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RESEARCH ARTICLE

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# Vegetation influences on infiltration in Hawaiian soils

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## Abstract

Changes in vegetation communities caused by removing trees, introducing grazing ungulates, and replacing native plants with invasive species have substantially altered soil infiltration processes and rates in Hawaii. These changes directly impact run-off, erosion, plant-available water, and aquifer recharge. We hypothesize that broad vegetation communities can be characterized by distributions of field-saturated hydraulic conductivity ($K_{fs}$). We used 290 measurements of $K_{fs}$ calculated from infiltration tests from 5 of the Hawaiian Islands to show this effect. We classified the data using 3 broad ecosystem categories: grasses, trees and shrubs, and bare soil. The soils of each site have coevolved with past and present ecological communities without significant mechanical disturbance by agriculture or urban development. Geometric mean values $K_{fs}$ are 203 mm/hr for soils hosting trees and shrubs, 50 mm/hr for grasses, and 13 mm/hr for bare soil. Differences are statistically significant at the 95% confidence level. These examples show that it is feasible to make maps of relative $K_{fs}$ based on field and ecosystem data. These ecosystem trends can be used to estimate ongoing changes to run-off and recharge from climate and land use change. Greater $K_{fs}$ for ecosystems with primarily trees and shrubs suggests that management decisions concerning reforestation or other changes of vegetation can have substantial hydrologic impacts.

**KEYWORDS**

infiltration, soils, Hawaii, land cover

## 1 | INTRODUCTION

Vegetation influences the chemistry, structure, organic content, and strength of soils. Roots and burrowing organisms' bioturbate soils, changing the pathways and generally increasing porosity and infiltration capacity (Devitt & Smith, 2002; Gabet et al., 2003; Noguchi, Tsuboyama, Sidle, & Hosoda, 1999; Perkins, Nimmo, Medeiros, Szutu, & von Allmen, 2014; Williams & Vepraskas, 1994). As a consequence, alterations in vegetation may create broad-scale changes in the way rainfall is partitioned into run-off and recharge. Vegetation can also modify soil properties in measureable ways over short timescales (Perkins, Nimmo, & Medeiros, 2012), influencing plant-available water, evapotranspiration, and drainage (D'Odorico, Caylor, Okin, & Scanlon, 2007; Grayson et al., 2006; Nimmo, Perkins, et al., 2009; Sandvig & Phillips, 2006). Infiltration experiments in the field are commonly used to measure the rate at which soil absorbs water at the ground surface. Infiltration capacity is a commonly used term which is the maximum rate at which soils can absorb water, generally occurring under dry conditions when sorptive influences are greatest. The infiltration capacity tends to decrease as the soil moisture content of the surface layers increases. Once infiltration rates become steady, the data can be used to calculate field-saturated hydraulic conductivity ($K_{fs}$). $K_{fs}$ is the ability of the soil to transmit water under field-saturated conditions, which includes some amount of trapped air within pores.

A number of studies have explored the link between ecosystem composition and hydrology (Agnese, Bagarello, Baiamonte, & Iovino, 2011; Alaoui, Caduff, Gerke, & Weingartner, 2011; Bachmair, Weiler, & Nützmann, 2009; Bormann & Klaassen, 2008; Harden & Mathews, 2000). Hawaiian ecosystems have high plant species diversity but have been fragmented, reduced, and ecologically degraded (Cabin et al., 2001; Medeiros, vonAllmen, & Chimera, 2013; Medeiros, Loope, & Holt, 1986; Rock, 1913). The impacts of introduced grazing ungulates, fire, and invasive species have resulted in replacement of native and endemic species with non-native grasslands and in some cases bare soil (Cabin et al., 2001). Several studies in Hawaii have highlighted the effects of the loss or restoration of native forest on the near-surface hydrology. For instance, Perkins et al. (2014, 2012) found that $K_{fs}$ calculated from infiltration rates, preferential flow, and hydrophobicity were increased by at least a factor of 2 on a decadal timescale with forest restoration efforts compared with nearby grassland which is representative of prerestoration conditions. Loss of native forests was also shown to result in the loss of recharge form fog drip from trees and shrubs (Giambelluca, DeLay, Nullet, Sholl, & Gingerich, 2011; Scholl, Giambelluca, Gingerich, Nullet, & Loope, 2007; Stock, Coil, & Kirch, 2003). General trends in near surface hydrology coupled with vegetation type have not been evaluated systematically using a large data set of direct field infiltration measurements from a wide variety sites with varying soil types. The aim of this study is to evaluate trends and their implications using new and previously published data.

## 2 | SITE DESCRIPTIONS

Some of the infiltration data presented and analysed here are from our own investigation and are previously unpublished. The remainder come from previously published studies from various locations across the Hawaiian Islands and contain varying degrees of information on site characteristics. Table 1 gives the locations of the studies and details on methods used to measure infiltration and the main purposes of the original investigations. Recently measured infiltration rates are also presented from the islands of Hawaii and Molokai. Mean annual precipitation ranges from 200 to 750 mm/year for most of the sites (Giambelluca et al., 2013). Where local gages measure precipitation, specific values are listed below. The data sets used in this study were chosen because they allow for land-cover comparisons; data sets not viable for this type of comparison were excluded. Data were compared on a site by site basis to keep variability of factors aside from vegetation minimal, such as parent material and soil type.

## 3 | RECENT MEASUREMENTS

Keamuku Maneuver Area (KMA; Figure 1) site is a grass and shrub land, part of the U.S. Army's Pohakuloa Training Area on the island of Hawaii. Pleistocene flows of the Hamakua Volcanics are covered by airfall and aeolian deposits of silt and fine sand. This fine-grained substrate varies from a few decimetres to 4–5 m thick. Mean precipitation ranges from 200 to 750 mm/year (Giambelluca et al., 2013). We conducted field infiltration experiments here to estimate the rainfall rate that would likely generate overland flow and to examine the influence of current vegetation communities on infiltation. Invasive grasses present at the infiltration sites included Buffel (*Cenchrus cillaris*), fountain (*Cenchrus Setaceus*), and kikuyu (*Cenchrus clandestinus*). The main tree species is non-native eucalyptus (*Eucalyptus robusta*) and the main native shrub is 'a'ali'i (*Dodonea viscosa)*. Measurements of field-saturated hydraulic conductivity ($K_{fs}$) at the KMA were conducted with small diameter, single-ring infiltrometers by the method of Nimmo, Schmidt, Perkins, and Stock (2009).

Infiltration measurements on the island of Molokai were collected to examine rainfalls that would generate hillslope erosion as part of a larger study. The field sites are steeplands on the Kawela watershed on Molokai's arid leeward side (Figure 1). Many of the soils are likely airfall deposits of silt, approximately 1.45 Ma old. The original organic soil has largely eroded away during historic landuse, leaving behind silt-sized airfall deposits that are up to 1 m thick. Lower regions of the watershed are now dominated by bare soil and sparse grasses, primarily kikuyu (*Cenchrus clandestinus*). Mean precipitation ranges from 200 to 750 mm/year (Giambelluca et al., 2013). Most $K_{fs}$ measurements were conducted with small diameter tension disk infiltrometers (described below) on bare soil; five measurements were conducted with small diameter, single-ring infiltrometers by the method of Nimmo, Schmidt, et al. (2009).

## 4 | PREVIOUS MEASUREMENTS

The Auwahi site on Maui is a dryland forest, which has relatively thin (~1 m), stoney soils with outcrops of basalt rubble that form ridges across the landscape, has two distinct and separate vegetation regimes: invasive grasses, primarily kikuyu; and native trees and shrubs, primarily *olopua* (*Nestegis sandwicensis*) and *'a'ali'i* (*Dodonaea*

**TABLE 1** Details relevant to the data sets (300 measured points in total) used in this analysis

| Site, Island | Vegetation categories present | # of measurements | Method used to determine $K_{fs}$ | Previously published | Primary purpose of measurements |
|---|---|---|---|---|---|
| Auwahi, Maui | Grasses, trees and shrubs | 54 | Small diameter, single-ring infiltrometer | Perkins et al., 2012 | Vegetation effects on infiltration |
| Various sites, Kaho'olawe | Grasses, trees and shrubs, bare soil | 110 | Tension disk infiltrometer | Loague et al., 1996 | Evaluation of run-off and erosion |
| KMA, Hawai'i | Grasses, trees and shrubs | 44 | Small diameter, single-ring infiltrometer | New data | Vegetation effects on infiltration |
| Kawela Fan, Molokai | Grasses and bare soil | 46 | Tension disk infiltrometer and Small diameter, single-ring infiltrometer | New data | Evaluation of run-off and erosion |
| Mililani Town, O'ahu | Grasses, trees and shrubs | 36 | Double-ring infiltrometer | Murabayashi & Fok, 1979 | Impacts of urbanization on infiltration and run-off |

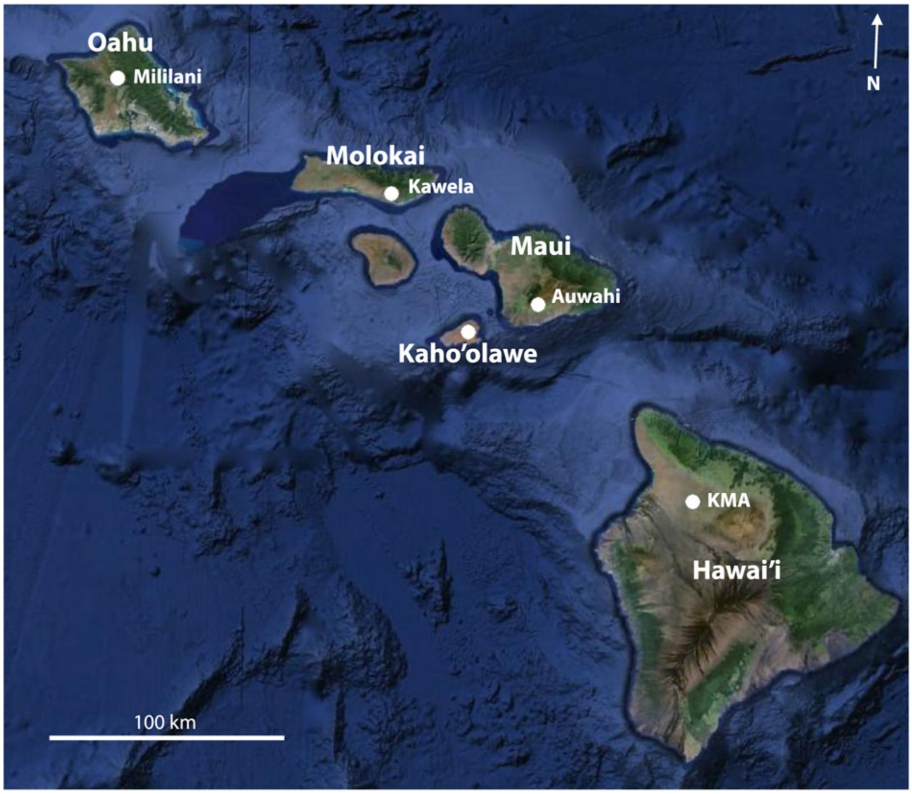


**FIGURE 1** Locations of field infiltration experiments

*viscosa*). Invasive grasses were introduced for cattle grazing in the 1950s (Medeiros et al., 2013) and quickly dominated much of the landscape. Native species are present in most part due to an ongoing forest restoration effort. $K_{fs}$ data from Auwahi, originally presented in Perkins et al. (2012), were conducted with small diameter, single-ring infiltrometers by the method of Nimmo, Schmidt, et al. (2009).

Once an island of primarily dryland forest, Kaho'olawe has experienced vegetation loss starting the in mid 1880s with the introduction of ranching practices and subsequent military activity starting in the 1940s, which has resulted in landscape degradation due to erosion. The island is relatively dry due to its low elevation and position in the rain shadow of Maui's volcano Haleaklā.. Mean annual precipitation is estimated to be 750 mm/year (Loague, D'Artagnan, Giambelluca, Nguyen, & Sakata, 1996). Loague et al. (1996) presents $K_{fs}$ data from Kaho'olawe as part of a study to understand run-off and erosion processes as related to restoration efforts. Although species information are not reported, they reported that 26.5% of the island was bare soil, 4.5% was grasses, and 69% was trees and shrubs at the time of the study. Data were analysed for all three landscape types. Loague et al. (1996) performed a spatial correlation analysis and concluded that no correlation exists for this data set.

Murabayashi and Fok (1979) measured $K_{fs}$ at Mililani Town on O'ahu to examine the effect of urbanization on rainfall–run-off relations. The soils are formed from highly weathered basalt with few stones and are relatively thick (~6 m). The vegetation associated with the data used in this study from the Mililani site is primarily butterfly bush (*Buddaleja davidii*) and natal red top grass (*Melinis repens*) allowing comparison of grasses and shrubs. Mean precipitation ranges from 750 to 1,350 mm/year (Giambelluca et al., 2013).

## 5 | METHODS AND ANALYSIS

The studies included here, although they have differing scopes and purposes, all provide data useful in analysing general trends in $K_{fs}$ as influenced by vegetation in the Hawaiian Islands. We used the 290 field estimates of field-saturated hydraulic conductivity from ecological communities in Hawaii, Maui, Kaho'olawe, Molokai, and Oahu (Figure 1). We stratified the data into field-saturated hydraulic conductivity ($K_{fs}$) from soils in three broad ecosystems categories: grasses, trees and shrubs, and bare soil. The soils of each site have coevolved with past and present ecological communities without significant mechanical disturbance by agricultural tillage practices; however, agricultural grazing has or may have occurred in the past at some of the grassland sites. We identified, but excluded published data, where agricultural practices may have had a significant influence (e.g., Green, Ahuja, Chong, & Lau, 1982). Hydraulic conductivity from these sites, therefore, represents the influence of natural ecological and soil-forming processes on the underlying parent material, mainly basaltic rock and airfall.

The $K_{fs}$ data we summarize were estimated using different methods as noted in Table 1. The two methods used for the newly presented data are tension disk and single-ring infiltrometers. The tension disk infiltrometers (Decagon Devices) employ a 4.5-cm-diameter, 3-mm-thick sintered stainless steel disk through which water flows into the soil under slight tension set at 0.5 cm water for all measurements. The method is described in detail by Zhang (1997). For the single-ring infiltrometer measurements, we used the method of Nimmo, Schmidt, et al. (2009), which employs a portable, falling-head, small-diameter (~20 cm) single-ring infiltrometer, and an analytical formula for $K_{fs}$, to compensate for both variable falling head and subsurface radial spreading that unavoidably occurs with small ring size. The method is of great value in comparative studies such as this, allowing for large numbers of measurements to be made relatively rapidly over rough terrain where water supplies are limited.

$K_{fs}$ data, 290 measurements in total, were evaluated statistically using two sample *t* tests assuming unequal variance at the 95% confidence level. Examining the data set as a whole, there are 130 data points for grasses, 83 for trees and shrubs, and 87 for bare soil. The null hypothesis proposes that no statistical significance exists in $K_{fs}$ among the ecosystem categories described above. To determine that any differences in infiltration attributable to vegetation type are statistically significant, a rejection of the null hypothesis, the resulting *p* value must be .05 or less. The data were evaluated on a site by site basis to look for trends in $K_{fs}$ with vegetation type within the data sets. Comparisons were only made for individual sites that would be similar in terms of other relevant properties such as parent material and soil type. Because the published data sets include different amounts of detail such as exact measurement locations, topographic setting, and soil properties, the data could not be analysed for spatial structure or by multivariate statistical techniques.

## 6 | RESULTS AND DISCUSSION

Results demonstrate that dominant land cover type correlates with infiltration rate in Hawaii. Box plots in Figure 2 show recently measured infiltration rates at KMA (grasses and trees/shrubs) and Molokai (grasses and bare soil). Trees and shrubs have greater $K_{fs}$ than grass and sites dominated by grass have higher infiltration rates than bare soil. Data from previous studies at Kaho'olawe (Loague et al., 1996), Auwahi (Perkins et al., 2012), and Mililani (Murabayashi & Fok, 1979) are shown in Figure 3 where the same trends are apparent; however, differences are less significant for Kaho'olawe than the other sites. The Kaho'olawe data set contained 50 measurements on bare soil with

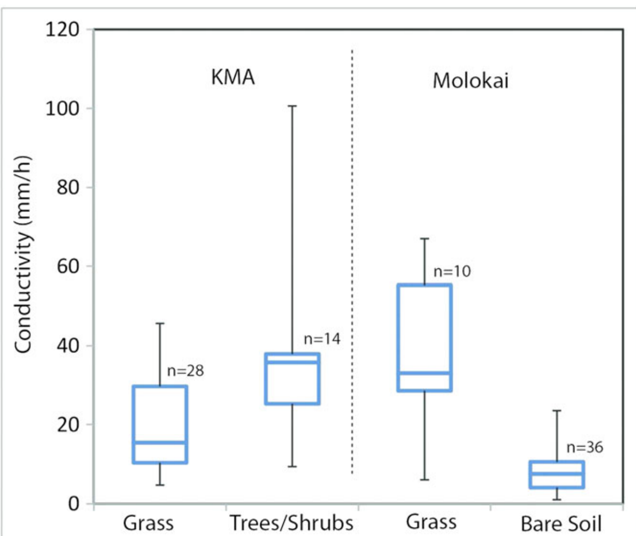


**FIGURE 2** $K_{fs}$ at Keamuku Maneuver Area and Molokai. The boxes indicate the first and third quartile of the data with the centre line being the median value. The whiskers indicate the maximum and minimum values

a single outlier of 14,760 mm/hr with all other values averaging 53 mm/hr. This single outlying data point was considered anomalous for the soil and beyond the capability of the method and was therefore not used in the statistical analysis.

Table 2 shows statistics for infiltration rates, including geometric mean, median, minimum and maximum values, standard deviation, and coefficient of variation (ratio of the standard deviation to the mean). The Auwahi site in Maui has the largest $K_{fs}$ with a geometric mean of 995 mm/hr for grasses and 2,328 mm/hr for trees and shrubs. Other sites are within one order of magnitude of each other with combined averages of 27 mm/hr for grasses, 63 mm/hr for trees and shrubs, and 17 mm/hr for bare soil. For bare soils, Kaho'olawe has larger and much more variation in infiltration values than Molokai. According to Loague et al. (1996), bare soils on Kaho'olawe exhibited extensive cracking at the time of the measurements, which was not an observed characteristic on Molokai. The Kaho'olawe data also have the highest coefficients of variation for all three land cover types. Restoration efforts at Kaho'olawe since the time of data publication have been significant, and, as demonstrated by Perkins et al. (2012, 2014), restoration can change near surface hydrology dramatically on decadal timescales. Future infiltration work on Kaho'olawe could be of great value to investigate trends with forest restoration.

The statistical analysis shows that the effect of land cover on infiltration is significantly different at the 95% confidence level or higher for all sites except for Kaho'olawe (Table 3) based on the calculated *p* values of .05 or less. There is some difference between grasses and trees and shrubs, but not at the 95% confidence level. Differences are statistically significant between grasses and trees and shrubs and between trees and shrubs and bare soil, but they are not significant between grasses and bare soils. Measurements on Kaho'olawe were conducted with a disk infiltrometer, which delivers water to the soil surface under slight tension. This can diminish or eliminate the effects of macropore flow, which is likely an important component of flow, especially where trees and shrubs are the dominant vegetation type. Measurements on Molokai were conducted on bare soil with both disk and ring infiltrometers. Because of the homogeneous nature of the soils and the lack of macropores, data from both techniques are not significantly different.

In some cases, Molokai and Auwahi in particular, the ecosystem progression started with the introduction of invasive grasses, which then outcompete native species for resources resulting in a degraded landscape. The establishment of invasive grasses is then followed by ungulate grazing (cattle and feral pigs and goats), which results in bare soil and often erosion. The reduction in infiltration rates with the bare soil landscape enhances the possibility of overland flow and erosion. As shown by Perkins et al. (2012, 2014), the reintroduction of native species reversed the process at the Auwahi site where the number of trees and shrubs has increased $K_{fs}$ by more than a factor of 2 over grasses in only 14 years. Increased $K_{fs}$ also has implications for aquifer recharge where deep, rapid infiltration may enhance the likelihood of water bypassing the root zone where it is not susceptible to evapotranspiration.

The analysis of new and previously published data shows that differences in infiltration can be attributed, at least in part, to dominant land cover. In general, deeper rooted species modify soil properties

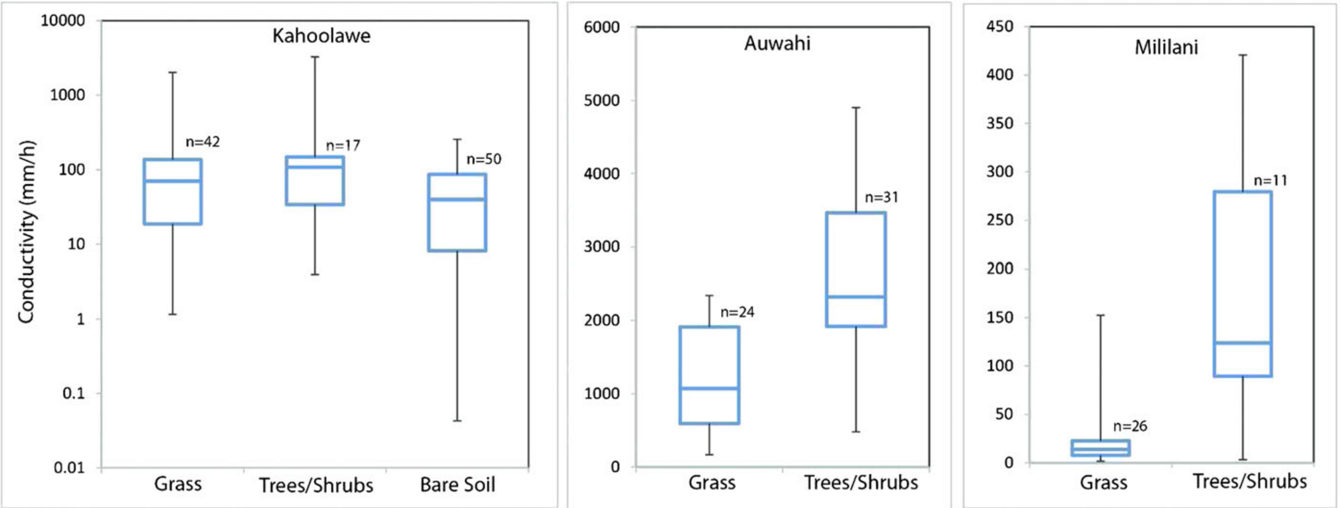


**FIGURE 3** $K_{fs}$ data from work at Kaho'olawe (Loague et al., 1996), Auwahi (Perkins et al., 2012), and Mililani (Murabayashi & Fok, 1979). The boxes indicate the first and third quartile of the data with the centre line being the median value. The whiskers indicate the maximum and minimum values (note the scale differences)

**TABLE 2** Summary statistics for the measured infiltration data from all sites based on land cover

| Site | Geometric Mean (mm/hr) | Median (mm/hr) | Minimum (mm/hr) | Maximum (mm/hr) | Standard deviation (mm/hr) | Coefficient of variation (unitless) |
|---|---|---|---|---|---|---|
| Grasses | | | | | | |
| Auwahi | 995 | 1,072 | 168 | 3,929 | 963 | 0.7 |
| Kaho'olawe | 47 | 70 | 1 | 2,016 | 326 | 2.2 |
| Molokai | 32 | 33 | 6 | 67 | 20 | 0.5 |
| KMA | 16 | 15 | 5 | 46 | 12 | 0.6 |
| Mililani | 15 | 14 | 2 | 152 | 41 | 1.3 |
| Trees and Shrubs | | | | | | |
| Auwahi | 2,328 | 2,322 | 482 | 5,758 | 1,427 | 0.5 |
| Kaho'olawe | 96 | 108 | 4 | 3,276 | 898 | 2.0 |
| KMA | 31 | 36 | 9 | 101 | 22 | 0.6 |
| Mililani | 114 | 124 | 3 | 421 | 131 | 0.7 |
| Bare soil | | | | | | |
| Kaho'olawe | 23 | 40 | <1 | 256 | 53 | 1.0 |
| Molokai | 7 | 8 | 1 | 24 | 7 | 0.7 |

**TABLE 3** *p* values from *t* tests assuming unequal variances at the 95% confidence level

| Site | Grass vs. trees/shrubs | Grass vs. bare soil | Trees/shrubs vs. bare soil |
|---|---|---|---|
| KMA | 0.0192 | | |
| Kaho'olawe | 0.2017 | 0.0639 | 0.0903 |
| Auwahi | 0.0007 | | |
| Molokai | | 0.0011 | |
| Mililani | 0.0037 | | |

to suit their water use needs as demonstrated by Perkins et al., 2014. There are undoubtedly spatial variations in soil characteristics and hydrology, which are not represented in this analysis, and those differences are likely the reason for the large site-to-site differences. For example, bare soil in one location may have higher infiltration than grasses at another location, likely attributable to other soil forming factors such as parent material, topography, aspect, climate, and soil age. However, this study does show promise for generalization of local or perhaps even island-wide trends, which would allow for mappable units of infiltration properties that can be related to processes of interest including areas of potentially high aquifer recharge or erosion susceptibility.

## 7 | CONCLUSIONS

Data from the Hawaiian Islands provide evidence that broad ecosystem types influence soil properties such as infiltration rate and preferential flow. The infiltration rates at 290 locations across the broad ecosystem categories of forest shrublands, grasslands, and bare soil are distinct from each other. Landscapes with trees and shrubs have the highest infiltration rates followed by grasses and then bare soil. As ecosystems are changed by human activity, they evolve and soils properties change thereby influencing how rainfall is partitioned into runoff, soil moisture, and groundwater recharge. A combination of vegetation mapping combined with field hydrology could provide a powerful tool for predicting these trends at other locations and under different land-management scenarios.

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