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A Rainwater Harvesting Accounting Tool for Water Supply Availability in Colorado

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Abstract: Rainwater harvesting (RWH) is a renewable water supply option for nonpotable use, most commonly used for landscaping irrigation. Water rights in Colorado prohibit all RWH except residential rain barrels and a pilot project program that allows centralized rainwater harvesting for new development. Development of a natural catchment creates impervious surfaces, thereby increasing runoff, with a subsequent decrease in infiltration and losses to evapotranspiration; pilot projects are allowed to harvest a volume equal to the predevelopment runoff losses that would have occurred on new impervious areas at the site. To support this administrative policy, a tool was developed for the efficient calculation of daily allowable harvest at nearly any project site in Colorado. A reliable and useful policy tool requires the incorporation of hydrologic science with widely applicable, user-friendly design, a challenging balance of rigor and accessibility that is welcomed by engineers and policymakers alike. The daily allowable harvest is determined for each soil group as a percentage of infiltrated rainfall less the groundwater return. Horton's infiltration method is used to model rainfall-runoff for a range of soil parameters (NRCS hydrologic soil groups) and precipitation events (0.25- to 25-year return periods and 15-min to 24-h durations). For most events, the percent infiltration is 90% of the precipitation depth; this ratio decreases when precipitation exceeds the infiltration rate. Results are simplified in a spreadsheet tool for policy application, with allowable harvest rules binned by event duration and frequency. Simulations using the tool for a 2010-2017 precipitation record from Colorado's Front Range showed that RWH can supply up to 50% of the annual demand for traditional landscaping and over 100% of the water-smart landscaping demand.

Keywords: rainwater harvesting; water rights accounting; Horton infiltration; water policy; prior appropriation

1. Introduction

In the arid western United States, a growing population and major economies like agriculture and recreation depend on a water supply that is simultaneously shrinking and becoming less reliable with climate change [1]. Water managers are exploring feasible options for increasing security including conservation, infrastructure expansion, and new supply sources [2]. Rainwater harvesting (RWH) is used across the globe to support water supply, particularly in times of shortage [3,4]. RWH can include the collection and use of either direct roof runoff or stormwater runoff collected at a catchment outlet, although most research considers only rooftop collection in rain barrels or cisterns [5–9]. In most western U.S. states, water is governed by a property rights system of water use administration that awards and defends usage rights by temporal seniority [10]. Most states in the Western USA have some level of regulation for rainwater harvesting, ranging from restrictions to incentives [11]. The state of Colorado has both the strictest water rights system and the most restrictive RWH laws [11,12].

In Colorado, any RWH other than private rain barrels requires 100% augmentation, defined as the replacement in equal time and place of depleted flows with water from a different source [13].

Along with recycled water and desalination, RWH can contribute to water resilience, the increased cost-efficiency of stormwater management, and decreased demand on other water supply and infrastructure [2]. However, RWH only contributes to water resource resiliency if it adds to the administrative water budget; the current 100% augmentation requirement in Colorado precludes this. In 2009, the Colorado legislature authorized up to 10 RWH pilot projects in new developments to harvest rainwater for nonpotable outdoor use, with an exception from the augmentation requirement [14]. The pilot program authorizes new developments to harvest, without augmentation, a volume equivalent to the decrease in evapotranspiration (ET) associated with newly impervious area at the site (Figure 1), or the "historic natural depletion" (HND). Conceptually, HND is defined as the portion of a rainfall event that remained available for ET from the root zone after infiltration; this is explained further in Section 2.1.

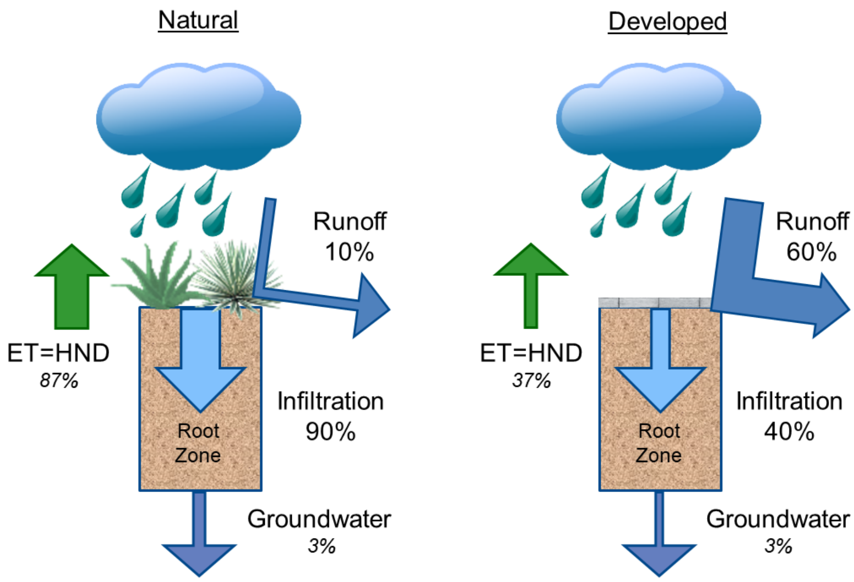

Figure 1. Water balance in natural and developed catchments. Infiltration = ET + Groundwater.

The difference between predevelopment and postdevelopment runoff is considerable, particularly in arid and semi-arid locations like Colorado. A pilot project on the Front Range of Colorado found the average annual HND to be 97% in a natural undeveloped catchment, with a runoff ratio of less than 3% [15]. Comparatively, runoff ratios in areas with residential land use typically range from 30% to 80% [16–18]. Per the pilot project statute, the postdevelopment runoff may be legally harvested for outdoor use because the volume was not part of the historically appropriated supply [14,19].

Pilot project legislation passed in 2009 required applicants to monitor development and provide site-specific HND estimation based on observed data. Authorized projects could harvest runoff prior to submitting these data, but in the interim were required to augment all stored water with another source [14]. In 2015, the legislature updated the program, asking the Colorado Water Conservation Board to provide widely applicable "factors" that estimate daily HND to facilitate pilot project operation in advance of site-specific data [20]. The factors are to serve in an easy-to-use water accounting tool to enable temporary RWH authorization for pilot projects while on-site data are gathered. The pilot project program is set to expire in 2026 and, with only one project to date, the 2015 legislature hoped the HND factors would reduce barriers to entry [20]. The primary goal of this study is to develop an HND accounting tool using established infiltration modeling methods informed by a systematic sensitivity analysis on key input parameters. An example application of the state-approved tool explores RWH supply and demand in Colorado, given the allowable harvest volume using these HND rules.

2. Methods

2.1. Accounting Tool Concept

To support the state-wide applicability of the tool, the HND estimate considers losses independent of catchment size, slope, or vegetation. A simple event-based water balance is evaluated at the point of infiltration-runoff partitioning, with the change in storage, dS, presumed to be negligible (Equation (1)):

$$\text{Precipitation} = \text{Runoff} + \text{Losses} + \text{Groundwater} + dS. \quad (1)$$

All runoff is assumed to accrue to the stream, including losses that occur in transit between the location where precipitation falls and the receiving stream (such as overland flow, evaporation, and further infiltration). The HND tool uses the U.S. Department of Agriculture Natural Resources Conservation Service's (NRCS) hydrologic soil groups, storm event depth, and event duration to estimate HND. Users input site soil group areas from the NRCS Web Soil Survey and the tool processes on-site precipitation data into storm events [21,22]. The HND tool returns a site-specific allowable harvest volume for each precipitation event from the estimated HND depth and the area made impervious in the development. The HND accounting for each soil group divides precipitation into three components: an infiltration factor (%Infiltration) and a groundwater factor (%Groundwater, Equation 2), and an ET-soil factor. The groundwater factor is 6% for hydrologic soil group A, 4% for soil group B, and 3% for soil groups C and D [22]. In this work, the HND is equal to infiltration minus groundwater, presuming both runoff and groundwater return to the stream (Equation (2)):

$$\text{HND} = \text{Precipitation} \times (\%\text{Infiltration} - \%\text{Groundwater}). \quad (2)$$

The ET-soil factor for monthly maximum harvest is limited by the lesser of either soil moisture storage or a weighted average monthly meadow grass ET. The groundwater and ET-soil factors are based on precedents in Colorado state administration; further detail on groundwater and ET-soil factor development is available in public policy documentation [22]. The technical work of this paper addresses the development of the infiltration factors (Equation (3)) via an infiltration modeling analysis, in addition to the final structure and application of the HND accounting tool:

$$\%\text{Infiltration} = \frac{\text{Precipitation} - \text{Runoff}}{\text{Precipitation}}. \quad (3)$$

2.2. Model Selection

There is extensive work characterizing water budgets and relating catchment characteristics to runoff and losses. However, the necessary simplicity of the accounting tool excludes most catchment variables; the HND relationship must be based on drivers that can be applied in statewide factors. Simple rainfall-runoff modeling in small catchments typically employs lumped precipitation; recent research has established the importance of storm intensity [23]. This type of runoff method, such as the NRCS curve number, was not sufficient for the infiltration factors due to the importance of modeling the effects of event intensity [24,25]. If factors were based solely on precipitation depth, the impact of intensity would be lost, resulting in over- and underestimation of HND [26]. The model needed to include catchment parameters that drive runoff in arid regions (soil infiltration rate and rainfall intensity), while remaining parsimonious in service of the policy application [24].

Model selection and parameter assumptions were made to minimize %Infiltration; this underestimates HND, thereby maximizing the protection of downstream water rights. Runoff modeling without overland flow routing, topography, or vegetation returns all runoff from the point of impact to the stream via surface runoff. A real-world catchment would offer more opportunities for evaporation or transpiration before the runoff reaches the stream, and a model with more physical parameters would estimate these transit losses [27]. Due to the need for both minimal parameters and continuous precipitation, neither a lumped precipitation-runoff method nor a more physical catchment model were suitable options.

In light of these considerations, a simple rainfall-runoff model using continuous precipitation was selected for developing the infiltration factor. The water quality capture optimization and statistics model (WQ-COSM) was developed to support stormwater detention sizing decisions [28,29]. WQ-COSM is a continuous model that can use high-resolution precipitation in version 3.1 (5- or 15-min); this accounts for storm intensity in runoff modeling and thus provides appropriate resolution for infiltration factor development. WQ-COSM models runoff depth for each event using Horton, Green and Ampt, or the rational method; this study used Horton's infiltration (Equation (4); F_t = total infiltration at time t [L^3], f_f = final infiltration rate [L/T], f_0 = initial infiltration rate [L/T], k = decay constant [T^{-1}], t = time [T]) [30]. The decay constant determines the rate at which infiltration decreases from the initial to the final infiltration rate:

$$\text{Infiltration} = F_t = \int_0^t \left(f_f + \left(f_0 - f_f\right)^{-kt}\right). \tag{4}$$

Horton's method underestimates infiltration and therefore minimizes %Infiltration because the infiltration decay constant assumes a constant precipitation rate that exceeds the infiltration rate for the full event duration. This tends to overestimate decreases in the infiltration rate because infiltration capacity would not exhibit constant decay with intermittent precipitation [31].

2.3. Sensitivity Analysis Methods

Prior to developing infiltration factors, a sensitivity analysis was performed to determine which soil and precipitation variables should be included in the factors to sufficiently account for precipitation and soil characteristics while remaining simple and widely applicable. Sensitivity results for WQ-COSM infiltration parameters also informed the final model values to minimize the infiltration estimates.

2.3.1. Soil Parameter Sensitivity Analysis

The sensitivity of the WQ-COSM infiltration simulation was evaluated by varying Horton's parameters of initial infiltration rate, final infiltration rate, and infiltration decay rate individually to the minimum and maximum values recommended in the model manual. This analysis used 15-min precipitation data recorded from March to August 2013 at a Front Range precipitation gage (COOP gage ID 053005) [32]. Results were used to select infiltration parameters that minimize HND estimates. Because infiltration varies with precipitation intensity, results vary between different precipitation events with the same infiltration parameters. The aggregates of percent infiltration from March-August 2013 are used to characterize sensitivity over a range of observed precipitation events.

2.3.2. Precipitation Sensitivity Analysis

Infiltration-runoff partitioning is directly impacted by event intensity; intensity can vary within an event, and this storm characteristic can vary geographically. Different intensity distributions from a 2018 characterization of Colorado and New Mexico regional precipitation regimes were used to evaluate the sensitivity of infiltration-runoff partitioning to intra-event variation in precipitation intensity [33]. The modeled storms were of equal depth and duration, with different intra-event precipitation distributions. This analysis compared %Infiltration differences between 6-h and 24-h precipitation intensity patterns for the east and west regions of the 2018 study and compared the 1-h and 2-h event distributions to uniform distributions (constant intensity) because the Colorado-New Mexico study only developed regional distributions for 6-h and 24-h events [33]. Finally, the %Infiltration differences from 5-min and 15-min precipitation data were compared for 1- and 2-h events as temporal resolution may alter the infiltration response to event intensity.

2.4. WQ-COSM Infiltration Modeling

Infiltration factor modeling scenarios were based on precipitation frequency events from the National Oceanic and Atmospheric Association (NOAA) and the hydrologic soil groups defined by the NRCS. The WQ-COSM manual recommends a range of infiltration rates for different soil types under different conditions. Ranges of these infiltration rates were assigned to each NRCS hydrologic soil group based on descriptors of infiltration conditions. The authors used the minimum recommended infiltration rates for each soil group (Table 1), based on the sensitivity results presented below and the WQ-COSM manual [30]. The NRCS soil groups are mapped with other soil data from the Web Soil Survey, an online geospatial database that can be referenced for a pilot project anywhere in the state [21]. All other model parameters were set to the WQ-COSM recommended values for the semi-arid climate of Colorado. These parameters were pervious depression storage (8.9 mm or 0.35 in), minimum depth to runoff (2.8 mm or 0.11 in), storm separation (3 h), and drying period (three days).

Table 1. Horton's infiltration parameters by soil group (minimum recommended values).

Soil Group	Soil Type	Initial Infiltration Rate (mm/h)	Final Infiltration Rate (mm/h)	Infiltration Decay Rate (h^{-1})
A	Sand	43.2	38.1	2
B	Sandy loam	35.6	30.5	3
C	Loamy sand	25.4	5.1	3
D	Clay	7.6	2.5	3

Precipitation events were based on the NOAA Atlas 14 precipitation frequency event depths from a Colorado Front Range location adjacent to the only approved pilot project site (Kassler station ID 05-4452) [34]. Events included one-, two-, five-, 10-, and 25-year precipitation frequency depths for durations of 0.25, 0.5, one, two, six, and 24 h. Smaller storms without precipitation frequency estimates were simulated for durations of 0.25-6 h using a fraction of the one-year event depth (0.25, 0.5, and 0.75). Storms smaller than the one-year event were important because these more common events comprise the bulk of events that might be harvested [35]. The modeled event depths ranged from 3.3 to 92 mm and intensities ranged from 1.0 to 100 mm/h. While precipitation frequency estimates will vary across the state, the ranges of depths and intensities used here appropriately represent the possible precipitation events across Colorado.

3. Results and Discussion

3.1. Sensitivity Results

3.1.1. Sensitivity to Soil Parameters

A soil parameter sensitivity analysis showed that the default model parameter values result in 78% mean infiltration. Lower initial and final infiltration rates result in lower %Infiltration (Table 2). Although the difference between the maximum and default infiltration rates is much higher than the difference between the minimum and the default, the change from default %Infiltration is nearly equal in magnitude for both the maximum and the minimum rates. This holds for both the initial and the final infiltration rates (Table 2). Conversely, the minimum infiltration decay rate increases %Infiltration, while the maximum decay rate decreases the estimate. The maximum decay rate is only one unit higher than the default and the minimum decay rate is three units lower, but the minimum decay rate results in a much larger change in %Infiltration (Table 2).

According to this analysis, lower initial and final infiltration rates and a higher infiltration decay rate should be used to minimize %Infiltration and provide maximum protection of downstream water rights (Table 2). In light of these results, HND infiltration modeling used the minimum recommended values for initial and final infiltration rates (Table 1). However, the infiltration decay rate is less impactful on model outputs when using the minimum infiltration rate for each soil group, and the WQ-COSM manual notes that model outputs are not highly sensitive to this parameter [30]. This analysis used the model recommended values of 2 h^{-1} for soil group A and 3 h^{-1} for soil groups B, C, and D.

Table 2. Soil parameter sensitivity results.

Parameter	Value	%Infiltration	Change
Initial Infiltration Rate (mm/h)	7.6	65%	−13
	50.8	78%	0
	127.0	89%	+11
Final Infiltration Rate (mm/h)	0.3	70%	−8
	2.5	78%	-
	50.8	91%	+13
Infiltration Decay Rate (h^{-1})	2	88%	+10
	5	78%	-
	6	77%	−1

3.1.2. Sensitivity to Precipitation

Model output for 6- and 24-h precipitation events using the east and west temporal distributions did not show a significant difference in infiltration estimates. %Infiltration results differed between regions only for soil groups C (five-year events and larger) and D (all events), with the largest difference in soil group D, with 10% less HND for one- and two-year events for the west distribution compared to east (Figure 2a). %Infiltration for 1- and 2-h events using uniform versus distributed precipitation intensity only impacted 1-h events in soil group D, returning up to 20% more HND with uniform event distribution. Comparison of the 5- and 15-min precipitation time step showed no impact on infiltration estimates, except for events in soil group D longer than 2 h; this allows 15-min precipitation records to be used without detracting from the accuracy of HND estimates (Figure 2b).

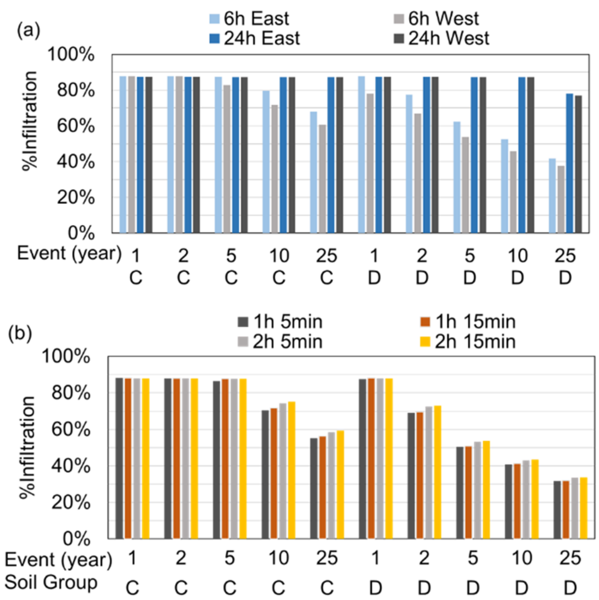

Figure 2. (**a**) Percent infiltration on soil groups C and D for 6- and 24-h events with east and west precipitation distributions at all frequencies. Results for soil groups A and B show no differences between east and west. (**b**) Percent infiltration for 1- and 2-h events with 5- and 15-min precipitation time steps. Results for soil groups A and B show no differences between east and west.

These minimal differences in %Infiltration demonstrated that the final allowable harvest rules need not account for variation of intra-event precipitation distribution (Figure 2a) or precipitation time step (Figure 2b). Hence, modeling to establish infiltration factors proceeded using the east distributions for 6- and 24-h events and 1- and 2-h distributions were used in lieu of a uniform distribution. Although events shorter than 1 h may be sensitive to distribution, the regional study did not provide temporal distributions for such short events; instead, these events were modeled with a uniform precipitation distribution.

3.2. WQ-COSM Infiltration Modeling Results

The majority of rain events fall on the final infiltration rate as it is modeled with rapid decay over a small difference in rates, reaching the final infiltration rate in 4-16 min, depending on soil group. Most event intensities in the modeling were less than the final infiltration rate of soil groups A and B, but most were higher than those of soil groups C and D (Figure 3). Figure 3 and the results in Table 3 show that nearly all depressed infiltration ratios for soil groups C and D are due to the precipitation rate exceeding the infiltration rate.

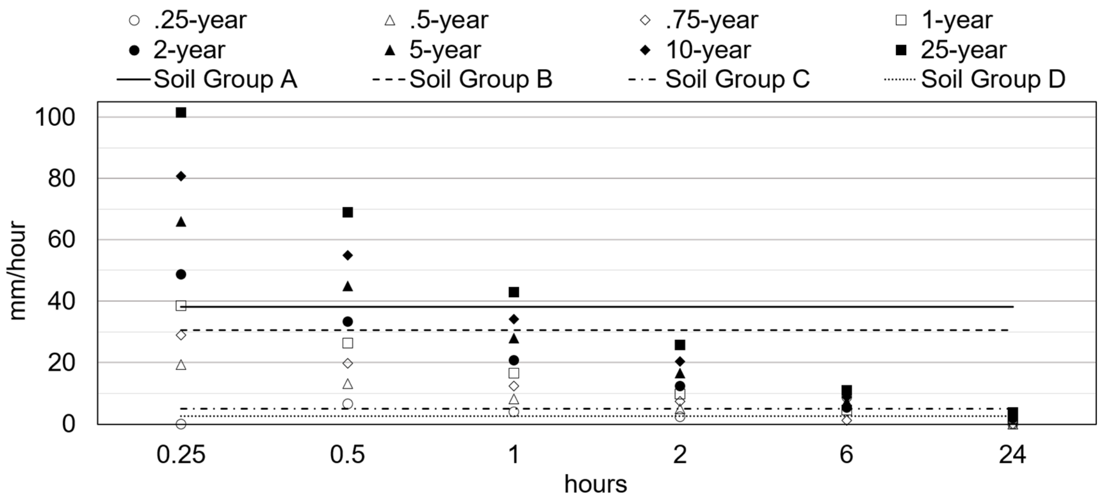

Figure 3. Event average precipitation intensity and soil group final infiltration rates.

Soil group A has initial and final infiltration rates higher than the typical precipitation intensity, resulting in a higher total infiltration capacity (Figure 3). %Infiltration on soil group A falls at 90% or higher for all but the most intense short events, where the ratio falls to as low as 70% (Table 3). Soil group A shows decreased infiltration when short, high-intensity events deliver precipitation at a rate that exceeds the infiltration rate (Figure 3). This allows most of the rainfall to infiltrate for longer events. With only the most intense rain events diverging from 90%, the HND tool divides infiltration factors by the 10-year event curve for a simple two-part rule (see Section 4 for further explanation).

The sandy loam B-group soils have initial and final infiltration rates higher than most precipitation intensities, similar to soil group A (Figure 3). Like soil group A, soil group B shows decreased %Infiltration when the precipitation rate exceeds the infiltration rate. On these soils, %Infiltration is 90% or higher for low- to moderate-intensity events, while %Infiltration falls as low as 62% for short, high-intensity events on soil group B (Table 3). The relationship between intensity and %Infiltration is not linear due to the combined impact of intensity and duration. The accounting tool structure for soil group B is a three-part rule that assigns infiltration factors based on the five-year and 10-year event curves.

Table 3. %Infiltration results by soil group for all event durations and depths. %Infiltration values <90% are highlighted in bold.

Event Frequency (year)	Event Duration (h)	Event Depth (mm)	Event Intensity (mm/h)	Soil Group A	Soil Group B	Soil Group C	Soil Group D
0.25	0.25	2.4	9.7	100%	100%	100%	100%
0.25	0.5	3.3	6.6	96%	96%	96%	96%
0.25	1	4.1	4.1	95%	95%	95%	95%
0.25	2	5.0	2.5	94%	94%	94%	94%
0.25	6	6.8	1.1	93%	93%	93%	93%
0.5	0.25	4.8	19.3	94%	94%	94%	94%
0.5	0.5	6.6	13.2	93%	93%	93%	93%
0.5	1	8.3	8.3	92%	92%	92%	92%
0.5	2	9.9	5.0	92%	92%	92%	92%
0.5	6	13.6	2.3	91%	91%	91%	91%
0.75	0.25	7.2	29.0	93%	93%	93%	93%
0.75	0.5	9.9	19.8	92%	92%	92%	92%
0.75	1	12.4	12.4	92%	92%	92%	92%
0.75	2	14.8	7.4	91%	91%	91%	91%
0.75	6	20.4	3.4	91%	91%	91%	91%
1	0.25	9.7	38.6	92%	92%	92%	92%
1	0.5	13.2	26.4	92%	92%	92%	80%
1	1	16.5	16.5	91%	91%	91%	**72%**
1	2	19.8	9.9	91%	91%	91%	**72%**
1	6	27.2	4.5	91%	91%	91%	**78%**
1	24	42.2	1.8	90%	90%	90%	90%
2	0.25	12.2	48.8	92%	92%	92%	**79%**
2	0.5	16.6	33.3	91%	91%	91%	**63%**
2	1	20.7	20.7	91%	91%	90%	**58%**
2	2	24.8	12.4	91%	91%	91%	**58%**
2	6	33.0	5.5	91%	91%	91%	**66%**
2	24	49.8	2.1	90%	90%	90%	90%
5	0.25	16.5	65.9	91%	91%	**76%**	**58%**
5	0.5	22.5	44.9	91%	91%	**68%**	**47%**
5	1	28.0	28.0	91%	91%	**67%**	**43%**
5	2	33.3	16.6	91%	91%	**70%**	**43%**
5	6	43.4	7.2	90%	90%	**81%**	**51%**
5	24	63.0	2.6	90%	90%	90%	**81%**
10	0.25	20.2	80.8	**88%**	**79%**	**62%**	**47%**
10	0.5	27.4	54.9	91%	**84%**	**56%**	**38%**
10	1	34.0	34.0	91%	91%	**55%**	**35%**
10	2	40.6	20.3	90%	90%	**58%**	**35%**
10	6	52.3	8.7	90%	90%	**71%**	**42%**
10	24	74.9	3.1	90%	90%	90%	**71%**
25	0.25	25.4	101.6	**70%**	**62%**	**50%**	**38%**
25	0.5	34.5	69.1	**78%**	**67%**	**44%**	**30%**
25	1	42.9	42.9	90%	**84%**	**43%**	**28%**
25	2	51.3	25.7	90%	90%	**46%**	**28%**
25	6	65.5	10.9	90%	90%	**58%**	**34%**
25	24	92.2	3.8	90%	90%	90%	**60%**

%Infiltration on soil group C (mixed clayey soils) follows the pattern of >90% up to the five-year event, breaking at a lower intensity than groups A and B (Figure 3). Soil group C demonstrates a different infiltration-excess pattern than soil groups A and B; on group C, the shortest and longest intense events have a higher infiltration than the mid-range event duration of 1-6 h. The effect of the low final infiltration rate is most significant on mid-range events (0.5-2 h); 6- and 24-h events have a lower intensity that allows a higher proportion of the event to infiltrate. To accommodate the higher variation in infiltration estimates, accounting rules for soil group C assign events to one of four infiltration factors based on the two-year, five-year, and 10-year event curves.

Soils in group D are clay soils with extremely low initial and final infiltration rates. As shown in Table 3, only smaller storms with less than a one-year frequency meet the 90% infiltration threshold. However, these are common storms, so a pilot project located on soil group D would still be able to harvest 90% of precipitation for many events. As with soil group C, the rule recommendation for soil group D includes more infiltration factors, assigned based on 0.75-10-year event curves.

The minimum recommended infiltration rates used in this modeling are considerably lower than the median and maximum; higher infiltration rates result from dry conditions with dense vegetation, while lower rates result from moist conditions with little or no vegetation [30]. Colorado's semi-arid climate results in dry soil conditions, but the vegetation may vary at pilot project sites. These results are thus presumed to reliably underestimate %Infiltration in most residential development settings in Colorado. The similarity of minimum infiltration rates for soil group A and B explains the strong similarity in %Infiltration for these soil groups. The final infiltration rate for soil group C is close to that of group D, explaining the similarity of the results for longer events (Tables 1 and 2). It is challenging to draw direct connections between precipitation intensity and %Infiltration due to the impact of the precipitation duration in combination with intensity.

4. Integrating Factors in Accounting Tool

The accounting tool developed for pilot project harvest accounting processes precipitation data into storm events and applies the infiltration factors based on power functions that are fit to the event frequency curves (Figure 4). For soil group A, events up to the 10-year frequency curve use a factor of 90%; events larger than the 10-year frequency curve use 70%, the lowest modeled %Infiltration. For soil group B, events up to the five-year frequency curve use a factor of 90%, events between the five- and 10-year curves use 79%, and events greater than the 10-year curve use 62%. For soil group C (Figure 4), events up to the two-year curve use a factor of 90%, events between the two- and five-year curves use 67%, events between the five- and 10-year curves use 55%, and larger events use a factor of 43%. For soil group D, events up to the 0.75-year curve use a factor of 90%, events between the 0.75- and one-year curves use 72%, those between the one- and two-year curves use 58%, those between the two- and five-year curves use 43%, those between the five- and 10-year curves use 35%, and those greater than the 10-year curve use 28%. Although many events return a higher than 90% infiltration (Table 3), factors were capped at 90% for all soil groups.

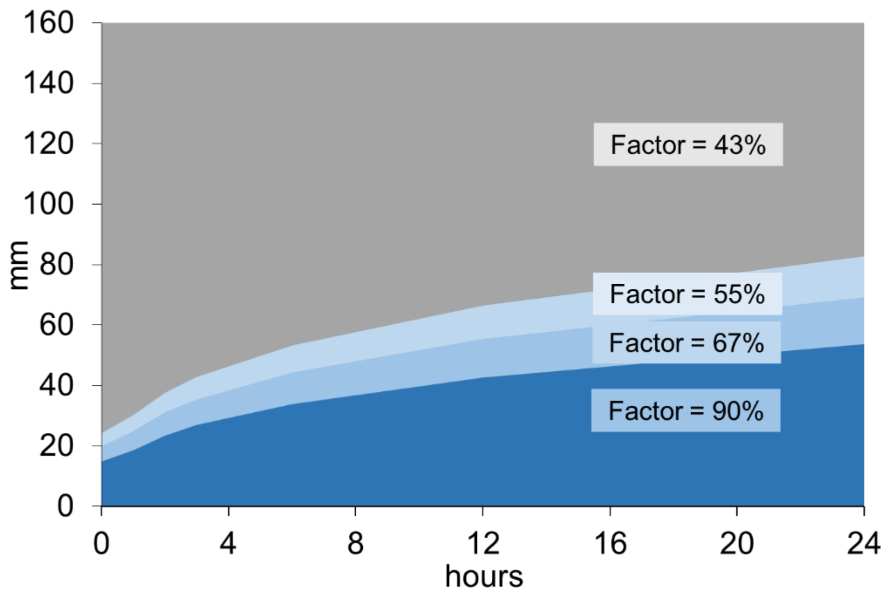

Figure 4. Accounting rule figure for soil group C.

The accounting tool inputs include soil group areas, impervious surface area over each soil group, and high-resolution precipitation data (5- or 15-min) from the pilot project site. Groundwater and ET-soil factors are included in the tool calculations; the ET-soil factor is applied as a rolling 30-d maximum given the user input of actual daily harvest. Infiltration and groundwater factors for each soil group are applied separately to precipitation events to determine HND depth; the tool uses impervious area over each soil group to provide a daily HND volume that may be legally harvested at the site. Further details on the use and limitations of factors is provided in the state's policy documentation and guidelines [22,36]. The factors and accounting tool were adopted by the state of Colorado in September

2019; the accounting tool is include in Supplementary Materials for this article and is available for use through the Colorado State Engineer's website [37].

5. Example Application of HND Factors

The following section compares the allowable harvest of historic precipitation with the monthly outdoor water use estimates for a high-density single-family development.

5.1. HND Factor Application

Consider a storm event of 25.4 mm (1 in) over 8 h at a site comprised entirely of soil group C, the soil conditions at the Sterling Ranch pilot project. The factors for this event are %Infiltration = 90% and %Groundwater = 3%. This means that 90% of the rainfall would have infiltrated in native conditions and after 3% deep percolated to groundwater return flow, 87% of the event would have been depleted by ET from the root zone. The allowable harvest is calculated from Equation (5), using the HND derived in Equation (2). In a development with 0.213 km^2 of impervious surface, the allowable harvest volume is estimated as follows:

$$\text{Allowable Harvest}\left(\text{m}^3\right) = \text{HND (mm)} \times \text{Area Made Impervious}\left(\text{km}^2\right) \quad (5)$$

$$\text{HND} = 25.4\text{ mm} \times (87\%) = 22.1\text{ mm}$$

$$\text{Harvest Volume} = 22.1\text{ mm} \times 0.213\text{ km}^2 = 4710\text{ m}^3.$$

From this single event, 4710 cubic meters of runoff (3.82 acre-feet) can be harvested for outdoor use at the pilot project site without the need for augmentation. The potential of rainwater harvesting to offset outdoor water use is demonstrated in the following application of the factors to long-term precipitation record in an example pilot project development.

In a full-scale pilot project, outdoor water use is driven by housing density and landscaping water needs. The Keystone Policy Institute published a collaboratively developed residential land use and water demand tool, an outdoor water demand estimator developed to inform planning in the Front Range region of Colorado [38]. This tool was used to develop water use estimates for a hypothetical pilot project with small single-family lots (2471 units/km^2 or 10 units/acre), a net 53% impervious area. Development variables used in the residential land use and water demand tool are presented in Table 4. The tool produces seasonal water demand estimates using different landscaping types and demand, and three landscaping types: turfgrass (traditional lawn), xeric (xeriscaping), and mixed (50% turfgrass, 50% xeric). These seasonal rates were converted to the monthly estimates in Table 5 using a ratio of monthly to seasonal (March-October) reference ET in Colorado [39]. Local ET is sometimes used to develop low-waste irrigation water budgets and schedules [40]; in this study local ET data are used to calculate the relative demand over the growing season to distribute seasonal demand estimates.

Table 4. Land use and seasonal water demand metrics for example development.

Total Area (km^2)	Dwellings (Units)	Density (Units/km^2)	Unit Pervious Area (m^2/unit)	Total Pervious Area (km^2)	Total Impervious (km^2)	Turfgrass Demand (L/m^2)	Mixed Demand (L/m^2)	Xeric Demand (L/m^2)
0.405	1000	2471	191	0.191	0.213	611	407	204

Table 5. Water demand for different landscaping types in Colorado's Front Range region. Volumes are based on the example development in Table 4.

Demand	March	April	May	June	July	August	September	October	Season
Turfgrass (m^3)	9993	12,453	15,672	19,487	20,326	17,343	13,008	8899	117,181
Mixed (m^3)	6627	8258	10,393	12,923	13,479	11,501	8626	5901	77,709
Xeric (m^3)	3366	4195	5279	6564	6847	5842	4382	2997	39,471

Observed precipitation from the 2010-2017 Sterling Ranch record was used to generate monthly supply estimates for comparison with the residential land use and water demand tool estimates [27]. The accounting tool factors for soil group C were applied to the Sterling Ranch precipitation record, using the example total impervious area from Table 4. The use of soil group C factors reduces HND estimates relative to the rules for groups A and B, in addition to representing clayey soil conditions at the Sterling Ranch pilot project and Colorado's Front Range urban corridor [41].

5.2. Example Allowable Harvest and Discussion

The annual irrigation-season precipitation at Sterling Ranch ranges from 13.0 to 39.4 millimeters (5.9 to 17.7 in) [27]. The average March-October HND factor harvest volume is 56,900 m^3, based on the 2010-2017 precipitation observed at Sterling Ranch (Figure 5). If the development used municipal water priced per 1000 gallons, this volume of potable irrigation water would cost $34,000-64,000, or $340-640 per household [42]. This example assumes that a pilot project's drainage infrastructure, storage sizing, and operational efficiency allow all allowable harvest to be put to use each month. The HND factors estimate an annual mean of 87% HND between March and October in the Sterling Ranch catchment, compared to the 93% average observed at Sterling Ranch [15]. A USGS study in Jefferson County, Colorado, a neighboring county with similar soil conditions but more mountainous terrain, found an annual mean of 83% ET [43].

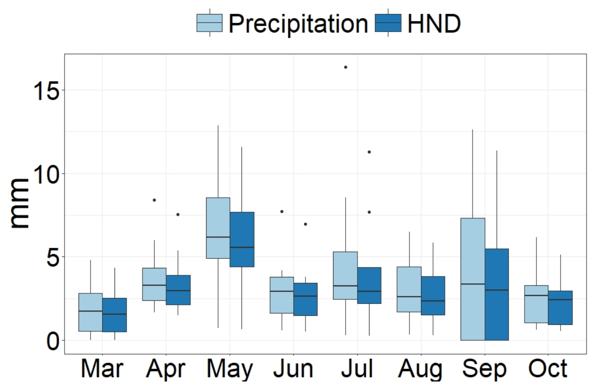

Figure 5. Monthly precipitation and factor HND at Sterling Ranch, 2010-2017.

In the example pilot project, the HND factors allow for enough harvest volume on average to meet or exceed 100% of monthly xeric demand (Figure 6). HND supply meets at least 100% of xeric monthly demand for three of the eight years on record. Average HND can contribute between 46% and119% of mixed demand, and 31-79% of turfgrass demand (Figure 6). Monthly HND met at least 100% of monthly mixed demand in at least three of the eight years in May, September, and October, but only in one or two years in March, June, July, and August. The HND in May exceeded turfgrass demand in three of the eight years evaluated, and the September supply exceeded the demand in two of the eight years. The HND in all other months exceeded the turfgrass demand in one or none of the eight years. There can be a meaningful reduction in potable water use even if the supply does not meet 100% demand. With xeric landscaping, a pilot project can meet at least 75% of seasonal demand in seven years and at least 50% of demand in all eight years. The precipitation record and allowable harvest provided at least 75% of mixed demand in five of the eight years and 50% in six years. HND supply met at least 50% of the traditional demand in five of the eight years, but none of the years on record provided enough harvest to meet even 75% of the traditional demand.

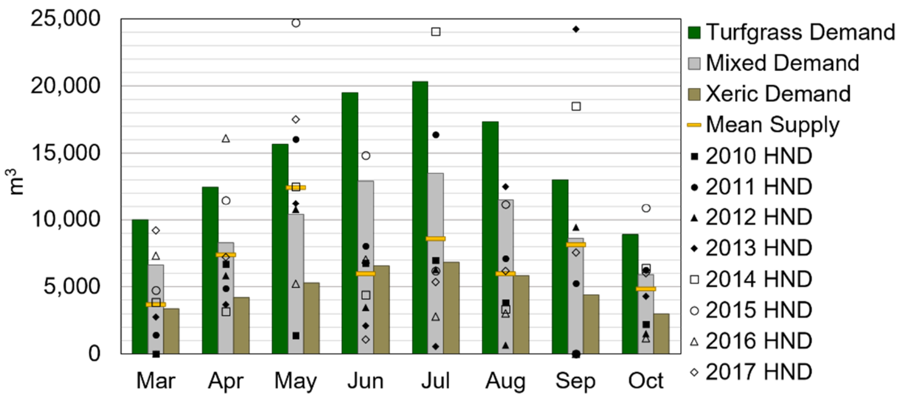

Figure 6. Monthly irrigation demand in example development compared with allowable harvest using HND factors at Sterling Ranch, 2010-2017 precipitation.

A rainwater harvesting pilot project can meet an annual average of 144% of xeric demand, 73% of mixed demand, and 49% of turfgrass demand. With xeric landscaping, a pilot project met at least 100% of seasonal demand in six of the eight years on record, at least 75% of demand in seven years, and at least 50% of demand in all eight years. The precipitation record and allowable harvest provided at least 100% of the mixed landscaping demand in only one year, but another year met 98%; they met at least 75% of mixed landscaping demand in five of the eight years and 50% in six years. The HND supply met at least 50% of the traditional demand in five of the eight years, but none of the years on record provided enough harvest to meet even 75% of the traditional demand.

These supply estimates from the Sterling Ranch precipitation record demonstrate the potential for rainwater harvesting to meet the outdoor water demand in Colorado, in conjunction with water-smart landscaping. Ultimately, potential use of the rainwater harvested via pilot projects will depend on actual precipitation, storage, and operations; one limitation of this analysis is the assumption of 100% efficiency in harvest and distribution of the allowable harvest volume. Demand will depend on residential density, landscaping, and irrigation design. Despite this uncertainty, this exercise demonstrates that rainwater harvesting can meaningfully offset outdoor water demand in the Front Range of Colorado. RWH has the highest potential when paired with landscaping methods like xeriscaping and efficient irrigation.

6. Conclusions

This work demonstrates the application of fundamental hydrologic methods (Horton's infiltration and water balance) in the service of water resources policy and administration needs, and investigates renewable supply availability given the legal limits on RWH. The accounting tool developed herein reduces barriers to RWH in Colorado by providing accessible means for pilot project accounting. Innovation in water supply requires the confluence of policy, infrastructure, and natural resources; in Colorado this is hindered not only by the inherent risk of infrastructure investment, but also the conservative nature of water rights administration in the state. Based on the HND estimates in this tool, RWH pilot projects in Colorado can supply 49-144% of nonpotable outdoor demand. Supply potential is higher when demand is lower; thus, water-smart landscaping methods like xeriscaping and smart irrigation should be part of new development planning when water is scarce.

Future work on this topic may develop a methodology for more meaningful location-specific estimates of RWH supply potential by refining the spatial and temporal resolution in addition to geographically specific variables. Location-specific estimates of RWH supply potential are critical to decision-making around RWH programs, incentives, and planning. Estimates of supply potential and resilience can be improved with local precipitation, demand, and harvest estimates based on locally allowed RWH systems and storage. Localized climate projections can provide inputs for simple (e.g., future precipitation) or complex (e.g., future demand) RWH investigations.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/11/11/2205/s1: HND accounting tool (Excel workbook).

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