 917–928. [CrossRef]
3. Viviroli, D.; Dürr, H.H.; Messerli, B.; Meybeck, M.; Weingartner, R. Mountains of the World, Water Towers for Humanity: Typology, Mapping, and Global Significance. *Water Resour. Res.* **2007**, *43*, W07447. [CrossRef]
4. CONANP; SEMARNAT; GIZ. *Valuation of Ecosystem Services*; Comisión Nacional de Áreas Naturales Protegidas; Secretaría de Medio Ambiente y Recursos Naturales; Deutsche Sesellschaft für Internationales Zusammenarbeit; Iztaccíhuatl-Popocatépetl National Park: Mexico City, Mexico, 2017.
5. Goeking, S.A.; Tarboton, D.G. Forests and Water Yield: A Synthesis of Disturbance Effects on Streamflow and Snowpack in Western Coniferous Forests. *J. For.* **2020**, *118*, 172–192. [CrossRef]
6. Garcia-Chevesich, P.A.; Neary, D.G.; Scott, D.F.; Benyon, T.R.; International Hydrological Programme; IHP-VIII; Unesco; Regional Office for Sciences for Latin America and the Caribbean. *Forest Management and the Impact on Water Resources: A Review of 13 Countries*; United Nations Educational, Scientific, and Cultural Organization International Hydrological Programme International Sediment Initiative: Paris, France, 2017; ISBN 978-92-3-100216-8.
7. Suding, K.; Higgs, E.; Palmer, M.; Callicott, J.B.; Anderson, C.B.; Baker, M.; Gutrich, J.J.; Hondula, K.L.; LaFevor, M.C.; Larson, B.M. Committing to Ecological Restoration. *Science* **2015**, *348*, 638–640. [CrossRef] [PubMed]
8. Anderson, H.W.; Hoover, M.D.; Reinhart, K.G. *Forests and Water: Effects of Forest Management on Floods, Sedimentation and Water Supply*; USDA Forest Serv. Gen. Tech. Rep.: Berkeley, CA, USA, 1976.

9. Ceci, P. *Forests and Water: International Momentum and Action*; FAO: Rome, Italy, 2013; ISBN 978-92-5-107418-3.
10. Keller, A.A.; Fox, J. Giving Credit to Reforestation for Water Quality Benefits. *PLoS ONE* **2019**, *14*, e0217756. [CrossRef] [PubMed]
11. Page, T.; Chappell, N.A.; Beven, K.J.; Hankin, B.; Kretzschmar, A. Assessing the Significance of Wet-Canopy Evaporation from Forests during Extreme Rainfall Events for Flood Mitigation in Mountainous Regions of the United Kingdom. *Hydrol. Process.* **2020**, *34*, 4740–4754. [CrossRef]
12. Stanchi, S.; Zecca, O.; Hudek, C.; Pintaldi, E.; Viglietti, D.; D'Amico, M.E.; Colombo, N.; Goslino, D.; Letey, M.; Freppaz, M. Effect of Soil Management on Erosion in Mountain Vineyards (N-W Italy). *Sustainability* **2021**, *13*, 1991. [CrossRef]
13. LaFevor, M.; Cissell, J.; Misfeldt, J. Agave Cultivation, Terracing, and Conservation in Mexico. *Focus Geogr.* **2018**, *61*, 1–7. [CrossRef]
14. Subbarao, G.V.; Kishii, M.; Bozal-Leorri, A.; Ortiz-Monasterio, I.; Gao, X.; Ibba, M.I.; Karwat, H.; Gonzalez-Moro, M.B.; Gonzalez-Murua, C.; Yoshihashi, T.; et al. Enlisting Wild Grass Genes to Combat Nitrification in Wheat Farming: A Nature-Based Solution. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2106595118. [CrossRef]
15. Preti, F.; Giadrossich, F. Root Reinforcement and Slope Bioengineering Stabilization by Spanish Broom (*Spartium Junceum* L.). *Hydrol. Earth Syst. Sci.* **2009**, *13*, 1713–1726. [CrossRef]
16. Apollonio, C.; Petroselli, A.; Tauro, F.; Cecconi, M.; Biscarini, C.; Zarotti, C.; Grimaldi, S. Hillslope Erosion Mitigation: An Experimental Proof of a Nature-Based Solution. *Sustainability* **2021**, *13*, 6058. [CrossRef]
17. Seddon, N.; Chausson, A.; Berry, P.; Girardin, C.A.J.; Smith, A.; Turner, B. Understanding the Value and Limits of Nature-Based Solutions to Climate Change and Other Global Challenges. *Philos. Trans. R. Soc. B Biol. Sci.* **2020**, *375*, 20190120. [CrossRef]
18. Ellison, D.; Morris, C.E.; Locatelli, B.; Sheil, D.; Cohen, J.; Murdiyarso, D.; Gutierrez, V.; van Noordwijk, M.; Creed, I.F.; Pokorny, J.; et al. Trees, Forests and Water: Cool Insights for a Hot World. *Glob. Environ. Chang.* **2017**, *43*, 51–61. [CrossRef]
19. Locatelli, B.; Homberger, J.-M.; Ochoa-Tocachi, B.; Bonnesoeur, V.; Román, F.; Drenkhan, F.; Buytaert, W. *Impactos De Las Zanjas De Infiltración En El Agua Y Los Suelos: ¿Qué Sabemos?* Doctoral dissertation, Infraestructura Natural para la Seguridad Hídrica; Forest Trends: Lima, Peru, 2020.
20. Beckers, B.; Berking, J.; Schütt, B. Ancient Water Harvesting Methods in the Drylands of the Mediterranean and Western Asia. *eTopoi. J. Anc. Stud.* **2013**, *2*, 145–164.
21. LaFevor, M.C. Restoration of Degraded Agricultural Terraces: Rebuilding Landscape Structure and Process. *J. Environ. Manag.* **2014**, *138*, 32–42. [CrossRef]
22. SAG. *Realizaciones en la Montaña de la Malinche*; SAG (Secretaria de Agricultura y Ganaderia): Ciudad de México, Mexico, 1963.
23. Cotler, H.; Cuevas, M.L. Adoption of Soil Conservation Practices through Knowledge Governance: The Mexican Experience. *J. Soil Sci. Environ. Manag.* **2019**, *10*, 1–11. [CrossRef]
24. SEMARNAT; CONANP; CONAFOR; PRONATURA; Coca-Cola de México. *Informe Anual: Programa Nacional de Reforestación y Cosecha de Agua*; Pronatura México: Ciudad de México, Mexico, 2010; p. 149.
25. Cota, E.; Marín, L.; Balcazar, M. Recargas de Acuíferos Mediante La Construcción de Tinas Ciegas. *ProNatura* **2011**, *3*, 12–14.
26. SEMARNAT. *Principales Impactos Del Programa de Empleo Temporal en las Áreas Naturales Protegidas (PET 2007–2012)*; Comisión Nacional de Areas Naturales Protegidas (CONANP), Secretaria de Medio Ambiente y Recursos Naturales, Mexico (SEMARNAT): Mexico City, Mexico, 2013; p. 66.
27. Martos-Rosillo, S.; Durán, A.; Castro, M.; Vélez, J.J.; Martín-Civantos, J.M.; Mateos, L.; Durán, J.J.; Gutiérrez, C.; Hermoza, R.M.; Peña, F. *Ancestral Techniques of Water Sowing and Harvesting in Ibero-America: Examples of Hydrogeoethical Systems*; Geoethics & Groundwater Management Congress: Porto, Portugal, 2020; p. 7.
28. Somers, L.D.; McKenzie, J.M.; Zipper, S.C.; Mark, B.G.; Lagos, P.; Baraer, M. Does Hillslope Trenching Enhance Groundwater Recharge and Baseflow in the Peruvian Andes? *Hydrol. Process.* **2018**, *32*, 318–331. [CrossRef]
29. LaFevor, M.C. Conservation Engineering and Agricultural Terracing in Tlaxcala, Mexico. Ph.D. Thesis, The University of Texas at Austin, Austin, TX, USA, 2014.
30. Mastretta-Yanes, A.; Moreno-Letelier, A.; Piñero, D.; Jorgensen, T.H.; Emerson, B.C. Biodiversity in the Mexican Highlands and the Interaction of Geology, Geography and Climate within the Trans-Mexican Volcanic Belt. *J. Biogeogr.* **2015**, *42*, 1586–1600. [CrossRef]
31. Werner, G. La Desforestacion en el Valcan "La Malinche" y sus Consecuencias en el Desarrollo de los Suelos así como en sus Propiedades Ecológicas. In *Proyecto Puebla-Tlaxcala. Comunicaciones*; El Proyecto México de la Fundación Alemana para la investigación científica; Gobierno del Estado de Tlaxcala; Universidad Autonoma de Tlaxcala: Puebla, Mexico, 1976; Volume 13, pp. 19–28.
32. SEMARNAT; CONANP. *Programa de Manejo Parque Nacional La Montaña Malinche O Matlalcuéyatl*; primera; Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT): Mexico City, Mexico, 2013.
33. Castro-Govea, R.; Siebe, C. Late Pleistocene–Holocene Stratigraphy and Radiocarbon Dating of La Malinche Volcano, Central Mexico. *J. Volcanol. Geotherm. Res.* **2007**, *162*, 20–42. [CrossRef]
34. Mora, A.; García-Gamboa, M.; Sánchez-Luna, M.S.; Gloria-García, L.; Cervantes-Avilés, P.; Mahlknecht, J. A Review of the Current Environmental Status and Human Health Implications of One of the Most Polluted Rivers of Mexico: The Atoyac River, Puebla. *Sci. Total Environ.* **2021**, *782*, 146788. [CrossRef]
35. Wong González, J.C.; de Villers Ruiz, M.L. Evaluación de Combustibles y Su Disponibilidad En Incendios Forestales: Un Estudio En El Parque Nacional La Malinche. *Investig. Geogr.* **2007**, *62*, 87–103. [CrossRef]

36. Cuautle, M.; Castillo-Guevara, C.; Juárez-Juárez, B.; Pérez-Toledo, G. Ants (Hymenoptera: Formicidae) in a Temperate Ecosystem from La Malinche National Park, Mexico. *Fla. Entomol.* **2020**, *103*, 321–328. [CrossRef]
37. Lauer, W.; Stiehl, E. *La Classificación Del Clima En La Región Puebla-Tlaxcala*; Fundación Alemana para la Investigación Científica: Mexico City, Mexico, 1973.
38. Castillo-Rodríguez, M.; López-Blanco, J.; Muñoz-Salinas, E. A Geomorphologic GIS-Multivariate Analysis Approach to Delineate Environmental Units, a Case Study of La Malinche Volcano (Central México). *Appl. Geogr.* **2010**, *30*, 629–638. [CrossRef]
39. Bolaños Suárez, Y.R. *Diagnóstico Socioeconómico Del Parque Nacional Malinche Bajo El Criterio de Cuencas Hidrológicas*; Universidad Autónoma del Estado de México: Tenancingo, Mexico, 2014.
40. Castro Pérez, F. La política gubernamental para el manejo del Parque Nacional "La Malinche": Una visión etnográfica desde el interior de las instituciones ambientalistas. In Proceedings of the the Commons in an Age of Global Transition: Challenges, Risks and Opportutnities, Tenth Biennial Conference of the International Association for the Study of Common Property (IASCP), Oaxaca, Mexico, 9–13 August 2004; p. 27.
41. Reynolds, W.D.; Elrick, D.E. In Situ Measurement of Field-Saturated Hydraulic Conductivity, Sorptivity, and the $\alpha$-Parameter using the Guelph Permeameter. *Soil Sci.* **1985**, *140*, 292–302. [CrossRef]
42. Juliá, F.E.; Snyder, V.A.; Vázquez, M.A. Validation of Soil Survey Estimates of Saturated Hydraulic Conductivity in Major Soils of Puerto Rico. *Hydrology* **2021**, *8*, 94. [CrossRef]
43. Ramos-Scharrón, C.E.; LaFevor, M.C. The Role of Unpaved Roads as Active Source Areas of Precipitation Excess in Small Watersheds Drained by Ephemeral Streams in the Northeastern Caribbean. *J. Hydrol.* **2016**, *533*, 168–179. [CrossRef]
44. Kattel, D.B.; Yao, T.; Yang, K.; Tian, L.; Yang, G.; Joswiak, D. Temperature Lapse Rate in Complex Mountain Terrain on the Southern Slope of the Central Himalayas. *Theor. Appl. Climatol.* **2013**, *113*, 671–682. [CrossRef]
45. Dingman, S.L. *Physical Hydrology*, 2nd ed.; Waveland Press Incorporated: Long Grove, IL, USA, 2002.
46. Monteith, J.L. Evaporation and Environment. *Symp. Soc. Exp. Biol.* **1965**, *19*, 205–234. [PubMed]
47. Návar, J. Modeling Rainfall Interception Loss Components of Forests. *J. Hydrol.* **2020**, *584*, 124449. [CrossRef]
48. Guevara-Escobar, A.; Gonzalez-Sosa, E.; Ramos-Salinas, M.; Hernandez-Delgado, G.D. Experimental Analysis of Drainage and Water Storage of Litter Layers. *Hydrol. Earth Syst. Sci.* **2007**, *11*, 1703–1716. [CrossRef]
49. Putuhena, W.M.; Cordery, I. Estimation of Interception Capacity of the Forest Floor. *J. Hydrol.* **1996**, *180*, 283–299. [CrossRef]
50. Link, T.E.; Unsworth, M.; Marks, D. The Dynamics of Rainfall Interception by a Seasonal Temperate Rainforest. *Agric. For. Meteorol.* **2004**, *124*, 171–191. [CrossRef]
51. USDA. *National Engineering Handbook*; Chapter 15—Time of Concentration; Part 630—Hydrology; United States Department of Agriculture (USDA): Washington, DC, USA, 2010.
52. Pianosi, F.; Beven, K.; Freer, J.; Hall, J.W.; Rougier, J.; Stephenson, D.B.; Wagener, T. Sensitivity Analysis of Environmental Models: A Systematic Review with Practical Workflow. *Environ. Model. Softw.* **2016**, *79*, 214–232. [CrossRef]
53. LaFevor, M.C.; Ponette-González, A.G.; Larson, R.; Mungai, L.M. Spatial Targeting of Agricultural Support Measures: Indicator-Based Assessment of Coverages and Leakages. *Land* **2021**, *10*, 740. [CrossRef]
54. Lozano-Trejo, S.; Aquino, J.O.; Pérez-León, M.I.; Castañeda-Hidalgo, E.; Díaz-Zorrilla, G.O.; Santiago-Martínez, G.M. Infiltración y escurrimiento de agua en suelos de una cuenca en el sur de México. *Rev. Terra Latinoam.* **2020**, *38*, 57–66. [CrossRef]
55. Price, K.; Jackson, C.R.; Parker, A.J. Variation of Surficial Soil Hydraulic Properties across Land Uses in the Southern Blue Ridge Mountains, North Carolina, USA. *J. Hydrol.* **2010**, *383*, 256–268. [CrossRef]
56. Robichaud, P.R. Fire Effects on Infiltration Rates after Prescribed Fire in Northern Rocky Mountain Forests, USA. *J. Hydrol.* **2000**, *231–232*, 220–229. [CrossRef]
57. Sosa-Pérez, G.; MacDonald, L.H. Effects of Closed Roads, Traffic, and Road Decommissioning on Infiltration and Sediment Production: A Comparative Study Using Rainfall Simulations. *Catena* **2017**, *159*, 93–105. [CrossRef]
58. CLICOM. CLImate COMputing Database. Available online: http://clicom-mex.cicese.mx/ (accessed on 14 August 2021).
59. Kelliher, F.M.; Leuning, R.; Schulze, E.D. Evaporation and Canopy Characteristics of Coniferous Forests and Grasslands. *Oecologia* **1993**, *95*, 153–163. [CrossRef]
60. Yihdego, Y.; Webb, J.A. Comparison of Evaporation Rate on Open Water Bodies: Energy Balance Estimate versus Measured Pan. *J. Water Clim. Chang.* **2017**, *9*, 101–111. [CrossRef]
61. Croke, J.; Hairsine, P.; Fogarty, P. Runoff Generation and Re-Distribution in Logged Eucalyptus Forests, South-Eastern Australia. *J. Hydrol.* **1999**, *216*, 56–77. [CrossRef]
62. Jencso, K.G.; McGlynn, B.L. Hierarchical Controls on Runoff Generation: Topographically Driven Hydrologic Connectivity, Geology, and Vegetation. *Water Resour. Res.* **2011**, *47*. [CrossRef]
63. Farrick, K.K.; Branfireun, B.A. Soil Water Storage, Rainfall and Runoff Relationships in a Tropical Dry Forest Catchment. *Water Resour. Res.* **2014**, *50*, 9236–9250. [CrossRef]
64. Cotler-Avalos, H.; Cram, S.; Martínez Trinidad, S.; Bunge, V. Evaluación de prácticas de conservación de suelos forestales en México: Caso de las zanjas trinchera. *Investig. Geogr. Bol. Del Inst. De Geogr.* **2015**, *2015*, 6–18. [CrossRef]
65. Wilken, G.C. *Good Farmers: Traditional Agricultural Resource Management in Mexico and Central America*; University of California Press: Berkeley, CA, USA, 1987; ISBN 0-520-05277-3.
66. Mastrocicco, M.; Colombani, N.; Salemi, E.; Boz, B.; Gumiero, B. Managed Aquifer Recharge via Infiltration Ditches in Short Rotation Afforested Areas. *Ecohydrology* **2016**, *9*, 167–178. [CrossRef]

67. Ramos-Scharrón, C.E.; LaFevor, M.C. Effects of Forest Roads on Runoff Initiation in Low-Order Ephemeral Streams. *Water Resour. Res.* **2018**, *54*, 8613–8631. [CrossRef]
68. Cotler, H.; Merino, L.; Martinez-Trinidad, S. Forest Soil Management: A Mexican Experience. *Open J. Soil Sci.* **2020**, *10*, 374. [CrossRef]
69. Cotler, H.; Cram, S.; Martinez-Trinidad, S.; Quintanar, E. Forest Soil Conservation in Central Mexico: An Interdisciplinary Assessment. *Catena* **2013**, *104*, 280–287. [CrossRef]
70. Miyata, S.; Gomi, T.; Sidle, R.C.; Hiraoka, M.; Onda, Y.; Yamamoto, K.; Nonoda, T. Assessing Spatially Distributed Infiltration Capacity to Evaluate Storm Runoff in Forested Catchments: Implications for Hydrological Connectivity. *Sci. Total Environ.* **2019**, *669*, 148–159. [CrossRef]
71. Baiamonte, G. Simplified Interception/Evaporation Model. *Hydrology* **2021**, *8*, 99. [CrossRef]
72. Levia, D.F.; Carlyle-Moses, D.; Tanaka, T. (Eds.) *Forest Hydrology and Biogeochemistry: Synthesis of Past Research and Future Directions*; Ecological Studies; Springer Science & Business Media: Dordrecht, The Netherlands, 2011; Volume 216, ISBN 978-94-007-1362-8.
73. Zheng, C.; Jia, L. Global Canopy Rainfall Interception Loss Derived from Satellite Earth Observations. *Ecohydrology* **2020**, *13*, e2186. [CrossRef]
74. Aalto, J.; Riihimäki, H.; Meineri, E.; Hylander, K.; Luoto, M. Revealing Topoclimatic Heterogeneity Using Meteorological Station Data. *Int. J. Climatol.* **2017**, *37*, 544–556. [CrossRef]
75. Ponette-González, A.G.; Brauman, K.A.; Marín-Spiotta, E.; Farley, K.A.; Weathers, K.C.; Young, K.R.; Curran, L.M. Managing Water Services in Tropical Regions: From Land Cover Proxies to Hydrologic Fluxes. *Ambio* **2015**, *44*, 367–375. [CrossRef]