HB15-1016 Rainwater Harvesting Pilot Project Regional Factors

2019

by

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July 1, 2019, revised September 2019

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1 Introduction

This report documents enhancements to work completed by Leonard Rice Engineers (LRE) in support of the Dominion Water & Sanitation District Water Plan Grant titled "Regional Factor Development for Precipitation Harvesting."[1] The goal of this effort is to extend LRE's work investigating Historic Natural Depletion (HND)[2] on the Sterling Ranch pilot project[3] area to statewide HND Factors that can be applied at rainwater harvesting pilot projects across most of Colorado. The HND Factors are used to determine the allowable rainwater harvest depth while protecting senior water rights. To be available for use by pilot projects, the Factors must be approved for incorporation into the Colorado Water Conservation Board's (CWCB) Criteria and Guidelines for Rainwater Harvesting Pilot Projects.

According to the 2016 Criteria and Guidelines, all proposed HND Factors submitted to the Board for inclusion to the Criteria and Guidelines shall include, at a minimum:

- A map of the region where the Factors can be applied,
- A description of the data collected by the sponsor,
- A description of the methodology used to develop the proposed Factors,
- A description of the proposed Factors and any limitations of use,
- Draft updated Criteria and Guidelines that incorporate the proposed Factors.

This report contains the required information and is submitted in conjunction with draft updated Criteria and Guidelines for CWCB approval in September 2019.

2 Background and HND Factors Summary

2.1 Pilot Project and Factors Background

Rainwater harvesting pilot projects are a program established by the Colorado State Legislature to explore the potential of neighborhood-scale rainwater harvesting as a portion of a new development's renewable water supply. In a pilot project, stormwater runoff can be stored and distributed for outdoor use in new residential or mixed-use development. If approved for a pilot project, a development may reuse rainwater onsite through a Substitute Water Supply Plan (SWSP) and apply for a decreed augmentation plan specific to the development[4]. Per CWCB Criteria and Guidelines, the SWSP can use HND Factors, rather than site-specific information, to estimate allowable harvest volume at a pilot project site.

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[1] Dominion Water & Sanitation District Colorado Water Plan grant awarded 2017.

[2] Historic Natural Depletion and allowable harvest volume are used interchangeably throughout this report. They both represent the amount of water that can be captured and reused without injury to senior water rights.

[3] LRE Colorado Water Plan grant deliverables, Task 4.

[4] Refer to DWR Rainwater Harvesting Legal Framework Memo for additional information about the SWSP and Augmentation Plan processes.

The pilot project statute allows the storage and outdoor use of water that was historically consumed by natural vegetation and thus was not available to water users in the priority system. The HND Factors proposed in this memo estimate the HND for a pilot project, based on hydrologic soil group (HSG)[5] and on-site precipitation monitoring. HND Factors calculate a depth, which is multiplied by the land area made impervious by the development, as shown in Figure 2.1.

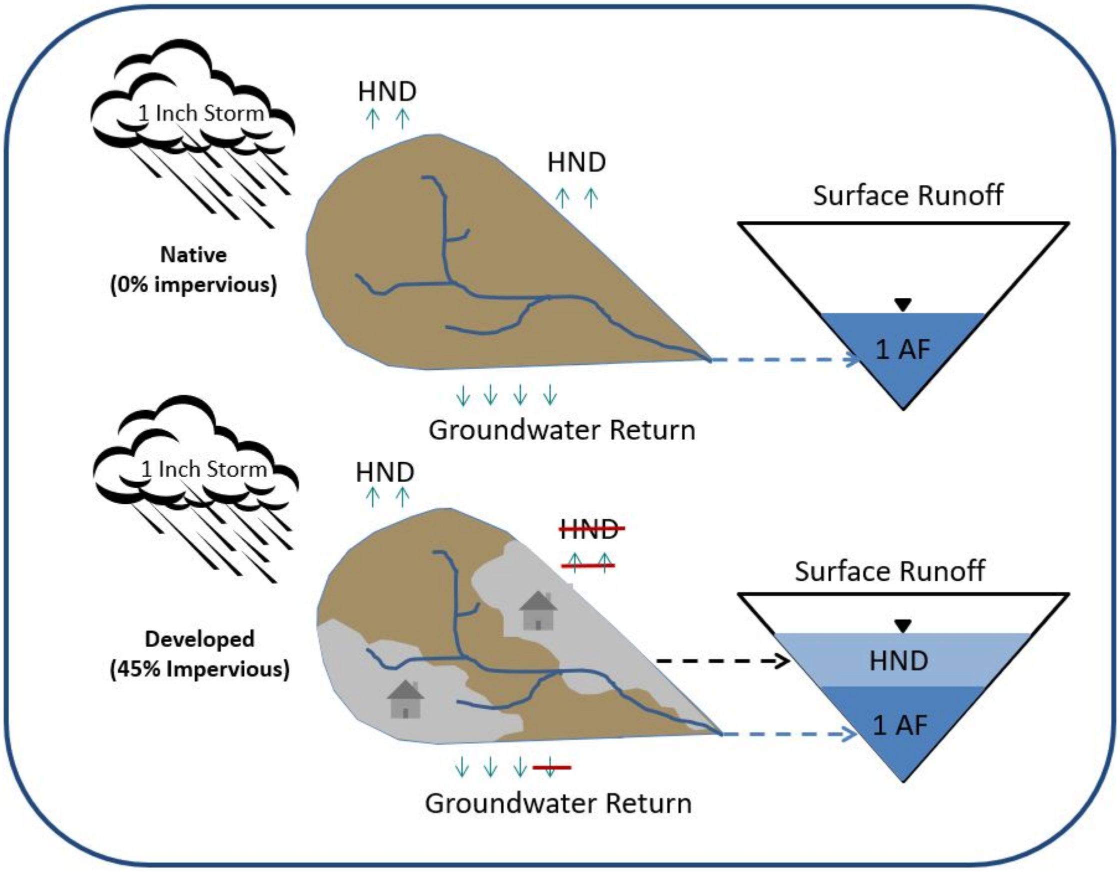

Figure 2.1: Comparison of runoff and Historic Natural Depletion (HND) in natural and developed catchments. HND occurs via evapotranspiration from soil moisture; increased impervious area decreases infiltration to the soil moisture storage.

2.2 HND Factors Summary

This memo proposes HND Factors based on three parts: Infiltration Factor, Groundwater Factor, and ET/Soil Factor. The three factors are applied together to estimate Daily HND and limit Monthly HND (Figure 2.2), which determines the amount of runoff that may be harvested on-site for pilot projects. The HND Factors are based on the concept that HND is equal to water that infiltrated to soil moisture storage, but did not become groundwater return flow, in other words, infiltration minus deep percolation. The Factors only apply to precipitation falling as rain during the growing season, in this case proposed as March through October.

[5] Soils are classified into four HSGs (A, B, C, and D) based on the soil's runoff potential. A's generally have the smallest runoff potential and Ds the greatest.

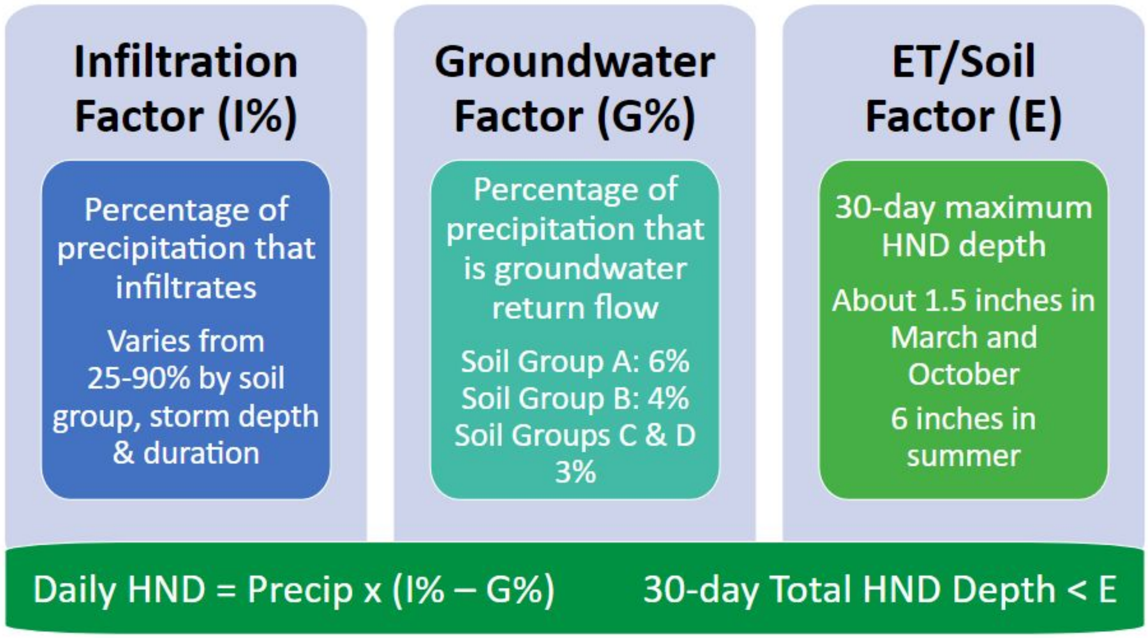

Figure 2.2. Summary of three-part HND Factor and HND calculation

The three parts of the HND Factor are:

1. Infiltration Factor (I%): the percentage of precipitation depth that infiltrated under natural conditions and was available for HND and groundwater return flow. For most storms, the Infiltration Factor is 90 percent of the precipitation depth, but for higher intensity storm events, the percentage decreases. The reduced infiltration percentage occurs more readily for finer soils, such as HSG A and B and less readily for coarser soils, HSG C and D. This memo defines different curves of the Infiltration Factor for each HSG. Figure 2.3 is an example of an Infiltration Factor curve.

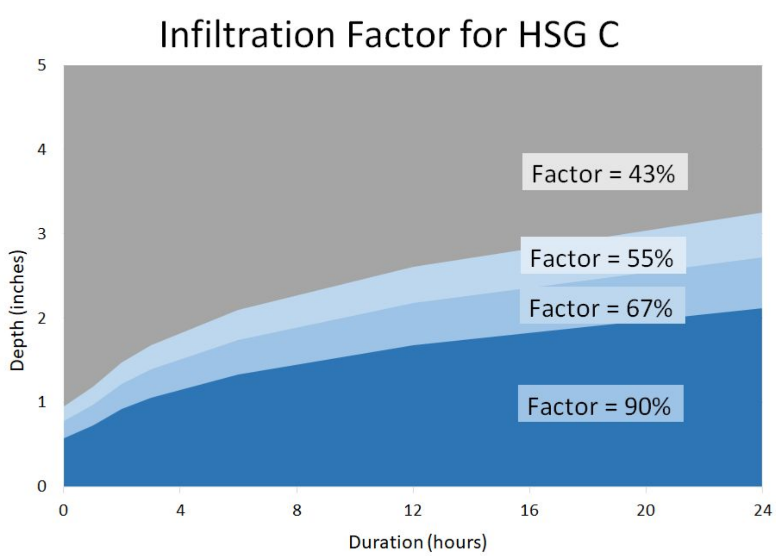

Figure 2.3: Example Infiltration Factor Curve

2. Groundwater Factor (G%): the percentage of precipitation event depth that infiltrated under natural conditions and then deep percolated past the root zone and is assumed to become groundwater return flow. This is a percentage of precipitation depth that varies by soil group as follows: HSG A = 6%, HSG B = 4%, HSG C = 3%, HSG D = 3%. The Daily HND is the portion of precipitation that infiltrated but did not continue past the root zone as deep percolation (Figure 2.2).

3. ET/Soil Factor (E): a maximum harvest rule applied as a 30-day running total limit on HND depth to account for natural processes that limit HND on a term longer than one day. These processes include back-to-back storms that reduce infiltration rates, soil moisture storage capacity that fills and cannot be depleted under wet conditions, and native vegetation ET rates that vary by season. The ET/Soil Factor 30-day limits on HND are much greater than average monthly precipitation in Colorado and would only limit rainwater harvesting under unusually wet conditions. The ET/Soil Factor 30-day limits are shown below.

Table 2.1: ET/Soil Factor 30-day HND Limit

	Mar	Apr	May	June	July	Aug	Sep	Oct
ET/Soil Factor (in)	1.4	3.9	5.4	6.0	6.0	5.8	4.0	1.5

The pilot project accounting template includes the calculations for all three parts of the HND. The user will set up the accounting template to include the area made impervious by development and the HSG proportions of the impervious areas. The template uses these parameters to calculate the Daily HND using 15-minute precipitation data from an on-site rain gage and provides the allowable harvest volume for that day at the pilot project site (Figure 2.4).

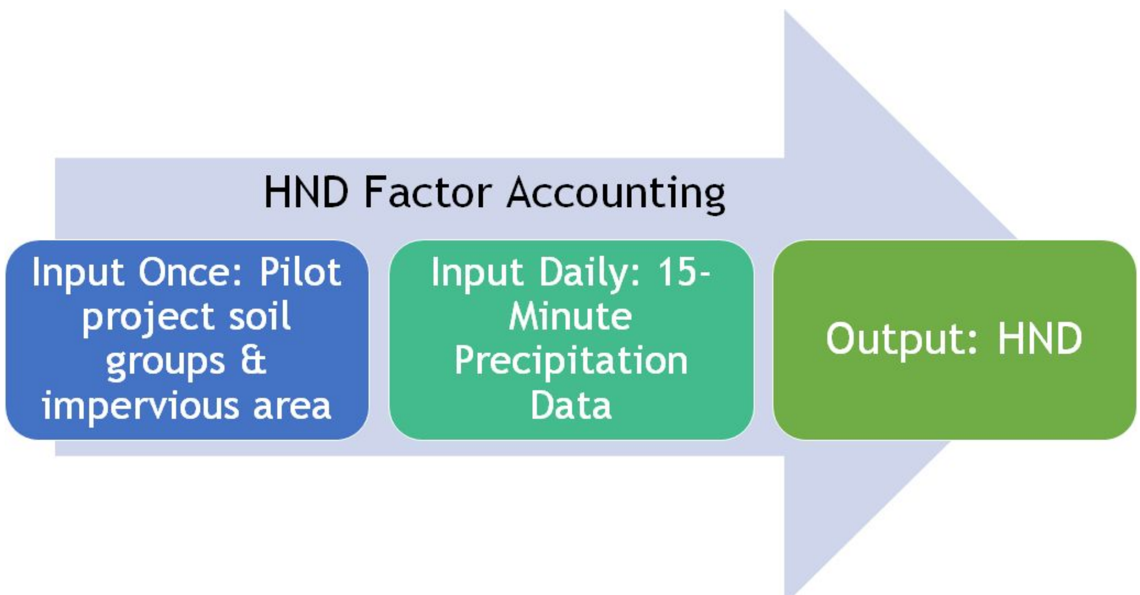

Figure 2.4: Summary of accounting procedure

2.3 Previous Work: Sterling Ranch Pilot Project

LRE's Colorado Water Plan Grant Task 4B developed Factors using data from Sterling Ranch, the only pilot project in operation. LRE found the average HND to be 95% of precipitation from 8 years of monitoring and modeling the Sterling Ranch catchment.[6] This is in accordance with other local observations such as a USGS study that found an annual mean of 83% HND in Jefferson County,[7] as well as hydrology literature for semi-arid regions, where modeled HND ratios vary from 74%-100% of precipitation.[8] LRE's Water Plan grant evaluated Factors applicable only to the HSG that occurs on Sterling Ranch (HSG C). LRE also developed a simplified approach to Factors based only on storm depth. This memo summarizes further analysis to develop Factors for all four HSGs based on considerations in addition to storm depth that impact HND. The analysis resulted in the conclusion that storm event intensity and duration can impact HND and can be reasonably incorporated in HND Factors.

2.4 Map and Limitations of Factors Application

The proposed Factors estimate HND for storm events on each HSG using precipitation depth and duration information combined with infiltration-runoff modeling. The runoff modeling was completed for precipitation falling as rain but did not consider snow. Thus, these Factors can be applied throughout most of Colorado, with three significant limitations: snowmelt may not be harvested, pilot projects cannot claim HND in absence of pre-development vegetation, and pilot projects cannot claim HND in areas of rock outcrop.

The map in Figure 2.5 generalizes the proposed areas of Colorado where the HND Factors can be applied in an SWSP. HND Factors can be applied in areas of Colorado with soil to support infiltration and vegetation. The NRCS Web Soil Survey should be used by applicants to show that appropriate soils exist in the catchment area. As shown in Figure 2.6, the Web Soil Survey provides spatial and tabular data for an area up to 100,000 acres, including HSG and soil descriptors. Rock outcrop is categorized as HSG D in the Web Soil Survey, with a soil descriptor field noting "rock outcrop". Any rock outcrop areas should be excluded from HND credit.

Natural depletion of snowmelt, and potential capture thereof, were not evaluated by either LRE for the Water Plan Grant nor this analysis. Therefore, precipitation that falls as snow and then melts to runoff should not be captured for reuse by a pilot project relying on the proposed Factors. The template accounting requires pilot project operators to exclude snow events from the precipitation record when determining daily HND for storage operations. A subsequent effort could propose the use of snowmelt in Factors. Or, a pilot project could propose a snow HND in a water court augmentation plan proposal to access snowmelt for harvest.

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[6] LRE Colorado Water Plan grant deliverables, Task 4A.
[7] Bossong et al., 2003. USGS WRI 03-4034.
[8] See Lesschen et. al (J. Geomorphology, 2009), Chauvin et. al (USDA-ARS, 2011).

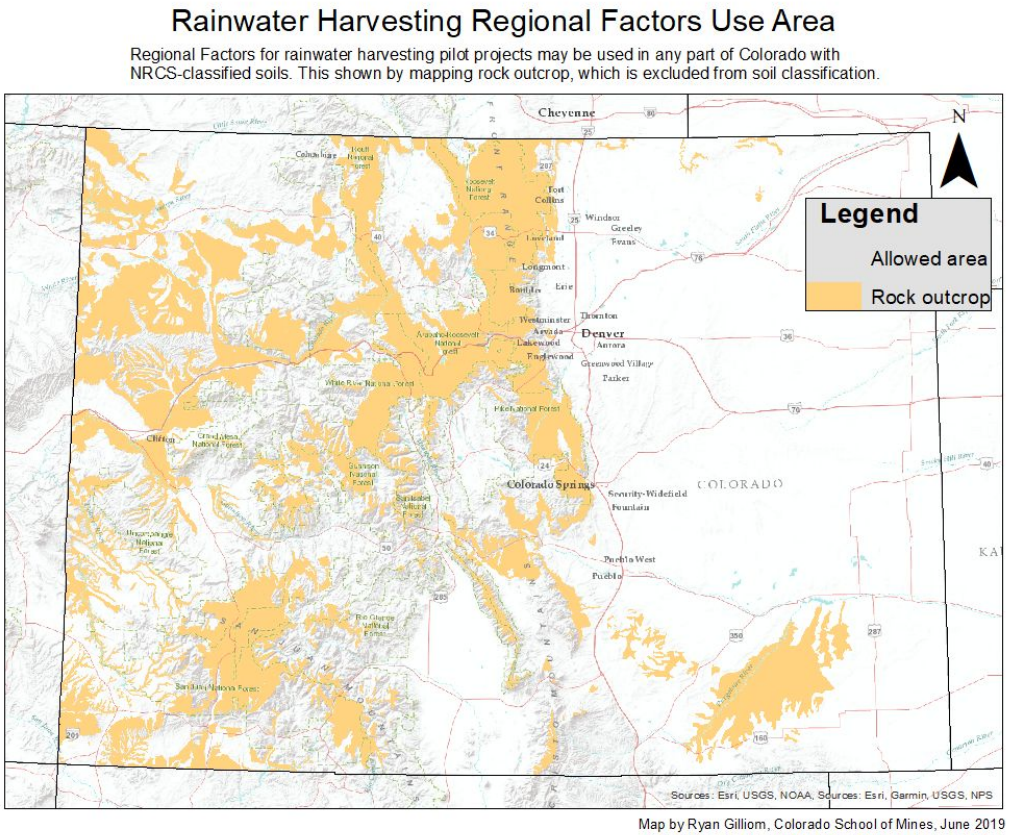

Figure 2.5: Map of areas eligible for proposed Factors.

Figure 2.6: Web Soil Survey user interface and HSG map

3 HND Factors Development

The HND is defined as the portion of a rain event that, in natural pre-development conditions, was consumed by evapotranspiration and did not enter the stream system (Equation 1). To ensure a conservative estimate that protects senior water rights, the proposed HND Factors consider precipitation followed by infiltration and runoff independent of catchment size, slope, or vegetation, as further described below. Infiltration is presumed to portion into deep percolation below the root zone (which becomes groundwater return flow) and natural depletion (plant uptake and direct evaporation). All runoff is assumed to accrue to the stream. This approach excludes historic ET that may have occurred in transit between the location where the rain falls and the receiving stream (overland flow, ET from puddles and vegetation). HND is calculated as infiltration (Equation 2) minus groundwater return flows (shown in Equation 1; Groundwater Return is assumed to equal 3-6% of precipitation, depending on soil group). Finally, the volume of HND that may be harvested is calculated based on impervious area in the development (Equation 3).

$$Historic\ Natural\ Depletion = Precipitation \times (\%Infiltration - \%Groundwater\ Return)$$

(Equation 1)

$$\%\ Infiltration\ = \frac{Precipitation - Runoff}{Precipitation}$$

(Equation 2)

$$Allowable\ Harvest\ [acft]\ =\ HND[in]\ \times\ Area\ Made\ Impervious\ [acres]\ \div 12$$

(Equation 3)

3.1 Infiltration Factors Development

3.1.1 Infiltration Modeling

3.1.1.1 Modeling Methods and Site Slope

Following LRE's work, this analysis modeled the partitioning of precipitation into runoff and infiltration using WQ-COSM version 3.1, a rainfall-runoff model developed by Denver's Urban Watershed Research Institute. Post-processing of model outputs further partitions infiltration into deep percolation, which becomes groundwater return flow, and water that remains in the soil root zone, which becomes HND via evapotranspiration. The model was selected by LRE for the following reasons: the Hortonian infiltration method underestimates infiltration;[9] the model is continuous, allowing for the simulation of wet or dry antecedent conditions, and the exclusion of overland flow modeling excludes infiltration in transit from the HND estimate, a conservative approach.

Land slope is not considered in the WQ-COSM model, but the impact of land slope on infiltration was researched for possible inclusion in HND Factors. Although high slope angle can affect infiltration-runoff partitioning due to reduced depression storage and

[9] Green, I.R.A. An explicit solution of the modified Horton equation. J. Hydrol. 1986.

infiltration rate,[10] experimental data from arid and semi-arid sites showed that slope angle does not considerably impact infiltration-runoff partitioning.[11]

Higher slope angles may decrease a site's capacity for depression storage, which can increase infiltration potential of initial runoff. Since the infiltration modeling using WQ-COSM excludes losses that may occur during runoff transport, the impact of slope on depression storage is not appropriate to consider for the HND Factors. Further data from arid and semi-arid sites found that runoff (and inversely natural depletion, per our assumptions) is most strongly related to total precipitation and precipitation intensity, which are accounted for in the Factors.[12]

3.1.1.2 Modeling Data

Data to develop statewide Factors were generalized to the highest level possible. Soil infiltration parameters for the model are based on the recommended values for the Natural Resources Conservation Service'sHSGs.[13] HSG are mapped in a geospatial database and can be referenced for a pilot project anywhere in the state.[14] Precipitation events were constructed using Front Range depth-duration storms for 1, 2, 5, 10, and 25-year return intervals with durations of .25, .5, 1, 2, 6, and 24 hours.[15] Smaller storms were simulated by using a fraction of the 1-year event depth (.25, .5, and .75); these are not true return interval events, but adequately represent smaller more frequent storm depths. The modeled events range in depth from 0.13-3.63 inches and in intensity from 0.04-4.00 inches/hour. While event depth for each duration and return interval will vary across the state, the range of depths used here will appropriately represent possible precipitation events across Colorado.

Distribution of precipitation within an event can vary, which can impact infiltration estimates. The difference between precipitation patterns in western and eastern Colorado was evaluated using regional distributions of intensity from the Colorado Regional Extreme Precipitation Study.[16] There was not a meaningful difference in infiltration between these precipitation regions, as further discussed in Appendix A.

3.1.1.3 Modeling Assumptions

Throughout Factor development, conservative assumptions were made such that the outcome would minimize the infiltration estimate (Equation 2). The Horton infiltration model projects a constant decay in infiltration rate over time, while infiltration rate

[10] Ebrahimian et al. 2012, Polish J. of Env. Studies; Mishra et al. 2014, Water Res. Mgmt.
[11] Yair and Raz-Yassif 2004, Geomorphology.
[12] Ries et al. 2017, J. Hydrology: Regional Studies.
[13] National Engineering Handbook Ch. 7: Hydrologic Soil Groups. USDA NRCS, 2007.
[14] USDA NRCS Web Soil Survey tool can be used to download soils mapping for an area up to 100,000 acres.
[15] Precipitation frequency depths were pulled from NOAA Atlas 14 for the Kassler Station near Sterling Ranch (ID 05-4452)
[16] CO-NM Regional Extreme Precipitation Study, Colorado Division of Water Resources Dam Safety, 2018.

actually decreases with infiltration and saturation in the field. Thus, in any rain event without constant precipitation, Horton provides a conservative infiltration estimate.[17]

Although these runoff modeling results are not validated with observed data, these minimizing assumptions give us confidence that the Factors are appropriately conservative for pilot project SWSPs. The Board may decide to apply an additional "safety factor" to the Factors in the Criteria and Guidelines if they deem it necessary.

3.1.1.4 Infiltration Sensitivity Analysis

As part of the modeling process, we conducted an analysis of modeled infiltration response to WQ-COSM parameters and precipitation input characteristics. The following parameters were evaluated to determine if changing their values within the model's recommended range would have a significant impact on infiltration: initial and final infiltration rates, infiltration decay rate, pervious depression storage, storm separation, minimum depth to runoff, and drying period (time to full infiltration rate recovery).This analysis is detailed in Appendix A of this memo. Findings were used to inform final model parameter values as well as accounting rules. HSG infiltration parameters are reported in Table 3.1; other model parameters are detailed in Table 3.1 of Appendix A.

Table 3.1: HSG Model Parameter Values[18]

Soil Group	Initial Infiltration Rate (in/hr)	Final Infiltration Rate (in/hr)	Infiltration Decay Rate (-/hr)
HSG A	1.7	1.5	2
HSG B	1.4	1.2	3
HSG C	1.0	0.2	3
HSG D	0.3	0.1	3

3.1.2 Infiltration Factors

The Infiltration Factors are based on precipitation depth and duration as well as HSG. If Factors were based solely on precipitation depth, the impact of intensity would be lost, resulting in over- and under-estimation of HND. This complexity is included in a template accounting sheet to be used by pilot projects. Infiltration Factor accounting rules require high-resolution precipitation data monitored at the pilot project site (15-minute timestep), which is processed into storm events using a 3-hour dry period to define storm separation. The rules are applied separately for HSG, requiring acreage of

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[17] For example, if a 6-hour event has rain only in the first 2 hours and last 2 hours, actual infiltration would reflect the dry 2-hour period in the middle. A Hortonian model of this event projects constant decline in infiltration rate over the 6 hours, independent of precipitation and cumulative infiltration. This results in a lower total infiltration.

[18] These parameter values are the lowest infiltration rate and fastest decay rate recommended for each soil group in the WQ-COSM manual.

area made impervious over each group. Some soils are classified as A/D, B/D, or C/D to indicate different infiltration capacity in different soil drainage conditions (water table more or less than 24 inches below surface).[19] For pilot project accounting purposes these combination soils should be classified as the well-drained HSG (A, B, or C) if the project sponsor can demonstrate that the water table is deeper than 24 inches.

3.1.2.1 HSG A

This sandy soil group has higher initial and final infiltration rates relative to typical precipitation intensity, resulting in a higher total infiltration capacity. The Infiltration Factor falls at 90% all but the most intense short events, where the ratio falls to 70% for events larger than 10-year (Figure 3.1). HSG A shows decreased infiltration when high-intensity events deliver precipitation at a rate that exceeds infiltration rate. The infiltration rate decays from initial to final in approximately 5 minutes, but HSG A has a final modeled infiltration rate that is higher than typical rain intensity, thereby allowing most of the rainfall to infiltrate for longer duration events. With only the most intense rain events diverging from 90%, a simple two-part rule is recommended (Figure 3.2).

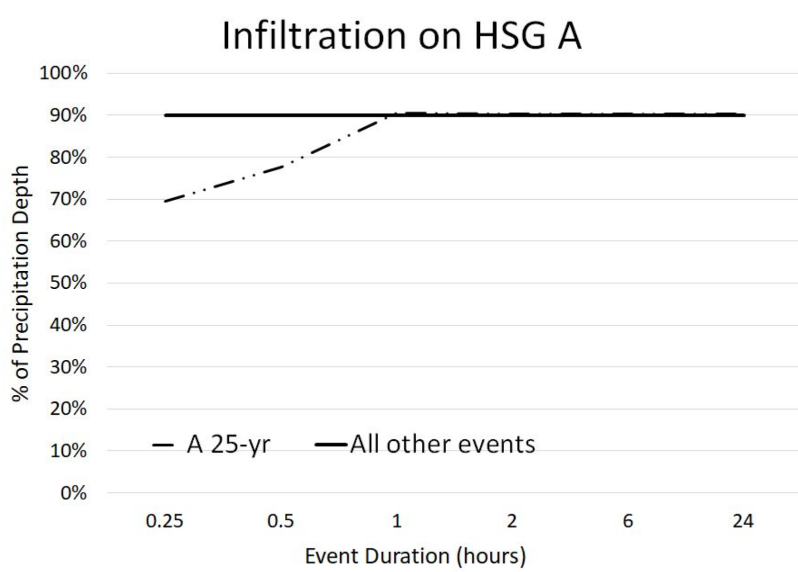

Figure 3.1: Infiltration modeling results for HSG A

[19] National Engineering Handbook Ch. 7: Hydrologic Soil Groups. USDA NRCS, 2007

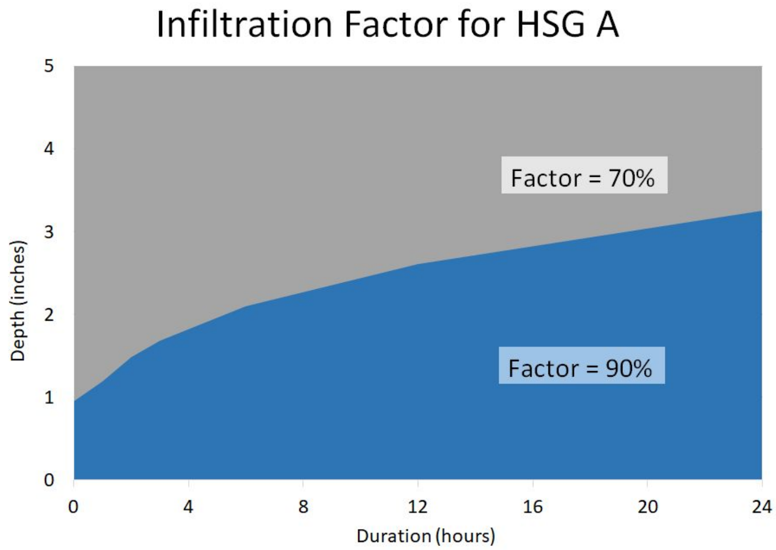

Figure 3.2: Infiltration Factor for HSG A. Events smaller than the 10-year event use I%=90%, while larger events use 70%.

3.1.2.2 HSG B

The sandy HSG B soils have higher initial and final infiltration rates similar to HSG A. On these soils, low-to-moderate intensity rain events have a 90% or greater infiltration/precipitation ratio, while short infrequent events of high-intensity diverge and the ratio falls to 62%-80% infiltration/precipitation for HSG B (Figure 3.3). Like HSG A, HSG B shows decreased HND when high-intensity events deliver precipitation at a rate that exceeds infiltration rate. The infiltration rate decays from initial to final in approximately 5 minutes, but HSG B has a final modeled infiltration rate that is higher than typical rain intensity, thereby allowing most of the precipitation to infiltrate. The recommendation for HSG B is a three-part rule (Figure 3.4).

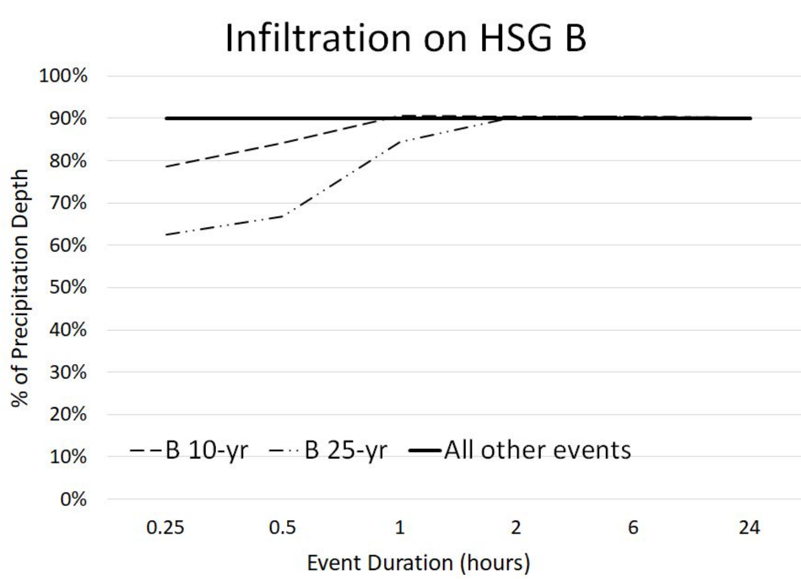

Figure 3.3: Infiltration modeling results for HSG B

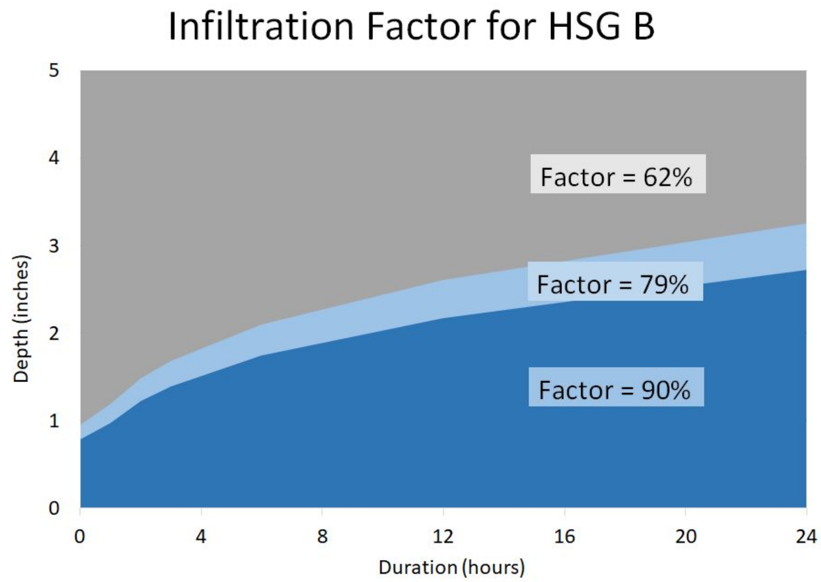

Figure 3.4: Infiltration Factor for HSG B. Events up to the 5-year use %I=90%; those greater than the 10-year event use 62%, with intermediate events using 79%.

3.1.2.3 HSG C

The more loamy and clay-dominant HSG C has an initial infiltration rate close to HSG B's final rate and a very low final infiltration rate. The infiltration/precipitation ratio on HSG C follows the 90% ratio up to the 5-year event, breaking at a lower intensity than HSGs A and B (Figure 3.5). A different pattern is observed with HSG C than A and B; on HSG C, the shortest and longest intense events have higher infiltration than mid-range event duration of 1-6 hours. Because the infiltration rate decays to the final value in 16 minutes, 15- and 30-minute events have a bulk of their precipitation falling on higher infiltration rates. Meanwhile, most precipitation in longer events falls on the lower final infiltration rate. The effect of this low final infiltration rate is most significant on mid-range events; longer events allow a higher proportion of the event to infiltrate, as even high-volume events are low-intensity over a long duration. The rule recommendation for HSG C includes more individual factors to accommodate the higher variation in infiltration estimates (Figure 3.6).

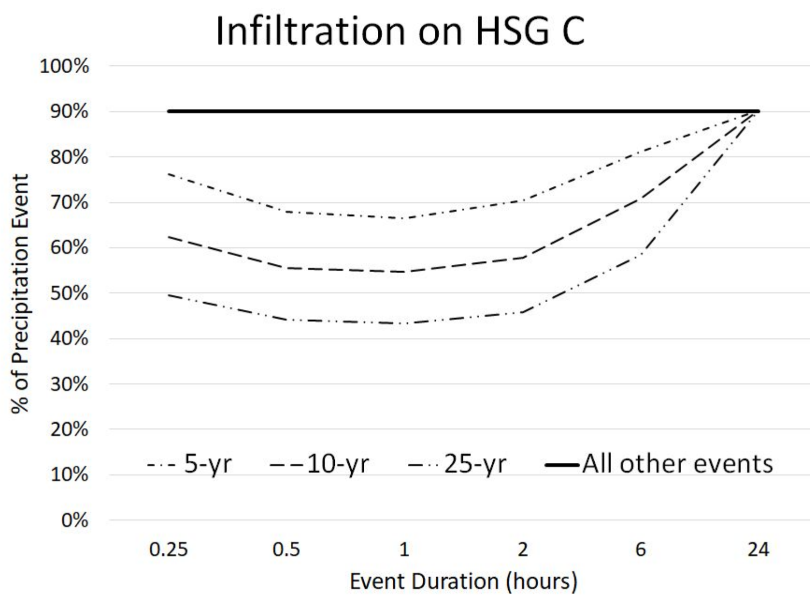

Figure 3.5: Infiltration modeling results for HSG C

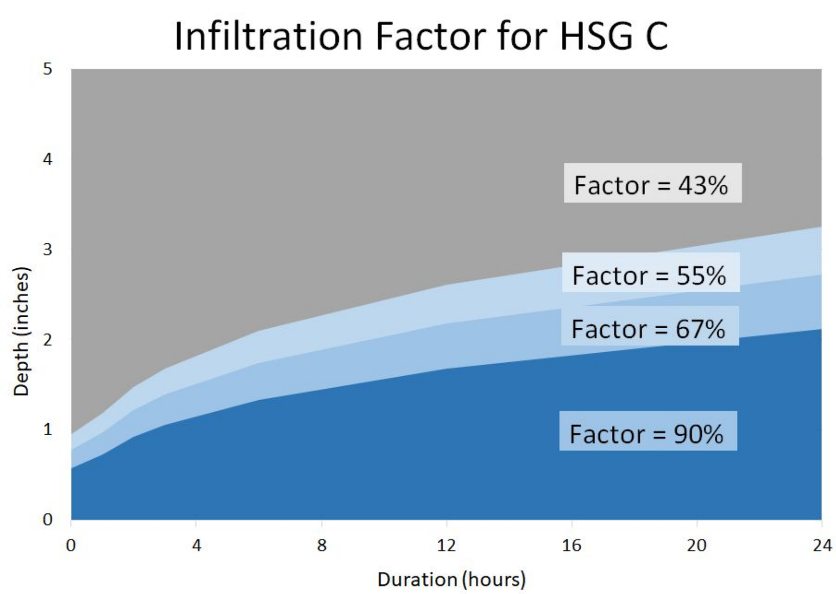

Figure 3.6: Infiltration Factor for HSG C. Events up to the 2-year use %I=90%; those greater than the 10-year event use 43%, with intermediate factors divided by the 5-year event.

Figure 3.7 shows the estimated HND depth from the LRE factors (based only on total storm depth),[20] compared to the variety of Factors that could occur when storm intensity is considered based on the Infiltration Factor recommended in this report. These results are for HSG C, the dominant soil type at Sterling Ranch and the soil group for which LRE developed an Infiltration Factor recommendation. For all but the smallest events, the Infiltration Factor proposed in this memo allow a higher harvest

[20] LRE Colorado Water Plan Grant deliverables, 2019.

volume than the depth-only findings by LRE, which were set to be conservative based only on a storm depth consideration. The HSG C Infiltration Factor recommended in this memo breaks down to three sections: 90% for lower intensity events and some small intense events (less than 0.5 inches), 55% for short high-intensity and long low-intensity events, and 40% for longer high-intensity events.

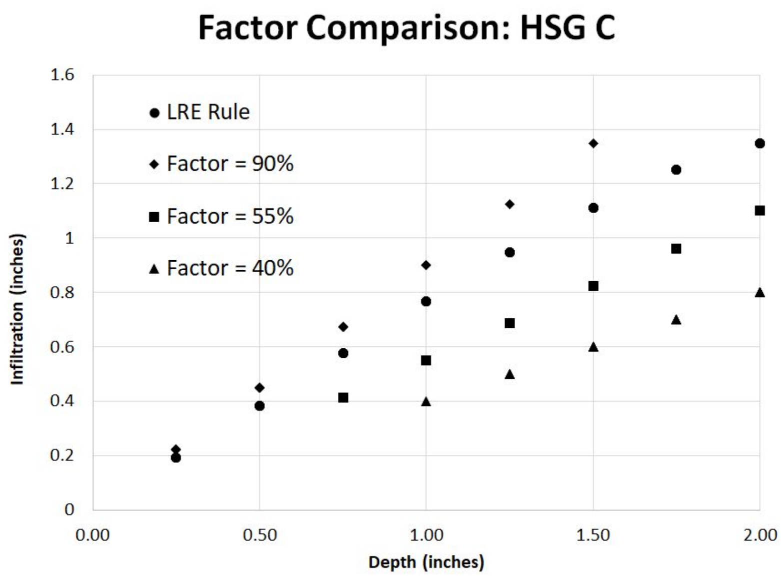

Figure 3.7: Comparison of infiltration estimates as determined by the LRE Water Plan Grant and the proposed Factors in this memo where Factors for each depth vary by intensity as a result of different event durations.

3.1.2.4 HSG D

This HSG is essentially clay, with very low initial and final infiltration rates. Initial infiltration is so low that time to the final rate is nearly irrelevant. As shown in Figure 3.8, only smaller storms with less than a 1-year return interval meet the 90% ratio of infiltration/precipitation. However, these are common, frequent storms, so a pilot project located on HSG D would be able to harvest 90% of precipitation for the majority of events. The rule recommendation for HSG D includes more individual factors to accommodate the higher variation in infiltration estimates (Figure 3.9).

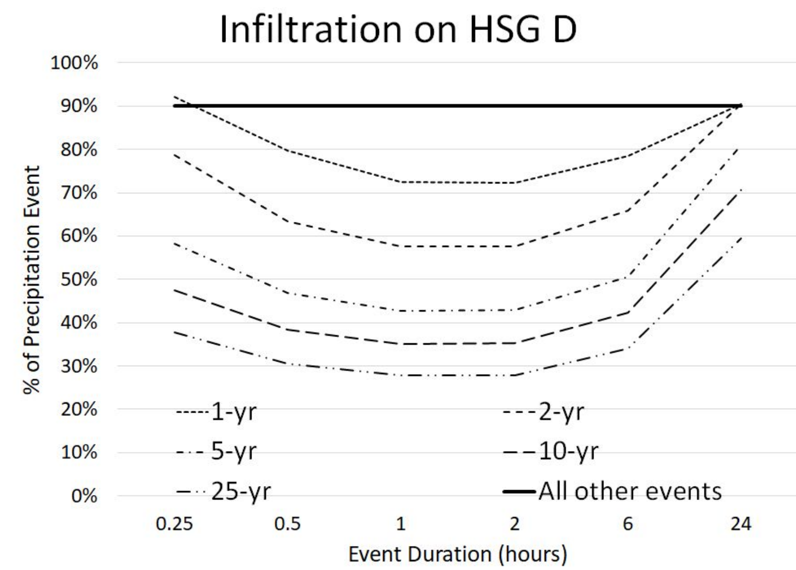

Figure 3.8: Infiltration modeling results for HSG D

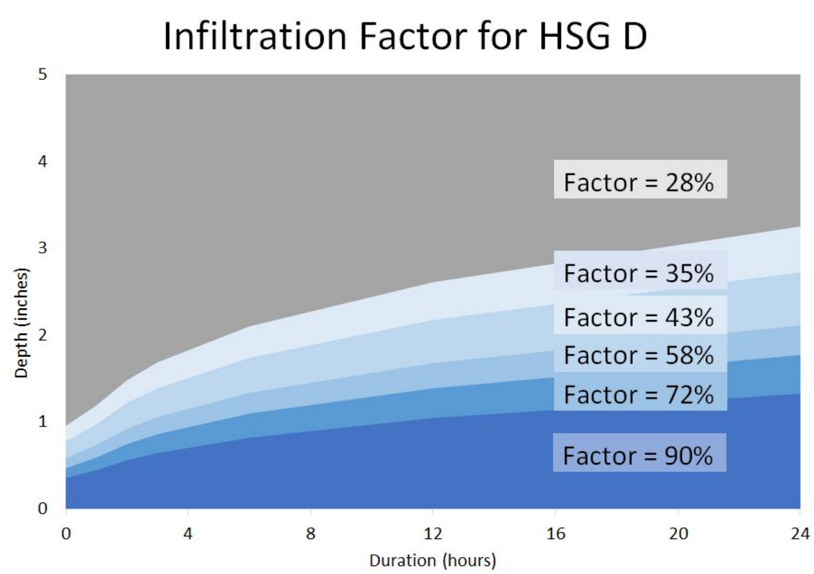

Figure 3.9: Infiltration Factor for HSG D. Events up to the 0.75-year use %I=90%; those greater than the 10-year event use 28%, with intermediate factors divided by the 1-, 2-, and 5-year events.

3.2 Groundwater Factors

3.2.1 Groundwater Factors Development

Groundwater return flows are a part of the infiltrated precipitation modeled in WQ-COSM. Therefore, the Infiltration Factor estimates both groundwater return flow to the stream and infiltrated water retained in soil moisture storage within the root zone for consumption by vegetation (HND). This analysis did not include a separate water budget accounting for infiltrated water, but bases the Groundwater Factor recommendation on (1) results summarized by LRE in their Task 4C grant memo, which include findings on Sterling Ranch and assumed deep percolation rates for several state-accepted models Colorado, and (2) other resources on deep percolation and soil type.

3.2.1.1 Sterling Ranch Observation and Simulation

As described in LRE's Task 4C memo, instruments were monitored at a weather station on Sterling Ranch in a small undeveloped natural catchment within the pilot project area. The installation included a 3.75 foot deep lysimeter, which monitored infiltration and deep percolation from April 2014 through July 2018. Over these 5 growing seasons, 0%-3% of the precipitation was observed percolating past the root zone in the locations HSG C soil. LRE also simulated runoff, soil moisture storage, evapotranspiration (using Penman-Monteith), and deep percolation at Sterling Ranch using the 1-dimensional Hydrus 1-D model calibrated to lysimeter observations. Over the model simulation period of April, 2010 through May, 2018, deep percolation totaled 2% of the observed precipitation. In a separate soil moisture model, LRE simulated deep percolation at the Sterling Ranch lysimeter using a daily soil reservoir accounting model and different infiltration estimates. The results of this effort, no matter what method was used to estimate infiltration, also simulated that 2% of total precipitation deep percolated between 2010 and 2018. Together these observational and model findings led to LRE's recommendation of 3% groundwater return.

In LRE's observations and simulations they note that deep percolation was rare, occurring only when soil moisture storage was exceeded.[21] Deep percolation was observed and simulated to occur after back-to-back large storms where there was not time for soil moisture storage to be depleted by evaporation and transpiration. With soil moisture remaining nearly full, a new precipitation event would cause infiltrated water to exceed soil moisture storage, resulting in deep percolation.

3.2.1.2 Deep Percolation in Colorado Models and Literature

LRE summarized that the South Platte and Arkansas River Decision Support System models both assume that deep percolation is 3% of precipitation on undeveloped pervious surface. In these two models, deep percolation does not vary with soil type. LRE further summarized the more complex approach for the Republican River Compact Administration Model, which uses deep percolation curves that increase with annual precipitation and that simulate higher recharge for coarser soils. A summary of the native soils recharge percentages is shown in the chart below (Figure 3.10). Model documentation states that the deep percolation assumptions in the model are based on a "compromise agreement,"[22] suggesting that the rates are not solely based on scientific understanding. However, scientific literature confirms the assumption that coarse-grained or sandy soils generally result in higher recharge rates than do fine-grained loam and clay soils.[23,24]

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[21] Only two years out of the 8-year record resulted in modeled deep percolation (2015 and 2017). LRE Colorado Water Plan Grant deliverables, 2019.

[22] Republican River Compact Administration Model, June 2003 (no author listed).

[23] Scanlon, B.R., et. al., 2002. "Choosing appropriate techniques for quantifying groundwater recharge." Hydrogeology Journal.

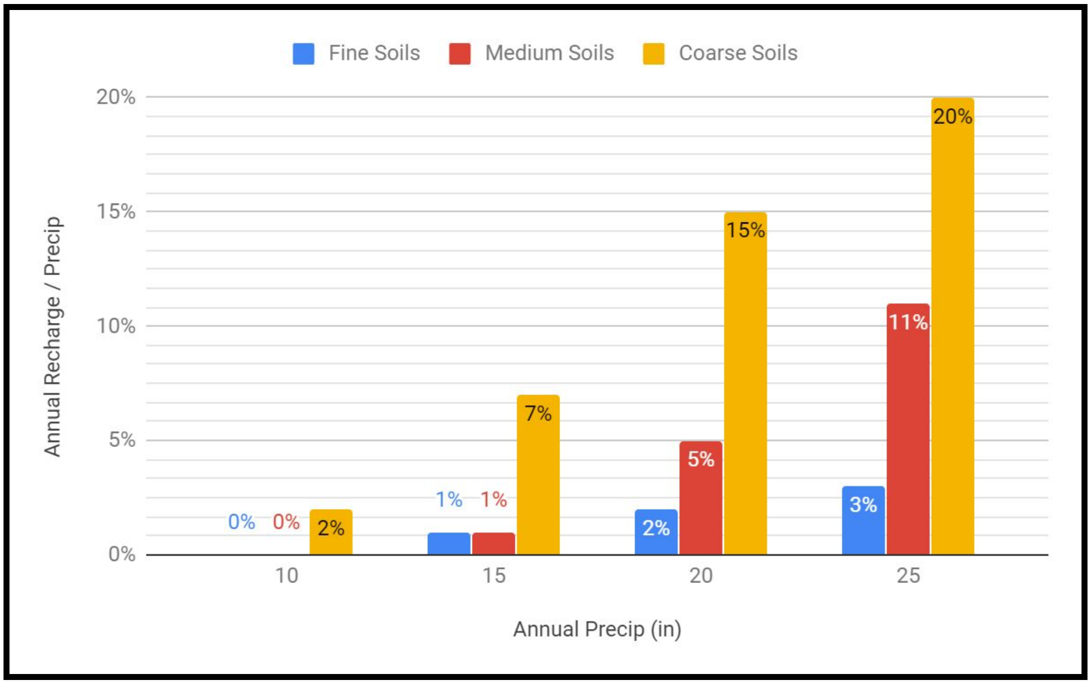

Figure 3.10. Republican River Compact Administration Model groundwater percentages

3.2.2 Groundwater Factors

This report recommends that groundwater return flows are accounted as a constant percentage of precipitation, varying by soil group. For the finer soils, HSGs C and D, a 3% groundwater-precipitation ratio (G%) is recommended. For the coarser soils HSGs A and B, groundwater-precipitation ratios (G%) of 4% and 6%, respectively, are recommended.

3.2.2.1 Groundwater Return Flow Timing

Pilot projects have two options for groundwater return flow replacement. The first is to return the Groundwater Factor volume to the stream system at a constant rate based on the last 5 year average rainfall totals. The second option is to return the Groundwater Factor volume of each rain event through onsite recharge. The constant rate return flow obligation is about 5 acre-feet per year for a 160-acre impervious area and 12 inches of annual precipitation, on HSG C or D (G% = 3%), a flow rate obligation less than 0.01 cfs.

LRE's Task 4D Report describes how deep percolation at a location very near the stream or located in areas with highly transmissive soils could result in spikes of groundwater return flows to the stream system after large storms. The Groundwater Factor allows for constant return flow replacement due to the following considerations:

[24] Bethune et al., 2008. "Understanding and predicting deep percolation under surface irrigation." Water Resources Research.

- Groundwater return flow from precipitation events is a small volume of water, 5 acre-feet per year for the example above.

- Many pilot projects, such as Sterling Ranch, will be located in areas where travel through the aquifer to the stream attenuates fluctuation in groundwater return flow amounts.

- When new developments create impervious surfaces this reduces infiltration and reduces groundwater return flow from precipitation, changing the historical pattern of groundwater return flow. When this happens in a new development that is not harvesting rainwater, there is not a legal requirement to maintain historical stream conditions for senior water rights. Requiring a constant groundwater return flow for the proposed Factors is conservative compared to a development that creates impervious surfaces with no consideration of groundwater return flows.

3.3 ET/Soil Factor

Under certain conditions, modeled infiltration from storm events can exceed 10 inches in a short period. In most locations, 10 inches of water cannot be stored in the soil root zone and would deep percolate and could not be consumed by vegetation. A more reasonable amount of soil moisture storage within the root zone of Colorado's native plants is 6 inches.[25] Under natural conditions, soil moisture storage can be filled by precipitation and then is reduced by native plant ET at a rate that is directly related to temperature and other weather conditions, reducing the amount of water in storage until the next rain event adds more water to soil moisture storage. In typical historical consumptive use calculations a soil moisture water balance performed on either a daily or monthly time-step is used to determine how the soil moisture storage changes over time. A temporal water balance is too complex to include as part of the Factors. A simplified alternative for the Factors is a 30-day running limit on HND to account for physical limits on HND during wet periods. The limit is based on ET rates and soil moisture storage as described below.

Figure 3.11 shows average monthly meadow grass ET in four populated areas of Colorado, which are potentially representative of pilot project locations. Average monthly meadow grass ET ranges from 1.5 inches in the early and late season to about 7-8 inches in June and July.[26,27] Although water may infiltrate at a rate greater than ET, HND cannot exceed the rate at which plants consume water.

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[25] Using the same assumption required for pilot projects pursuant to Criteria and Guidelines for Fallowing-Leasing Pilot Projects, 2016.
[26] Thompson, K.L. 2019. Evaporation and Evapotranspiration Estimates for Colorado (Draft). Under review by I.A. Walter, T.W. Ley, and Wilson Water Group. Technical Memorandum, Colorado Division of Water Resources, Denver CO.
[27] ASCE Standardized ET Equation with Manual 70 perennial ryegrass crop coefficients. ASCE Manual 70. 2016. Evaporation, Evapotranspiration, and Irrigation Water Requirements. Second Edition. Eds. Marvin E. Jensen and Richard G. Allen; Environmental and Water Resources Institute of the American Society of Civil Engineers.

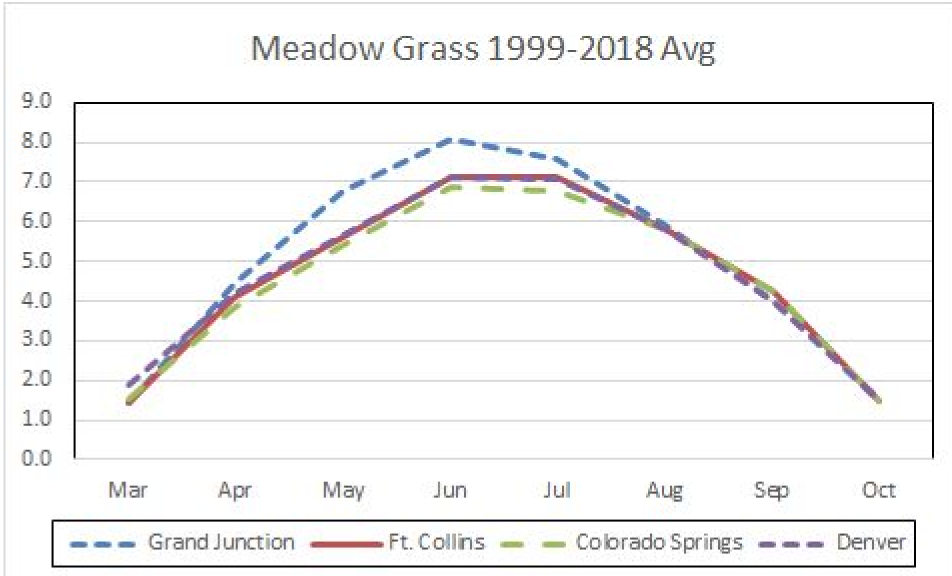

Figure 3.11: Monthly Meadow Grass ET in Colorado developed areas

In June and July, when plant ET is greatest, during a wet period, HND could potentially be limited by soil moisture storage of 6 inches rather than plant ET. Figure 3.12 shows the minimum monthly ET from the four locations in Figure 3.11 with a 6 inch limit applied in June and July as the ET/Soil Factor. The average monthly precipitation in Denver totals 13 inches between March and October with a maximum monthly total of 2.3 inches in May. Under "average" precipitation conditions, the ET/Soil Factor will not limit rainwater harvesting.

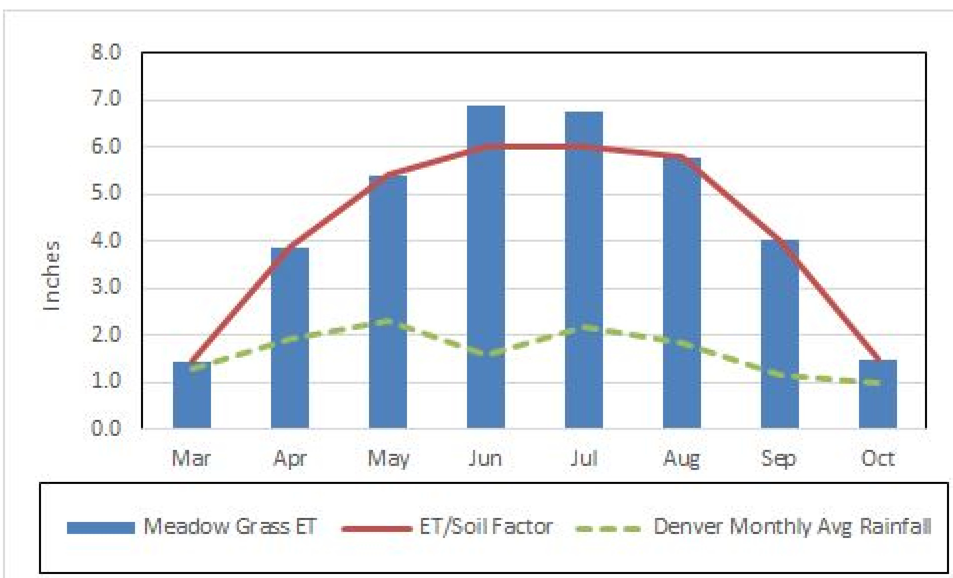

Figure 3.12: ET/Soil Factor compared to Meadow Grass ET and average precipitation

4 *Comparison of Factors with Effective Precipitation Methods*

HND is similar to the concept of effective precipitation, the amount of precipitation that is consumed by irrigated crops. Different effective precipitation methods are used in water accounting tools in the State of Colorado. This section compares the proposed HND Factor with two effective precipitation methods, Soil Conservation Service (SCS) and the Bureau of Reclamation, to provide a comparison with the HND Factors.

The SCS method of estimating monthly effective precipitation considers usable soil water storage, monthly precipitation, and monthly crop evapotranspiration.[28] Entering this data for Denver results in a monthly amount of precipitation that may be consumed by irrigated crops. As shown in Figure 4.1, the SCS effective precipitation method estimates that on average between 68% - 91% of precipitation is consumed by crops, with a greater percentage of the consumption occurring in the summer months. These percentages are within the realm of the results of the HND Factors for consumption of precipitation by native vegetation. The documentation of the SCS method describes that there are two important factors that affect how much precipitation is consumed by crops: infiltration rate and rainfall intensity. Both of these considerations are part of the proposed HND Factors.

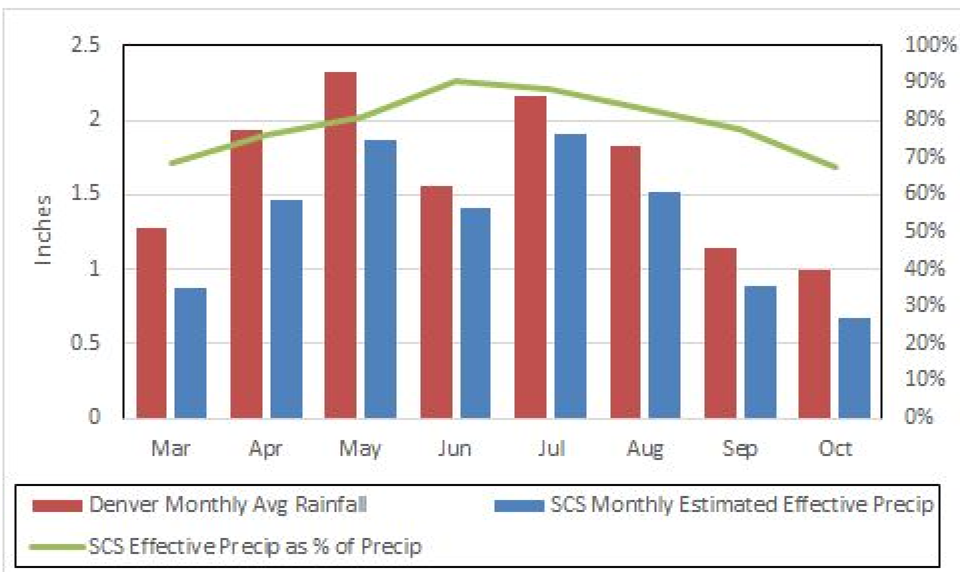

Figure 4.1: Comparison of average rainfall and SCS Effective Precipitation for Meadow Grass for Denver, assuming 6 inches of soil water storage.

As described in Colorado's StateCU model documentation (2008), Bureau of Reclamation's effective precipitation estimation is based only on monthly precipitation totals, where the first inch of precipitation is 95% consumed by plants, the second inch is 90% consumed, and less percent consumption with each subsequent inch of rainfall. Figure 4.2 shows how the percentage of rainfall that becomes effective precipitation decreases as monthly precipitation increases. This approach can be related to the

[28] National Engineering Handbook Part 623. United States Department of Agriculture, Soil Conservation Service. 1993.

proposed Factors in that with greater precipitation depth, a smaller percentage of the water is available for plant consumption. Furthermore, after six inches of precipitation in a month, very little additional precipitation contributes to Bureau of Reclamation's effective precipitation estimate, similar to the 6 inch limit established in the ET/Soil Factor.

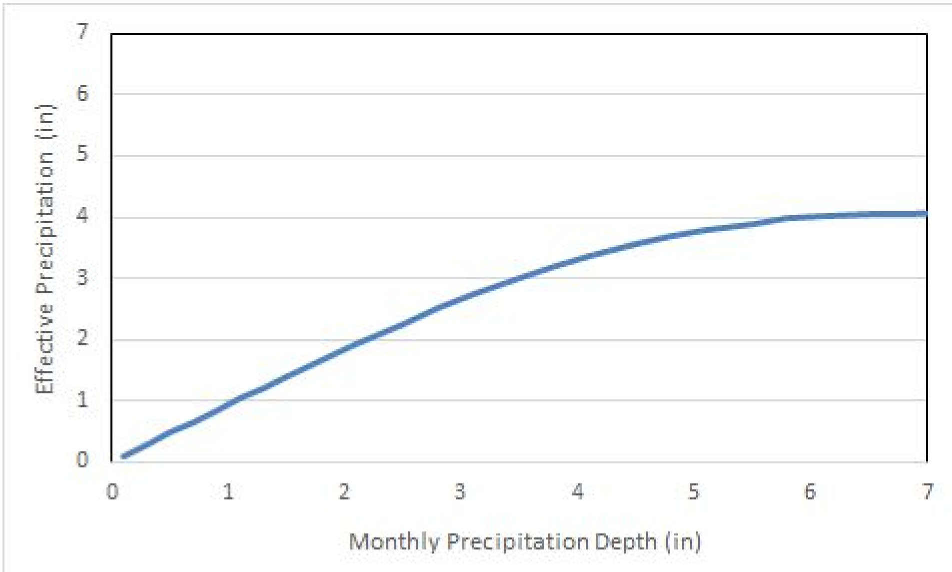

Figure 4.2: Bureau of Reclamation Effective Precipitation varies with monthly precipitation depth.

5 *Accounting Procedure*

Due to HND Factor complexity necessary to incorporate the impact of precipitation intensity, the HND Factor rules are programmed into an Excel accounting template. This will ease integration with pilot project daily accounting, which is required for all SWSPs. Daily allowable harvest volume is determined using on-site 15-minute observed precipitation, which the tool separates into storm events.[29] As shown in the accounting rule figures in Section 3, the Infiltration Factor is based on total storm depth and storm duration for that particular storm. The Excel accounting tool uses power trendlines fit to the depth-duration curve of Factor thresholds, allowing the tool to automatically determine which Infiltration Factor plot a given event should use. The ET/Soil Factor and Groundwater Factor are also included in the accounting template. Operators need to enter precipitation data daily as well as logging actual storage to track total harvest relative to the ET/Soil Factor limit. Any stored water in excess of the HND must either be released or augmented.

[29] Precipitation data will be processed using 3-hr storm separation period.

6 *Example Application of Proposed Factors*

6.1 Applying the Factors to an Event

Consider a storm event of 1 inch over 8 hours on HSG C. As shown in Figure 3.6 and Figure 2.2, respectively, the Factors for this event are I% = 90% and G% = 3%. This means that 90 percent of the rainfall would have infiltrated in native conditions and 3 percent would have deep percolated to become groundwater return flow, so that 87 percent would have been consumed. In a development with 45 acres impervious area, the allowable harvest is calculated as:

HND (in) = Precipitation x (I% - G%)

Harvest Volume (acft) = HND x (Area made impervious) ÷ 12 in/ft

Thus, for 45 acres of impervious surface, we find the allowable harvest volume as:

HND = 1.0 in x (90%-3%) = 0.87 in

Harvest Volume = 0.87 in x 45 acres ÷ 12 in/ft = 3.26 acft

From this event, a total of 3.26 acre-feet can be harvested for outdoor use at the pilot project site without augmentation.

Most precipitation events result in I% = 90% on HSG C, as in this example; in the 8-year precipitation record at Sterling Ranch, 290 of 297 observed events fall within the band where I% = 90% (Figure 6.1). The rules for HSGs A and B will allow even more events to use 90%, while HSG D will have a lower percentage of events where 90% of precipitation infiltrated under natural conditions.

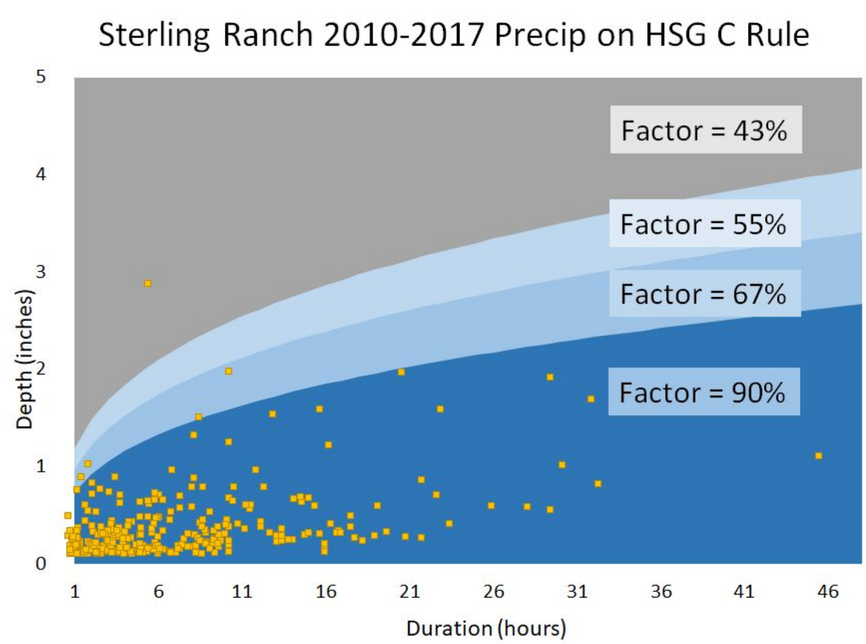

Figure 6.1: 2010-2017 Sterling Ranch precipitation record plotted on HSG C Rule

6.2 Meeting Outdoor Demand with Rainwater Harvesting

For context of supply and demand, we compare observed precipitation events in the Sterling Ranch record for the years 2010-2017 in the months March-October to a water demand estimate. For HSG C, annual HND with this precipitation ranges from 0.61-2.19 inches. In the same example development as above (45 acres impervious, HSG C), these depths convert to a monthly harvest volume of 2.28-8.20 acft. The median annual total harvest volume operating March-October is 42 acft, based on 2010-2017 precipitation observed at Sterling Ranch (see Table 6.1).

In an average Front Range residence, household water use is 0.4-0.5 acft with 55% use outdoors.[30] This equates to 0.22-0.25 acft of annual outdoor demand in an average home.[31] Assuming there are 400 homes in the example 100-acre development (45 acres of which are impervious surface), this results in 88-100 acft of average annual outdoor demand. The median 2010-2017 rainwater harvesting amount of 42 acre-feet meets 42-48% of this demand (Table 6.1).

Table 6.1: Annual HND supply compared to average outdoor demand.

Mar-Oct	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**Median**
HND supply (ac-ft)	19.2	45.3	26.3	42.4	52.7	58.1	29.5	41.6	42.0
% of full demand	22%	51%	30%	48%	60%	66%	34%	47%	48%
% of half demand	44%	103%	60%	96%	120%	132%	67%	95%	95%

Assuming that a water-smart household uses 50% of this average outdoor use estimate, the annual outdoor demand in the example development would be 44-50 acft. In this case, the median allowed rainwater harvesting almost fully meets demand, and 5 of the 8 years at Sterling Ranch would nearly meet or exceed this demand estimate. Outdoor water use in pilot projects may be even lower than these estimates due to the combination of landscaping and irrigation system design. These estimates from Sterling Ranch precipitation demonstrate the potential for rainwater harvesting to meet outdoor water demand in Colorado. Ultimately, beneficial use of rainwater harvested at pilot projects will depend on actual precipitation, storage pond size, and operations, and demand will depend on residential layout, landscaping, and irrigation. The sizing and usage of harvest facilities, as well as design and operation of the non-potable irrigation systems, are beyond the scope of this report.

[30] Fact Sheet No. 9.952: Water Conservation In and Around the Home. Colorado State University, 2014.

[31] Outdoor water demand in a pilot project will be less than the Colorado average due to Criteria and Guidelines requirements of water-smart landscaping and efficient irrigation.

Appendix A: Infiltration Modeling Sensitivity Analysis

HB15-1016 Rainwater Harvesting Pilot Project Regional Factors

2019

by

Ryan Gilliom

July 1, 2019

COLORADO
Division of Water Resources
Department of Natural Resources

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FIGURES

1 Purpose

This appendix to the DWR Historic Natural Depletion (HND) Factors memo describes methods and results of a sensitivity analysis used to inform development of the Factors. The purpose of this analysis is to evaluate the sensitivity of infiltration estimates (Infiltration Factor) to varying model parameters and precipitation variables. This informs the scope of HND Factors (detailed in Factors memo) that can account for storm depth and duration, recent precipitation events, and precipitation event characteristics in different regions of Colorado. The results of the sensitivity analysis show which variables should be included in HND Factors to offer better estimates of HND than a simpler approach based on precipitation depth alone. Sensitivity results for WQ-COSM model parameters also ensured that the final parameter values minimize infiltration estimates to minimize the HND (the conservative result). Finally, findings related to recent precipitation events were used to inform the ET/Soil Factor part of the HND Factors.

2 Methods

2.1 WQ-COSM Parameters

WQ-COSM runoff modeling sensitivity was evaluated by varying each parameter individually to the minimum and maximum values recommended in the model manual. This analysis used 15-minute precipitation recorded from March-August 2013 at a Front Range precipitation gage.[1] Infiltration conditions vary between precipitation events, so sensitivity results can vary between different events with the same parameters. Therefore, a seasonal analysis is used to see the sensitivity of infiltration over a wide range of event depths and durations.

2.1.1 Soil Infiltration Parameters

Soil infiltration parameters include initial and final infiltration rates and infiltration decay rate. These values vary by soil type and condition, which are attributed to NRCS Hydrologic Soil Group (HSG) in the model manual. A range of initial and final infiltration rates are recommended based on soil and vegetation conditions; these were adapted to fit HSG definitions. The “maximum value” used for final infiltration rate was capped by the default value of initial infiltration rate. The WQ-COSM manual recommends a single infiltration decay rate for each HSG, citing low sensitivity to this parameter. The parameters included in the sensitivity analysis are described in Table 1 below.

2.1.2 Other Parameters

Other parameters include the precipitation processing setting of storm separation time and overall catchment parameters including pervious depression storage, minimum depth to runoff, and drying period. The WQ-COSM parameter of impervious depression storage was excluded from the sensitivity analysis because catchment percent impervious is set to 0.01% to simulate the natural pre-development conditions where all land surfaces are pervious.

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[1] Precipitation frequency values were pulled from NOAA Atlas 14 for the Kassler Station near Sterling Ranch (ID 05-4452).

2.2 Precipitation

2.2.1 Temporal Distribution & Timestep

Infiltration-runoff partitioning is directly impacted by event intensity; intensity can vary within an event, and these storm characteristics can vary geographically. Sensitivity of infiltration-runoff partitioning to distribution of precipitation within an event was evaluated using an existing study of Colorado and New Mexico regional precipitation regimes (REPS).[2] The modeled storms are of equal depth and duration with different intensity patterns within the event. This analysis compared 6-hour and 24-hour intensity patterns for "east" and "west" precipitation regions of Colorado (Figure 1) and compared the 1-hour and 2-hour event distributions with uniform distributions (uniform distribution is constant intensity for the duration of the event, Figure 2).[3] Finally, the outputs of 5-minute and 15-minute precipitation data were compared for 1- and 2-hour events to determine if higher-resolution precipitation data improves infiltration estimates.

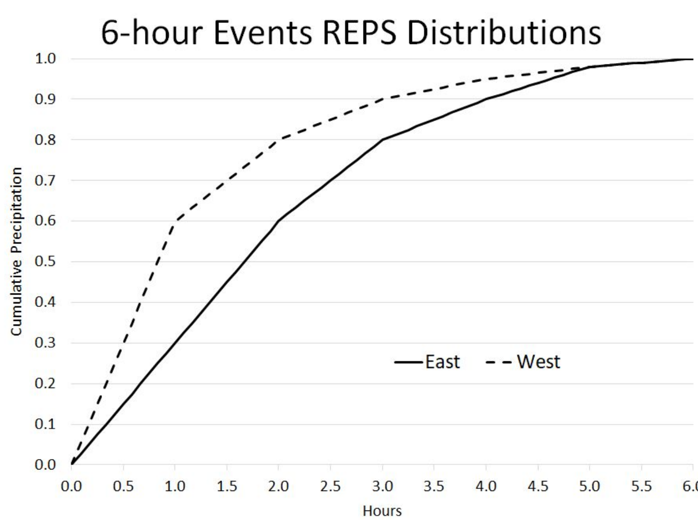

Figure 2.1: 6-hour event distribution in the East and West REPS regions of Colorado.

[2] CO-NM Regional Extreme Precipitation Study Volume III, Colorado Division of Water Resources Dam Safety, 2018.

[3] The CO-NM REPS study only developed regional distributions for 6- and 24-hour events; 1- and 2-hour events are represented with the same intensity distribution across the state.

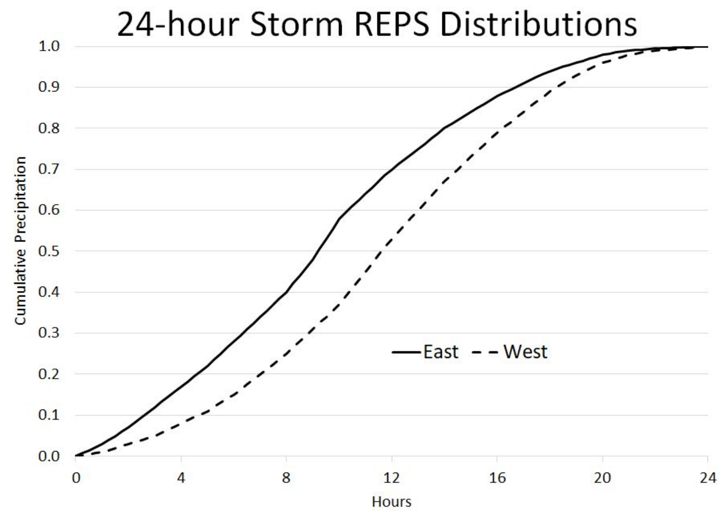

Figure 2.2: 24-hour event distribution in the East and West REPS regions of Colorado.

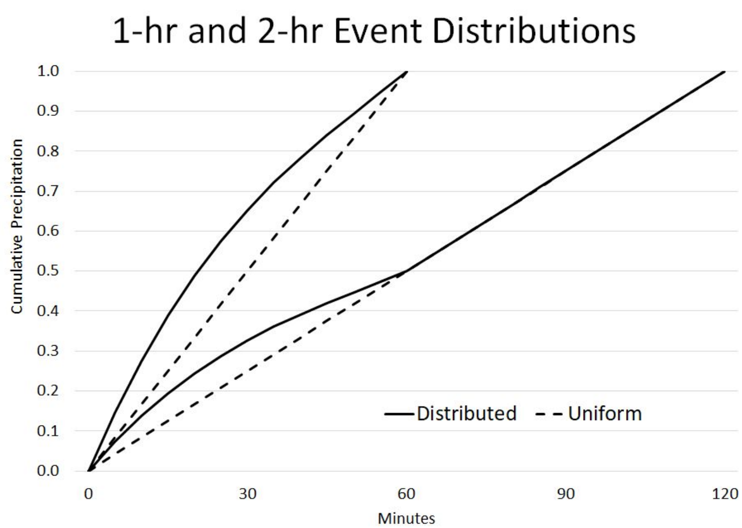

Figure 2.3: Precipitation distribution within 1- and 2-hour events in Colorado and New Mexico. Distributed line shows Colorado and New Mexico REPS study results, while Uniform lines shows equal intensity throughout the event.

2.2.2 Antecedent Precipitation

Infiltration can be affected by recent precipitation, when the soil infiltration capacity does not fully recover to the initial infiltration rate. Because the WQ-COSM model does not directly model soil moisture storage, recovery of infiltration capacity is based solely on the Drying Period parameter, which defines the duration over which soil infiltration capacity and depression storage return to initial model values. With Drying Period set to 3 days, initial infiltration may be impacted by events in the preceding three days. We examined the impact of recent precipitation on modeled infiltration to inform the HND Factors. A total of 27 scenarios were evaluated. 30-minute, 1-hour, and 2-hour events with events of .5-, 1-, and 5-years return intervals preceded by events of .5-, 2-, and 10-year return intervals. Preceding events were 24 hours, 48 hours, or 72 hours before the event.

We explored a potential 4-day total harvest depth limit based on antecedent conditions modeling scenarios. The rule would be a rolling four-day maximum, limiting cumulative storage in any given four-day period. The four-day limit emanates from the 3-day Drying Period parameter; events modeled more than 3 days prior cannot affect modeled infiltration rates. The four-day limit was generated by modeling with a 24-hour, 200-year event on Day 1 followed by three days with 2-hour, 25-year events. This 4-day limit is not recommended in the HND Factors because it is sufficiently accounted for with the 30 day limits.

3 Results

3.1 WQ-COSM Parameters

Results of the sensitivity analysis identify the driving factors of infiltration-runoff partitioning as HSG infiltration parameters, precipitation depth and duration,[4] and antecedent precipitation. Other aspects of infiltration estimates, such as REPS regions of temporal distribution, did not show impacts sufficient to warrant further consideration in developing Factors. Sensitivity of infiltration to WQ-COSM parameters is shown in Figure 3; lower initial and final infiltration rates and lower pervious depression storage result in less infiltration. The maximum and minimum are not evenly distributed around the default parameter values (which return 75% infiltration over the period); refer to Table 1 for the exact values used.

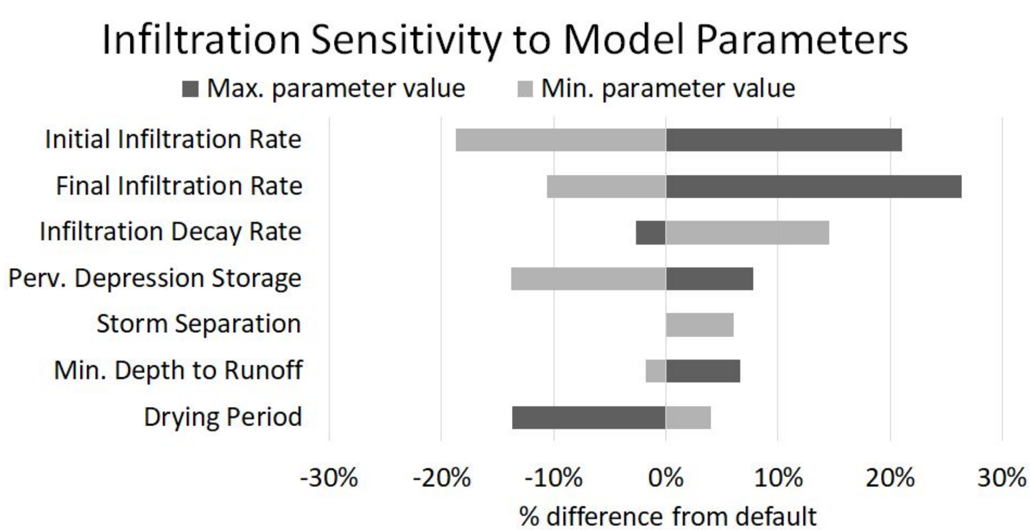

Figure 3.1: Seasonal infiltration response to maximum and minimum WQ-COSM parameter values compared to default or mid-range parameter values. Default or mid-range parameters produce a baseline percent infiltration of 75%.

[4] Sensitivity of infiltration to storm intensity is discussed in the main report due to its significance in final Factors.

3.1.1 Soil Infiltration Parameters

Soil infiltration parameter values were sourced from the WQ-COSM User's Manual recommended values. The seasonal sensitivity analysis found that in order to reduce infiltration estimates, Factors should be modeled with lower initial and final infiltration rates and a higher infiltration decay rate (Figure 3). The manual recommends a range of infiltration rates for different soil types under different conditions. These ranges were linked to each NRCS HSG and we used the minimum infiltration rates for each HSG. The minimum recommended infiltration rates are considerably lower than the median and maximum, particularly for HSGs A and B (Figure 4); higher rates result from dry conditions with dense vegetations, lower rates result from moist conditions with little or no vegetation. Colorado's climate lends itself to dry conditions, but vegetation may vary at pilot project sites. The similarity of minimum infiltration rates for HSG A and B explains the strong similarity in infiltration results for these soil groups.

According to our sensitivity analysis, infiltration decay rate should be higher to minimize infiltration (Figure 3); however, we used the recommended value for each HSG. The infiltration decay rate parameter is less impactful to model outputs when using the minimum infiltration rate for each HSG (Figure 4), and the model manual notes that model outputs are not highly sensitive to this parameter per their own analyses. The model manual recommends 2/hr for HSG A and 3/hr for HSGs B, C, and D.

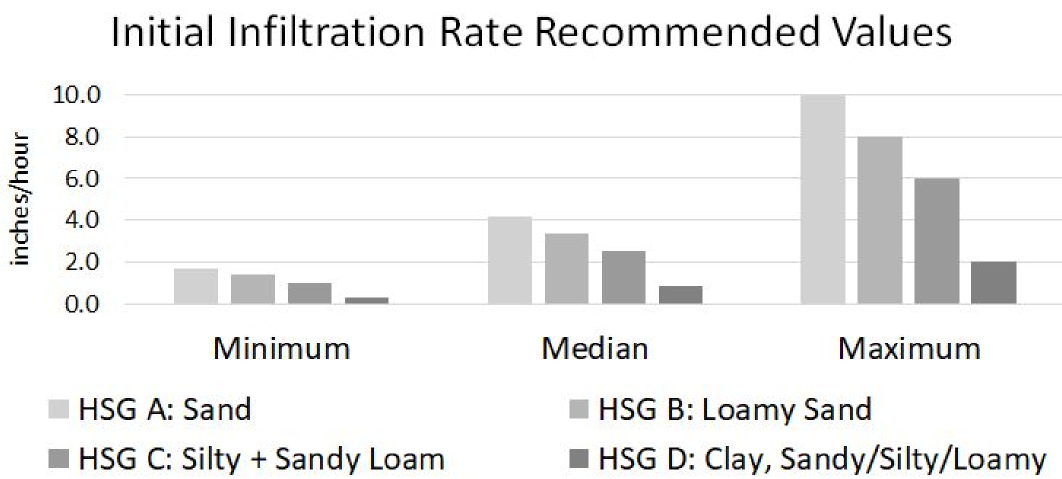

Figure 3.2: Range of recommended initial infiltration rate from WQ-COSM manual

3.1.2 Other Parameters

Sensitivity analysis results informed WQ-COSM parameters beyond HSG for infiltration modeling; these parameters were held constant at the values noted in Table 1. Not all parameter ranges reflect realistic values for infiltration-runoff modeling in Colorado; this was considered when selecting final values, and we did not use the end-member parameter value suggested by sensitivity analysis results for some. These parameters are pervious depression storage, minimum depth to runoff, storm separation, and drying period.

The analysis showed that lower values of pervious depression storage and minimum depth to runoff results in lower infiltration estimates (Figure 3); we used low recommended values instead of the absolute minimum, as noted in Table 1. While the sensitivity analysis suggested that a longer Drying Period value reduces infiltration estimates, we used LRE's Drying Period of 3 days which was based on observed lysimeter data at Sterling Gulch. This agrees with the manual recommended value for Colorado's semi-arid climate. Storm separation was set at the minimum parameter value of 3 hours to maintain consistency with LRE's analysis.[5] Although this minimum storm separation value does result in higher infiltration estimates than the default 6 hours (Figure 3), this parameter is ultimately not relevant to this infiltration modeling as the synthetic precipitation events were separated by 24 hours or more.

Table 3.1: WQ-COSM parameter sensitivity analysis results. Each parameter was varied from the model minimum to maximum except Final Infiltration Rate, where the maximum is limited by default Initial Infiltration Rate.

Parameter	How to Decrease Infiltration	Parameter Driver	Sensitivity Range (min, default, max)	Modeling Value	
Initial Infiltration Rate (in/hr)	↓ lower	Soil	0.3, 2.0, 5.0	Minimum HSG value	Varies by HSG
Final Infiltration Rate (in/hr)	↓ lower	Soil	0.01, 0.1, 2.0	Minimum HSG value	Varies by HSG
Infiltration Decay Rate (1/hr)	↑ higher	Soil	2, 5, 6	Minimum HSG value	Varies by HSG
Pervious Depression Storage (in)	↓ lower	Vegetation	0.1, 0.35, 0.5	Average of lawn & field values	0.35 inches
Storm Separation (hr)	↑ higher	Data processing	3, 6, 24	Minimum value	3 hours
Min. Depth to Runoff (in)	↓ lower	Soil & Vegetation	0.09, 0.25, 0.5	Low value (recommended for urban)	0.11 inches
Drying Period (days)	↑ higher	Climate	3, 5, 14	Min. recommended value for semi-arid	3 days

[5] LRE found a longer storm separation period (6 hours) grouped Sterling Ranch precipitation data into a smaller number of longer and bigger events. A shorter separation period (1 or 2 hours) grouped data into many shorter and smaller events. However, the total modeled infiltration did not change with these different storm separation periods. LRE recommended a 3-hour value.

3.2 Precipitation

3.2.1 Temporal Distribution & Timestep

Model output for precipitation events distributed by the East and West temporal distributions did not show a significant difference in infiltration estimates. The results allowed us to determine that intra-event precipitation distribution need not be included in final allowable harvest rules. Comparison of the 5-minute and 15-minute precipitation time-step showed no impact on infiltration estimates; this allows a more common 15-minute precipitation record to be used without detracting from the quality of results. Uniform versus distributed precipitation data only impacted 1-hour events on HSG D. All events were modeled with the REPS distribution; for 6- and 24-hour events we used the East REPS distribution because there was no significant difference in infiltration estimates between these distributions. Although events shorter than 1 hour are presumably sensitive to uniform distribution, REPS does not provide temporal distributions for such short events. Thus, events shorter than 1 hour were modeled with a uniform precipitation distribution.

3.2.2 Antecedent Precipitation

The impact of antecedent precipitation varies by HSG, the number of dry days in between, and the magnitude of the preceding event, as shown for HSC C in Figure 4. There is an impact on infiltration from antecedent precipitation, but the multi-dimensional precipitation variables (duration and depth of both the event and prior events; time since last event) make it difficult to translate these results into a basic limit to apply to Factors. Furthermore, the antecedent rain events that do impact infiltration are larger infrequent events, suggesting this impact will rarely occur.

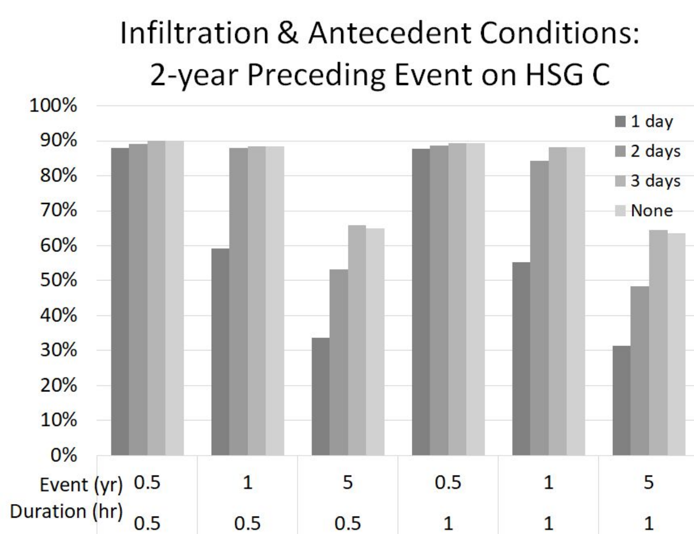

Figure 3.3: The portion of an event that infiltrates decreases when an event occurs shortly after a 2-year event (1 day prior, 2 days prior, etc.).

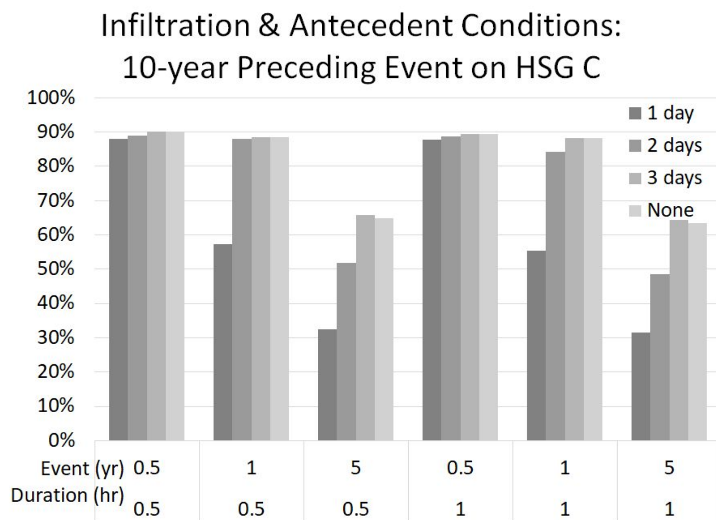

Figure 3.4: The portion of an event that infiltrates decreases when an event occurs shortly after a 10-year event (1 day prior, 2 days prior, etc.).

Consecutive events were modeled to potentially inform multi-day maximum allowable harvest; the events were a 200-year, 24-hour event followed by three days with a 2-hour 25-year event. HSGs A and B maintained 90% infiltration all four days, while HSGs C and D started at 70% and 42%, respectively, and declined to 21% and 11%. Results are shown by soil group in Table 3.2 and compared to the proposed ET/Soil Factor elements. The modeled 4-day maximum infiltration is conservatively limited by the soil moisture rule for HSGs A and B.

Table 3.2: Comparison of options for maximum HND limit and average rainfall. The 4-day modeled infiltration used serial precipitation events totaling 11.5 inches.

Limit	HSG A	HSG B	HSG C	HSG D
4-day modeled infiltration	10.4 inches	10.4 inches	5.3 inches	3.1 inches
Soil Moisture limit	6 inches			
Monthly ET (Mar-Oct)	1.5 - 7.5 inches			
Average Monthly Rainfall (Mar-Oct)	1.0 - 2.5 inches			

While 4-day maximum modeled infiltration for HSGs C and D is less than 6 inches, the proposed ET/Soil Factor is still an appropriate limit because the modeled infiltration is an artifact of using the minimum infiltration rates for each soil group. That is to say, this modeled limit is unrealistically low. Furthermore, LRE observations over an eight-year period at Sterling Ranch showed a record that is unlikely to exceed these limits, with a maximum observed event depth of 2.88 inches.[6] In the 2010-2017 observations, there were 62 instances of multiple storms in a 4-day period during the March-October growing season.[7] Of these 4-day total event depths, 55% were 1 inch or less, 89% were 2 inches or less, and only two total depths were greater than 3 inches. These statistics demonstrate the rarity of back-to-back events large enough to impact HND.

After comparing these modeling and observation results to a soil moisture storage amount of 6 inches[8] and monthly potential evapotranspiration maximums in Colorado, we determined that monthly evapotranspiration and limits on soil moisture storage are appropriate limiting depths maximum allowable harvest. Although antecedent precipitation does decrease infiltration and thus HND (Figures 3.3 and 3.4), the total depth of HND for rainwater harvesting can be effectively limited by monthly evapotranspiration and the 6-inch soil moisture storage rule.

4 Conclusions

The sensitivity analyses conducted for this work informed which aspects of infiltration modeling are important to include in Factors. WQ-COSM parameter values were informed by the sensitivity analysis to minimize infiltration estimates in defense of vested water rights. Aspects of precipitation data, including temporal distribution and timestep, were evaluated to confirm that our chosen methods provide a reasonably conservative approach. After assessing the impacts of data and modeling choices, we examined the impact of different soil and precipitation conditions (i.e. HSG, precipitation depth and duration, and antecedent precipitation).

HSG determines infiltration rate, and is therefore a significant control on infiltration; there should be different Factors by HSG to reflect this. Precipitation depth and duration impact infiltration estimates through their relationship to initial and final infiltration rate; two storms of the same depth but different duration (e.g. 1 and 6 hours) have different infiltration depths. The maximum allowable harvest is not based on antecedent precipitation results discussed in this document, but rather soil moisture storage limits and monthly reference evapotranspiration (see discussion above and in 4.2 memo).

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[6] LRE CWP Grant Task 4B Memo. This depth is less than a 2-year 24-hour event, 10-year 6-hour event, or a 25-year 2-hour event, for example

[7] This count does not include multiple storms in one day.

[8] Using the requirement of 6 inches in Historic Consumptive Use modeling from Criteria and Guidelines for Fallowing-Leasing Pilot Projects, 2016.