Memorandum

To:	Tracy Kosloff, Colorado Division of Water Resources and Kevin Reidy, Colorado Water Conservation Board
From:	Mark Mitisek and Greg Roush, LRE Water, Inc.
Copy to:	Mary Kay Provaznik and Sarah Stone, Dominion Water & Sanitation District
Date:	July 31, 2020
Project:	Colorado Water Plan Grant – Regional Factor Development for Precipitation Harvesting
Subject:	Executive Summary of Tasks, Deliverables, and Key Findings

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On September 18, 2019, the Revised Criteria and Guidelines were adopted by the Colorado Water Conservation Board. This is a major milestone for the legal harvesting of precipitation as a water supply in the State of Colorado. Below is a summary of the key documents provided by the state to support/incentivize precipitation harvesting pilot programs throughout the state:

Regional Factors and Criteria and Guidelines Documents
(http://water.state.co.us/SurfaceWater/RainwaterCollection/Pages/default.aspx)

-September 2019 Revised Criteria and Guidelines
-Beginner's Guide to Rainwater Harvesting Pilot Projects and Regional Factors (pdf)
-Report on HB15-1016 Rainwater Harvesting Pilot Projects Regional Factors (pdf)
-Rainwater Harvesting Pilot Projects Legal Framework Memo
-Accounting template (Excel file)
-Rainwater Harvesting Pilot Projects Regional Factors for Accounting Presentation, July 2019 (pdf)

In response to HB 15-1016 requirements, the Colorado Division of Water Resources (CDWR) and Dominion Water & Sanitation District (Dominion) began to work cooperatively on the development and completion of Regional Factors to support the update to the Revised Criteria and Guidelines. The information developed by the State was supported by the data from the Sterling Ranch Pilot Program and methods/ findings from the CWP Grant. This document is a guide to the information developed, objectives completed, and the deliverables associated with each task supporting the 2019 Revised Criteria and Guidelines. This memorandum also provides important information regarding the methods, data, accounting, and lessons learned during the development of site-specific and regional precipitation harvesting factors.

Task 1 - Document Current Precipitation Harvesting Legal Framework

Objectives Completed:

- ✓ Complete a legal framework in consultation with CDWR guiding pilot program applicants through the substitute water supply plan and augmentation plan processes.

- ✓ Provide clarity and guidance from the State on how precipitation harvesting will be administered.

State policies dictate the type of SWSP and the associated augmentation plan requirements to be filed for the legal harvest of precipitation. The introduction of HB 15-1016 provisions made it difficult to understand how the process has changed and what the benefits are for using Regional Factors. In Task 1, LRE worked with the CDWR staff to understand and document the process, requirements, and benefits of applying for a SWSP and augmentation plan to capture precipitation using Regional Factors.

Deliverable(s) – Appendix 1

- **Rainwater Harvesting Legal Framework, Supporting CWCB Water Plan Grant Project: Regional Factor Development for Precipitation Harvesting, Task 1 (Tracy Kosloff, Deputy State Engineer, April 7, 2020) -** This memorandum and the associated flowchart describe the legal process for obtaining approval through a Substitute Water Supply Plan (SWSP) or augmentation plan to operate a rainwater harvesting pilot project. It also summarizes the unique requirements of applying for and operating an SWSP for harvesting precipitation. This document helps applicants interpret and understand the legal framework and requirements of precipitation harvesting.

Task 2 - Proposed Regionally Applicable Methodology

Objectives Completed:

- ✓ Collaborate with the Colorado Water Conservation Board, Colorado Division of Water Resources, and external peer reviewer to develop, document, and obtain approval for proposed methods for establishing Regional Factors.

Task 2 introduces the concept and fundamentals for the development and use of site-specific and regional factors for the administration of precipitation harvesting. The memorandum includes important principles, assumptions, objectives, definitions, and examples of the proposed step methodologies used to develop site-specific and regional precipitation harvesting factors and associated water budget accounting. LRE Water worked with the CDWR and an external peer reviewer on the proposed methods and models to be used for development of site specific and regionally applicable factors.

Deliverable(s) – Appendix 2

- **Task 2 – Proposed Regional Factor Development Methodologies** - The memorandum outlines the proposed methodology for establishing 1) site-specific and regional precipitation-surface runoff relationships; 2) site-specific and regional groundwater return flow (deep percolation) factors and; 3) delayed groundwater return flows. The Task 2 memorandum includes the following sections:

- o Guiding principles for regional factor development
- o Important assumptions
- o Objectives
- o Proposed methodology for developing site-specific and regional factors
- o Steps for developing regional factors
- o Technical approach for developing regional factors
- o Application of regional runoff curves and groundwater factors

Task 3 - Summary of Site Specific Data

Objectives Completed:

✓ Utilized Sterling Ranch Precipitation Pilot Program data to support the development of Regionally Applicable Factors.

Site specific data collection efforts for the Pilot Program began in 2010 with the installation of the climate station. Since that time a significant amount of natural conditions field data has been collected at Sterling Ranch to support the water budget of inflows (precipitation), outflows (runoff, deep percolation, and evapotranspiration-ET) and change in soil moisture reservoir. Task 3A is the summary of site specific observed data from the Sterling Ranch Pilot Program and Task 3B is a description of the pilot watershed Sterling Gulch physical characteristics including land use, and soils, which are key in in defining site specific parameters required for site specific factor development.

Deliverable(s) – Appendix 3 and Task 3 Data Files

- **Task 3A Site Specific Data Compilation -** This memorandum summarizes the site-specific data collected from the natural conditions monitoring program at Sterling Ranch, the data sets that were compiled to support the development of regional factors; and the QA/QC procedures used to validate each dataset.
- **Task 3B - Site Characterization –** This memorandum provides a summary of the Sterling Gulch drainage basin characteristics including geology, soils, vegetation, and topography of the drainage. This memorandum also summarizes the results of infiltration testing that has been completed at the site.

Task 4 - Site Specific and Regional Factor Development

Objectives Completed:

✓ Develop methodology to calculate Regionally Applicable Factors for future applicants in other regions of the State.

Develop site-specific factors independently using methods from Task 2 and the site specific data summarized as a part of Task 3. Work with State staff and peer reviewer to verify calibrated factors using site specific data and the correct application of readily available methods to calculate precipitation-runoff, soil moisture accounting, and ground water return flows. Assist state in the development of a process to calculate regional factors, and the criteria for determining the extent to which they are applicable.

Deliverable(s) – Appendix 4 and Task 4 Data Files

- **Task 4A Site Specific Water Balance -** The purpose of this memorandum is to outline the methods, assumptions, results, and conclusions of a site-specific water balance model (Hydrus 1-D) of the Sterling Ranch drainage basin Sterling Gulch. The objective is to simulate and calibrate the soil moisture water balance components evaporation, transpiration, deep percolation, and runoff with observed information. In addition to the site specific factors, the model was developed to support and validate factors for precipitation harvesting regionally.
- **Task 4B - Site Specific and Regional Surface Water Return Flows -** This memorandum documents the development and application of site-specific and regional runoff relationships providing a practical and conservative solution to quantifying surface return flows owed to the stream under pre-existing natural conditions. The use of these relationships in a Substitute Water Supply Plan (SWSP) provides the applicant with a simple method for administering precipitation harvesting while protecting downstream vested water rights. This task focuses on the development and support of site-specific and regional runoff relationships for hydrologic soil group C.
- **Task 4C - Site-Specific and Regional Groundwater Return Flow Factors (Deep Percolation) –** This memorandum outlines the methods, assumptions, and results of calculating the site specific deep percolation flows and deep percolation factor using numerical and analytical modeling approaches. The memorandum provides a recommendation for regional groundwater deep percolation factor for hydrologic soil group C and compares the findings to published values.
- **Task 4D - Delayed Groundwater Return Flows -** This memorandum summarizes the results of our stream accretion timing analysis for groundwater returns from precipitation recharge in the Sterling Gulch watershed. This memorandum also summarizes our initial investigation to determine the aquifer conditions for which groundwater return flows from precipitation can be assumed to occur on a relatively constant basis in contrast to a watershed where the variability of return flows requires the use of a site-specific unit response function (URF).

Task 5 - Precipitation Harvesting Accounting Procedures

Objectives Completed:

- ✓ Complete a sample water budget accounting forms for the administration of precipitation harvesting using regional factors, and local climate data for future applicants.

Sample water budget accounting was completed to comply with SWSP and/or augmentation plan requirements. It incorporates the proposed methods and information developed as a part of this investigation, SEO defined accounting procedures and protocols, and suggested instrumentation required to properly administer captured precipitation as a developed water supply. Note the sample accounting workbook developed includes many of the elements required for accounting, but is not the final accounting workbook approved for use by the State .

Deliverable(s) – Task 5 Data Files

- Example_RW_Accounting_SEO_DRAFT_01172019

Key Findings/Lessons Learned

Below is a summary of the key findings and lessons learned during the investigation of the development of site-specific and regional precipitation harvesting factors.

- HYDRUS 1-D proved to be an effective tool for modeling the site specific water balance at Sterling Ranch (Task 4A). Model components included runoff, evaporation, transpiration, and deep percolation. The model was calibrated to observed deep percolation and soil water balance data from an on-site lysimeter and observed runoff in the drainage. Input data was taken from the onsite climate station, field infiltration testing, and field observations of the vegetation. The site specific water balance results show that over an 8-year modeling period, 95% of recorded precipitation evaporates or transpires (natural depletion), 2% accrues to the stream by groundwater return flows, and 3% accrues to the stream by surface runoff.
- Rainfall runoff (surface water return flows) is best expressed as a relationship for each storm depth. Multiple relationships are required to account for variations in storm depths and intensities (durations). The methods evaluated in this investigation focused on developing a rainfall runoff relationship (single curve) from observed storm depths at Sterling Ranch. One of the key findings after Task 4B was completed is that a single curve is overly conservative and not sufficient for covering both average and maximum rainfall runoff depths. Multiple curves are required to correctly characterize the full range of rainfall runoff depths and intensities that can naturally occur. The overly conservative results from a single curve will limit the legal availability of most storm events, resulting in reductions in rainwater yield.
- To understand the range or results and better characterize runoff events, regional rainfall runoff curves need to include storm intensity in the calculation. The use of design storms with varying depths (0.1 to 2.0 inches) and intensities (durations) is key in defining multiple regional rainfall and runoff relationships.
- Hourly precipitation data cannot be used to correctly characterize rainfall runoff or administer precipitation harvesting. High resolution (15-min, 5-min, 1-min) precipitation data is required.
- Water Quality Capture Optimization Statistical Model (WQ-COSM) developed by the Urban Watershed Research Institute (version 3.1) updated for this study, is an important tool for evaluating site specific and regional rainfall runoff relationships. The continuous simulation of rainfall runoff relies on several infiltration methods resulting in a robust and straight forward approach to determining runoff (surface returns) from a variety of rainfall events and soil moisture conditions.
- Prolonged periods of constant rainfall/infiltration are the primary contributor to deep percolation events, not large infrequent rainfall events. Although large infrequent precipitation events occasionally result in a spike in deep percolation they are a small contributor to the annual volume.
- Although deep percolation is highly variable based on land use, geology, slope, soil, and precipitation. This study recommends the use of a single constant percentage of annual

precipitation (for each soil group) to conservatively account for groundwater return flows (deep percolation) on a regional scale. Specifically, this study confirmed the average annual observed deep percolation from the Sterling Ranch lysimeter is about 2% of the total annual precipitation observed (hydrologic soil group C). Which is comparable to published literature from the South Platte Decision Support System Groundwater Flow Model (3%), the Rio Grande Decision Support System Model (3%), and in the Republican River Basin groundwater flow model (2%). Based on these findings it is recommended that 3% of annual precipitation be used to conservatively account for groundwater return flows (deep percolation) for hydrologic soil group C.

- Task 4D provides some insight into whether it is reasonable to assume that groundwater return flows (deep percolation) accrue to the accretion location at a constant rate, or whether a site-specific unit response function (URF) is required to compute return flows. When computing return flows using the Glover equation, a lumped parameter known as a Stream Depletion Factor (SDF) can be used to simplify the Glover equation. A sensitivity analysis was performed by varying aquifer parameters and distance to the stream to determine the SDF values that result in steady (i.e. constant) accretions. The analysis demonstrated that for a rectangular parcel located within an alluvial aquifer of the same width as the parcel, the SDF values must be greater than or equal to 25.81 days to assume a constant groundwater return flow rate. In our analysis a section sized (i.e. 640 acre parcel that is 1 mile on each side) parcel was used, and the threshold for concluding that that return flows from deep percolation of recharge varied from month to month was set such that if the variation from month to month was less than 0.1 cfs, constant accretions could be assumed. If a section-sized parcel at a given location does not meet this SDF requirement, and the computed SDF is less than 25.81 days, then it may be necessary to lag groundwater return flows utilizing a site-specific Glover analysis, or other accretion timing method.
- The use of a State approved accounting template to correctly administer precipitation harvesting to comply SWSP and/or augmentation plan requirements is critical to protect senior vested water rights.

Although not all methods or findings from the CWP Grant were used by the State to develop Regional Factors. A significant amount of knowledge was gained about the process, data sources, methods, and accounting of precipitation as a legal water supply. The final methods presented by the State are reasonable, defendable, and transferable. The Revisions to the Criteria and Guidelines and updates to the legal framework are important milestones. Overall, Dominion is very pleased with the outcome of the CWP Grant and the actions that CDWR has taken to support and promote precipitation harvesting as a viable water supply. Both Dominion and LRE Water appreciate the collaboration with the State and look forward to starting the administration of the State’s first precipitation harvesting project.

Appendix 1
(Task 1)

COLORADO
Division of Water Resources
Department of Natural Resources

MEMORANDUM

To: Mark Mitisek, Leonard Rice Engineers, Inc.
From: Tracy Kosloff, Deputy State Engineer
Date: April 7, 2020
Subject: **Rainwater Harvesting Legal Framework**
Supporting CWCB Water Plan Grant Project: Regional Factor Development for Precipitation Harvesting, Task 1

This memorandum and the associated flowchart (attached) describe the legal process for obtaining approval through a Substitute Water Supply Plan (SWSP) or augmentation plan to operate a rainwater harvesting pilot project. It also summarizes the unique requirements of applying for an SWSP for rainwater harvesting, which are not addressed in the existing SWSP guidance. This process is based on 37-60-115(6), C.R.S. and the Colorado Water Conservation Board's (CWCB) Criteria and Guidelines for the "Rainwater Harvesting" Pilot Project Program, as amended September 8, 2019.

This memorandum covers the water operations legal aspects of pilot projects, which are SWSPs and augmentation plans[1]. It assumes that the pilot projects have been given approval by the CWCB and comply with the substantial water conservation requirements of the program including implementing advanced outdoor water demand management in the development as described further in the Criteria and Guidelines. Also of note is that there is a limit of 10 pilot projects and no more than three in each water division. Lastly, subsection 37-60-115(6), which authorizes pilot projects, is repealed on July 1, 2026.

This memorandum is organized in the following 3 sections:

A) Process without Using Regional Factors
B) Process Using Regional Factors
C) Unique SWSP Application Requirements for Rainwater Harvesting

The description of the processes is supported by the attached flowchart.

Figure 1 below shows a comparison of runoff and return flows in the native condition and with development and rainwater harvesting in place. This figure is for reference throughout the document.

[1] Pilot projects were not contemplated to operate within the Designated Basins as the statute directs their operation through SWSPs approved in accordance with the 1969 Act and then augmentation plans approved by the water court.

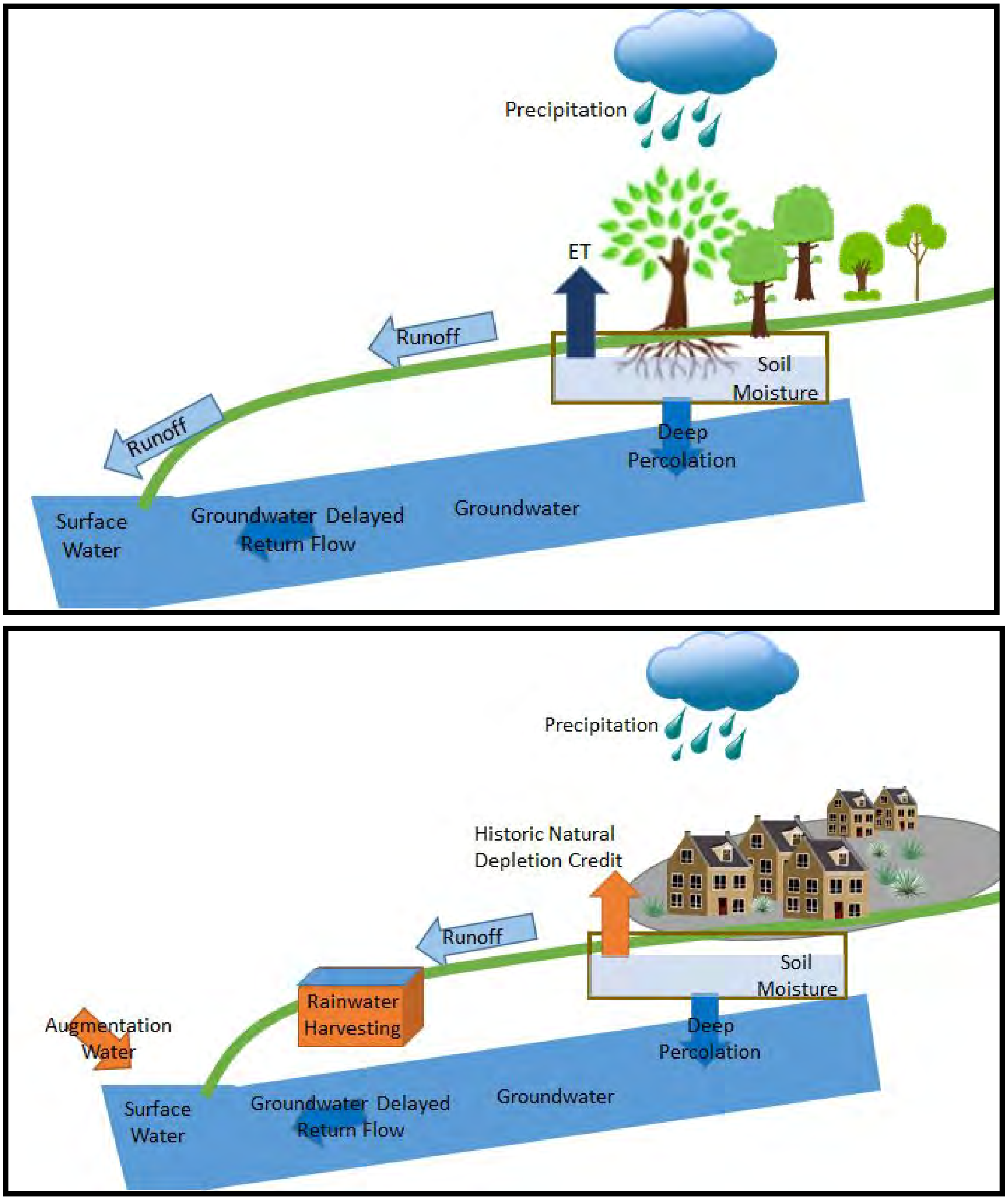

Figure 1. Rainfall-Runoff-Return Flows in Native Condition and with Rainwater Harvesting

A. Rainwater Harvesting Pilot Project Process without Using Regional Factors

1. Project sponsor initiates rainwater harvesting project by obtaining approval from the CWCB board pursuant to the Criteria and Guidelines.
2. Document the plan to capture precipitation out-of-priority and provide augmentation water for the prevention of injury. The plan must consider how much precipitation will be collected from rooftops and impermeable surfaces for non-potable uses,

describe measurement, and provide proposed accounting (see additional discussion of unique SWSP Application Requirements Section C).

3. Collect two years of data to determine historic natural depletion as described in 37-60-115(6)(a)(II).[2] The Criteria and Guidelines (2019)[3] also specifically require "a minimum of two years of implementation of rainwater harvesting applied to non-potable uses with advanced outdoor water demand management," and replacement of 100 percent of the out-of-priority depletions (no credit for historic natural depletion) during those two years. The Criteria and Guidelines specifically require a two-year data collection period including operation of the rainwater harvesting system applied to non-potable uses, which is an out-of-priority diversion. Placing the water to beneficial use can only occur pursuant to an SWSP[4]. Data collection, such as that related to weather data, could occur prior to the two years of operation pursuant to an SWSP.
4. Based on at least two years of data collection, determine historic natural depletion (the portion of historical precipitation that did not return to the natural stream system due to vegetative cover evapotranspiration (ET)) and historical precipitation return flows:

Historical Precipitation	
Historical Precipitation Return Flows	Historic Natural Depletion
"quantify the site-specific amount of precipitation that, under preexisting, natural vegetation conditions, accrues to the natural stream system via surface and groundwater return flows" 37-60-115(6)(a)	"amount of historic natural depletion... caused by the preexisting natural vegetative cover evapotranspiration" 37-60-115(c)(I)

Determine the historic natural depletion of precipitation intercepted by surfaces made or to be made impermeable by the pilot project. Pursuant to 37-60-115(c)(I), this is the amount of depletion that does not need to be replaced when operating pursuant to an SWSP after the first two years of operation and data collection. This is also the amount of precipitation that "would not have accrued to a natural stream under preexisting, natural vegetation conditions" and can be consumed without replacement under a permanent augmentation plan pursuant to 37-60-115(c)(II)(A).

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[2] Create a baseline set of data and sound, transferable methodologies for measuring local weather and precipitation patterns that account for variations in hydrology and precipitation event intensity, frequency, and duration, quantifying preexisting, natural vegetation consumption, measuring precipitation return flow amounts, identifying surface versus groundwater return flow splits, and identifying delayed groundwater return flow timing to receiving streams;

[3] Page 4, paragraph 2

[4] The SWSPs described in this memo are authorized in accordance with Section 37-92-308(4) and 308(5). They are referred to in shorthand as 308(4) SWSP, where there is a corresponding water court application for an augmentation plan, and 308(5) SWSP, where there is not a corresponding water court application.

5. After the required two years of data collection, operate pilot project pursuant to an SWSP[5] or augmentation plan without a need to replace the historic natural depletion. Any water stored in excess of historic natural depletion must be augmented. Sponsor may first apply to the water court for an augmentation plan and a 308(4) SWSP (option **a**) or operate pursuant to a 308(5) SWSP without a court application (option **b**). After operating under a 308(5) SWSP, an applicant may file an augmentation plan application in water court and then operate pursuant to a 308(4) SWSP prior to obtaining a decree (i.e. transition from Option b to Option a).

<table>
<tr><th>Option a - File Application in Water Court</th><th>Option b - No Water Court Application</th></tr>
<tr><td>File augmentation plan application in water court.</td><td rowspan="2">Apply for and operate under 37-92-308(5) SWSPs approved annually for no more than 5 years.[6]</td></tr>
<tr><td>Apply for and operate under 37-92-308(4) SWSPs approved annually.</td></tr>
</table>

6. The pilot project will either operate permanently pursuant to an augmentation plan decree or cease operation as shown below:

Option a - Obtain Court Decree & Operate	Option b - Cease Operation
Operate project pursuant to Court Decree without a need to replace the historic natural depletion.	As described in 115(6)(c)(II)(A), Applicants must apply to and obtain approval from the state engineer to permanently retire the rainwater collection system. The state engineer will require replacement of ongoing delayed depletions.

7. Submit a final report to the CWCB board and the state engineer by January 15, 2025, as required by section 37-60-115(6)(d).

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[5] The standard guidance for applying for an SWSP is Suggestions on Submittals of SWSP Requests and Comments (12/20/2017) and Policy 2003-2: Implementation of Section 37-92-308, C.R.S. (2003) Regarding Substitute Water Supply Plans. Additional information about SWSP requirements for rainwater harvesting is included in Section C of this memo.

[6] 37-92-308(5)(a) states, “the depletions associated with such water use plan or change will be for a limited duration not to exceed five years”. Similar to the pumping of a well, the capture of precipitation that historically would have accrued to the stream slowly through the groundwater creates a lagged depletion. Therefore, the operation of a precipitation harvesting project may create depletions that lag for several years. If the lagged impact of operating the project exceeds five years, it is not possible to operate pursuant to a 308(5) SWSP except pursuant to the limited exception described in 308(5)(b)(II), where a precipitation harvesting pilot project sponsor “may request renewal of a plan that would extend the plan past five years from the initial date of approval if the project sponsor demonstrates to the state engineer that an additional year of operation under the plan is necessary to obtain sufficient data to meet the Colorado water conservation board's criteria for evaluating the pilot project or an application for a permanent augmentation plan is pending before the water court.”

B. Rainwater Harvesting Pilot Project Process Using Regional Factors

Project sponsors in areas where Regionally Applicable Factors (Factors) have been adopted by CWCB can follow a process similar to Section A but may opt to rely on the Factors rather than collecting two years of site-specific data for a site-specific estimate of historic natural depletion. The reliance on Factors allows an applicant to operate and beneficially use the historical natural depletion amount without collecting two years of climate and operation data with 100 percent replacement. For a proposal that will rely on the Factors, once step 2 of Section A (Document Plan) is completed, the sponsor may move to step 5 of Section A (Operate with Natural Depletion Credit) (see also flowchart, attached).

As described in section 37-60-115(6)(b)(VI), the Factors "specify the amount of precipitation consumed through evapotranspiration of preexisting natural vegetative cover". Existing documentation by Denver Urban Drainage and Flood Control District and others has led to a broad understanding of the relationship between rainfall and runoff from different types of surfaces for rainfall of varying intensity and duration. Precipitation is partitioned between runoff that quickly returns to the stream and infiltration. Infiltrated water will either be trapped in soil moisture storage or deep percolation to become a groundwater return flow. Infiltrated water trapped in soil moisture storage is available for plant ET. In this case, the ET amount, which is the majority of infiltrated water, would be the historical natural depletion.

Using the Factors described in the Criteria and Guidelines, a project sponsor would use the template accounting for the surface conditions at their site in order to quantify the historical natural depletion credit that can be beneficially used without replacement after any given storm event within their development area. Section 37-60-115(6)(b)(VI) describes, "If an applicant uses the factors, the state engineer shall give the factors presumptive effect, subject to rebuttal."

Within section 37-60-115(6) and the Criteria and Guidelines, the Factors are described only in the context of an SWSP. Therefore, the Factors do not have a presumptive effect with the water court for augmentation plans. In fact, in regards to decreed augmentation plans for rainwater harvesting, section 37-60-115(6)(c)(II)(A) requires that the amount of historical natural depletion be proven "by a preponderance of the evidence"[7]. Therefore, a system may operate pursuant to an SWSP using the Factors but would likely need to rely on a site-specific data to operate permanently pursuant to an augmentation plan.

C. Unique SWSP Application Requirements for Rainwater Harvesting

The existing guidance available for SWSP submittals is generally applicable to rainwater harvesting projects. The following lists additional requirements for rainwater harvesting SWSP applications:

1. Summarize the overall rainwater harvesting and stream replacement operation.

[7] The statutes and Criteria and Guidelines only describe the Factors in terms of their use and acceptance in the SWSP / pilot project process but stop short of precluding use of the factors in an augmentation plan.

2. Describe each diversion (for storage of rainwater) and if that results in instantaneous or lagged depletion (or both). Descriptions of depletions should list stream impacts in terms of location, timing and amount;
3. Describe if the rainwater harvesting system could potentially store an amount of water in excess of the historical natural depletion, and if such excess storage occurs, will the water be released or augmented, and
4. Describe each replacement water source by timing, location, and amount.

Each item in the application may be supported by several detailed calculations. Also, the Application must be supported by a summary table showing monthly diversions, lagged depletions, monthly replacements (including transit loss if applicable), and net impact to the river. The net impact to the river must result in replacement either equal to or greater than depletions. Maps of all facilities included are also required.

The existing SWSP guidance was written prior to rainwater harvesting legislation and does not consider the unique method of causing depletions through rainwater harvesting. For pilot projects that are not using Factors, for the first two years 100 percent of captured precipitation is considered a depletion. After the two year data collection phase (without Factors), the historic natural depletion need not be replaced. When Factors are used, the two year data collection period with full replacement is not required.

Chart 1 is an example of how precipitation is divided into ET, soil moisture storage, surface and groundwater return flows. ET & soil moisture storage is equal to historic natural depletion. The total to the stream is the sum of runoff, deep percolation, and augmentation. Under a pilot project with rainwater harvesting (case B), if some of the reused precipitation is in excess of that amount attributable to the historical natural depletion, the excess amount is an out-of-priority depletion requiring a delivery of augmentation water to the stream. This example also shows that a project operating under an SWSP for the first two years without using the factors (case C), and needing to augment all of the harvested precipitation, results in more water accruing to the stream than historical conditions.

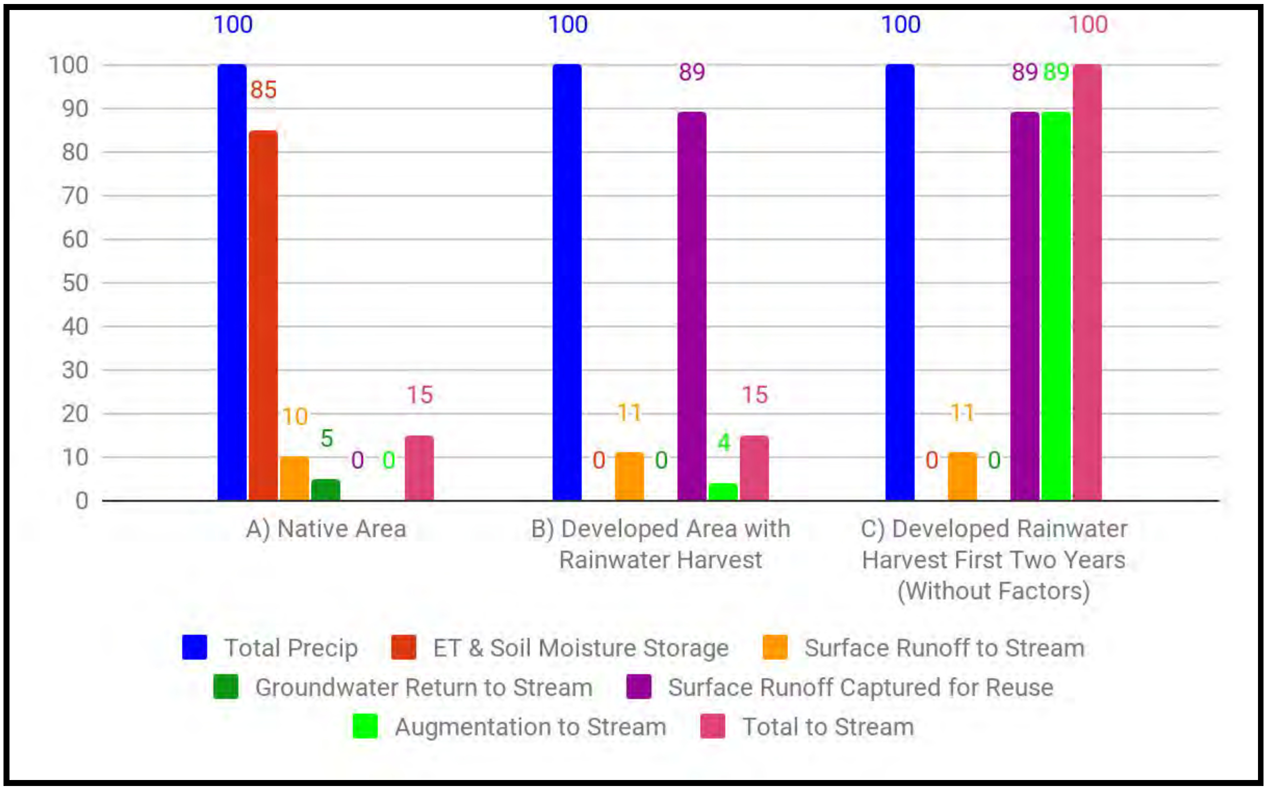


Chart 1. Stream Impacts of Native Condition compared to Rainwater Harvesting

For rainwater harvesting, an SWSP application must show how historic natural depletion (ET & soil moisture storage in the Native Condition in Chart 1) will be estimated, either using Factors or a site-specific analysis. If Factors are not used, the amount of water that must be replaced to the stream system is based on a direct measurement of the amount of rainwater captured by the rainwater harvesting system. The timing of the replacement depends on if that capture results in an instantaneous or lagged depletion (or both).

If Factors are not used, findings of historic natural depletion could potentially be based on the following observation and analysis procedures:

Observation	Analysis
Precipitation	
Observed precipitation data collected from an on-site rain gage (during at least the two year observation period).	Since the full range of possible storm frequencies and durations will not occur during the two year observation period, the observed precipitation data should be supplemented with data from a longer period of nearby recorded precipitation data and/or synthetic design storm data.
Distribution of Precipitation into Runoff & Infiltration	

Measurements of infiltration using a lysimeter, and measurements of runoff, to the extent possible[8], through surface water measurement.	Simulate surface runoff for each storm using Denver Urban Drainage and Flood Control District's Colorado Unit Hydrograph Procedure (CUHP) model or another model such as WQ-COSMs using 15-minute precipitation data. Calibrate simulation to lysimeter and other on-site measurements. Precipitation - Simulated Runoff = Infiltration
Soil Moisture Balance	
Measurement of soil moisture in the lysimeter.	For the water that infiltrates, there is a water budget accounting where soil moisture may be consumed by ET and where any water in excess of the soil moisture capacity is assumed to deep percolate and slowly return to the stream system. This analysis will inform how infiltration on the site is partitioned to historic natural depletion vs. deep percolation to ground water return flow to the stream system.
Ground Water Return Flows	
None	Groundwater modeling or lagging calculations estimate the delay of deep percolation to surface water.

Rainwater harvesting projects must install a high quality precipitation gage that records data at a 15-minute frequency and can provide that data for use in daily accounting. If Factors are not used, it may be necessary to install a lysimeter to measure infiltration and deep percolation in the native condition. A lysimeter allows for the direct calculation of historic natural depletion. Since the data collection phase occurs when the harvesting system is in place, but the historic natural depletion is based on the native condition, a lysimeter must be placed in an area of the development that is preserved in its undisturbed natural condition. This will allow data collection of the soil water balance and historic natural depletion under a range of storm conditions that occur during the two-year data collection phase, while full replacement of captured rainwater is made to the stream.

The SWSP application will need to provide the following:

Information Related to Historic Natural Depletion (may not all be required if Factors are used):

1. Describe and map instrumentation associated with measuring historic natural depletion in relation to the location of the rainwater harvesting system: rain gage (minimum 15-minute frequency), lysimeter, and surface flow measurement, if any.

[8] Measurements of surface runoff on Sterling Ranch have been difficult to calibrate to precipitation and lysimeter observations and modeling.

Describe any additional nearby rain gages that may be used to verify on-site observations.

2. Describe runoff model used to estimate runoff (and therefore infiltration as precipitation - runoff) in the native condition. Describe model inputs such as soil types and slopes and other assumptions. Describe how field observations and any other measurement have been/will be used to calibrate and verify runoff model results.
3. Describe soil water budget model used to parse infiltration into ET, storage and deep percolation in the native condition. Describe how field observations and soil water monitoring have been/will be used to calibrate and verify soil water budget model results.
4. For both the runoff and soil water budget models: If Applicant is seeking credit for historic natural depletion, the application must show reasonable success in using the models to simulate runoff and the soil water budget in the native condition based upon two years of data collection.
5. Estimate the timing when captured precipitation would have accrued to the stream system without the rainwater harvesting system through (a) surface flows, and (b) ground water return flows. Describe how the amounts vary with rainfall intensity or other factors. Describe glover model parameters and their basis. It may be necessary to divide the precipitation collection area into multiple regions with different lagging results based on differing geology or distance to the stream.
6. Provide all model files for review.
7. For the two-year data collection phase when historical natural depletions must be replaced, the Applicant may assume that historical natural depletions accrued to the stream system in the same ratio as surface and ground water return flows, for the purpose of determining the timing for replacing the volume attributable to historical natural depletions. If the Applicant proposes a different method for timing replacements from historical natural depletions, the application should justify that alternative approach.

Other Information Related to Rainwater Harvesting System:

8. Describe and map the systems that will capture precipitation for non-potable reuse as well as their catchment areas.
9. Describe and map the surface area of natural vegetative cover made impermeable and associated with the pilot project.
10. Describe and map measuring devices for rainwater harvesting system including inflow, outflow and stage recording devices.
11. Describe if there is a maximum amount that will be captured in any storm event, month, or over the 12-month period total, given the constraints of the rainwater harvesting system or potentially the limits of replacement water available.
12. Describe how and if any captured precipitation will be released to the stream system and map the release system (and describe measurement if any amount released by the system is to be credited toward depletions).
13. Complete SWSP monthly summary table (projection) with rows for each:
    a. Diversions: potential maximum rainwater captured,
    b. Depletions: surface return flow obligations, ground water return flow obligations, historical natural depletion, total depletion
    c. Replacements: list each replacement source and timing.

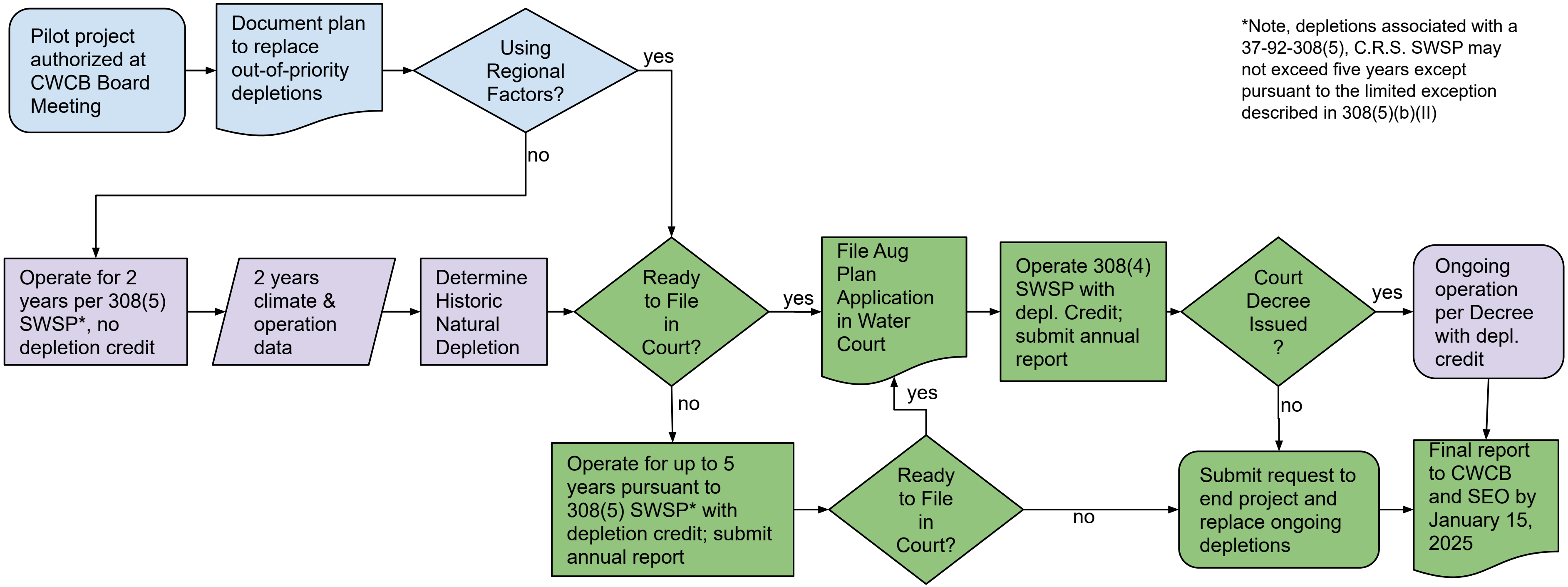
14. For replacement obligations extending beyond the one-year SWSP approval period, the application must show how ongoing depletions will be replaced.
15. Provide a spreadsheet file with proposed daily accounting to be submitted monthly. The proposed accounting should be consistent with the requirements in the Pilot Project Criteria and Guidelines.

With Regional Factors

SWSP application requirements are similar for projects employing Factors, except that rather than providing details of how historical natural depletion is estimated, historical natural depletion is based on application of the appropriate Factor. If Factors are incorporated into the Pilot Project Criteria and Guidelines, this section may be expanded to explain additional differences.

Storm Water Detention Statutory Exemptions

Since rainwater harvesting facilities are constructed for the purpose of putting the captured water to beneficial use, rainwater harvesting facilities do not qualify for the exemptions described for “storm water detention and infiltration facilities” in Section 37-92-602(8). The definition of storm water detention and infiltration facilities in 602(8)(b)(I) requires continuous release of most of the water within days of a storm event and the requirements in 602(8)(e) preclude the use of detained or released water.



*Note, depletions associated with a 37-92-308(5), C.R.S. SWSP may not exceed five years except pursuant to the limited exception described in 308(5)(b)(II)

Rainwater Harvesting Pilot Project Process
6-14-2019

Appendix 2
(Task 2)

DRAFT Memorandum

To:	Tracy Kosloff, Colorado Division of Water Resources
From:	Mark Mitisek, Leonard Rice Engineers, Inc.
Copy:	Sarah Stone, Dominion Water and Sanitation District
Reviewed by:	Greg Roush, Leonard Rice Engineers, Inc.
Date:	November 30, 2018 (Updated March 5, 2020)
Project:	Colorado Water Plan Grant – Regional Factor Development for Precipitation Harvesting
Subject:	Task 2 – Proposed Regional Factor Development Methodologies

Task Summary

The original proposed draft methodology associated with House Bill 15-1016 for the development of regional factors was presented by Leonard Rice Engineers (LRE) on behalf of the Dominion Water and Sanitation District, to the State Engineer's Office (SEO) and Urban Drainage and Flood Control District (UDFCD) in December 2015, and received positive feedback. The information and methods described in that memo (Leonard Rice Engineers, 2015) provide a strong framework to build on. Since that time we have gained additional knowledge from the State's Division of Water Resources staff about their expectations, the practicability of the proposed methods, and the process and data requirements needed to support the development of both site-specific and regionally applicable factors for precipitation harvesting. This memorandum summarizes the refined proposed methodology for the development of Regional Applicable Factors for use in Substitute Water Supply Plans (SWSP's) to capture rainwater out of priority with an augmentation requirement that is less than 100%. This memorandum includes the following sections:

I. Guiding principles for regional factor development
II. Important assumptions
III. Objectives
IV. Proposed methodology for developing regional factors
V. Steps for developing regional factors
VI. Technical approach for developing regional factors
VII. Application of regional runoff curves and groundwater factors

I. Guiding Principles for Regional Factor Development

The development of regional factors is a balance between technical detail required and practical application to reasonably protect the stream from increased depletions. The following "principles" were developed in cooperation with the Colorado Division of Water Resources staff to make sure the methods meet the objectives of the State. Methods are to be:

1. Proven – The method should utilize existing proven tools/models currently being relied upon in the water resources community.
2. Validated - Results of the method must be validated using observed data.

3. Conservative – The selected method should provide results that are conservative to the stream in order to ensure the protection of vested water rights.
4. Transferrable – The method should allow transferability to other parts of the State.
5. Administrable – The methods or results can be simplified to accommodate easier administration.

The sections below outline the proposed technical approach based on these principles describing how the regional factors and a summary of how regional factors would be applied.

II. Assumptions

Initial investigations of available methodologies required an understanding of the key drivers and important assumptions, which are summarized below:

Infiltration: Infiltration rates of the soil are the primary driver that determines the amount of precipitation available to runoff and the amount of precipitation that enters the soil available for natural ET. Therefore, infiltration rates are the primary focus of this analysis and the methodologies described herein.

Surface Water Runoff: Surface water runoff is defined as the maximum amount of potential runoff from a storm event at the soil before conveyance losses or channel routing.

Storm Events: The amount of rainfall converted to either surface water runoff or infiltration is sensitive to the frequency, duration, and intensity of storm events. Previous efforts only looked at the intensity of individual storm events to develop rainfall-runoff relationships. The methods described herein evaluate storms of varying magnitude, frequency, duration, and intensities that occur over a number of years to adequately investigate this phenomenon. For the purposes of this study, a storm event is defined as the continuous observation of precipitation followed by no more than three consecutive hours of no observed precipitation.

High-Resolution Precipitation Data: During the evaluation of infiltration methods it became apparent that higher resolution precipitation data improves the accuracy of the calculated rainfall-runoff relationship. A minimum of 15-minute precipitation data was found to adequately represent actual rainfall patterns to then replicate rainfall-runoff relationships for storm events. Utilizing hourly rainfall can underestimate runoff significantly.

Wintertime Historical Natural Depletions: Natural depletions occur year-round from evaporation and transpiration. This study only investigates naturally historical depletions occurring from March through October.

III. Objectives

The objectives of the methodology are: 1) quantify the amount of water (precipitation) that has historically returned to the natural stream system as runoff and delayed groundwater returns under natural conditions for observed precipitation events; 2) quantify the amount of natural depletion of precipitation consumed through ET of existing natural vegetative cover for observed precipitation events; and 3) develop validated relationships between rainfall, runoff, and natural depletion that can be used regionally based on site-specific observed datasets.

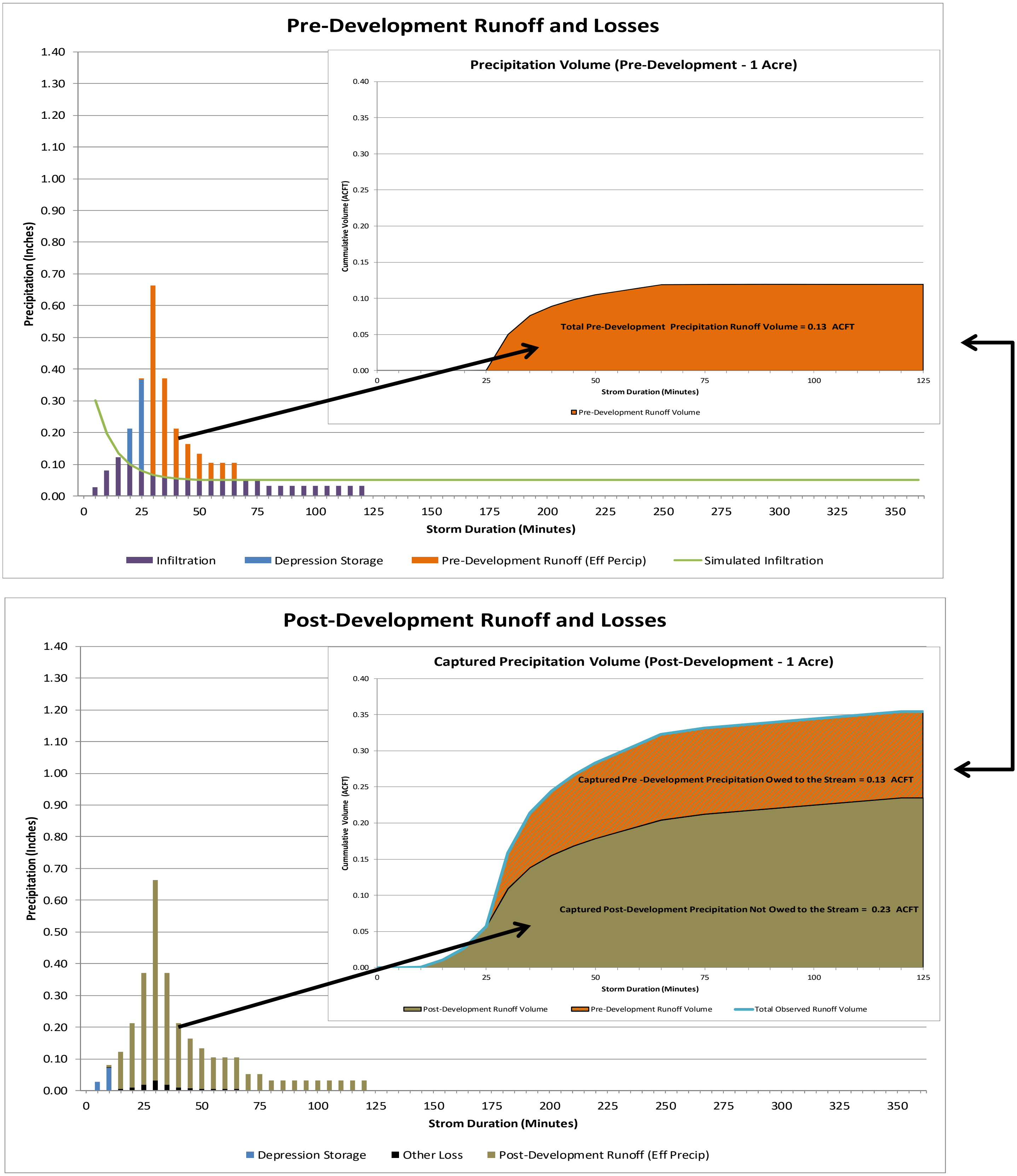
Administratively, based on the simplified equation below, the return flows from a rainfall event are the portion relied upon by Colorado Water Users. For a precipitation harvesting pilot project, the historical natural precipitation return flows within a capture facility's watershed represents the amount of water owed to the natural stream system to protect downstream water rights. The calculated natural runoff owed to the stream would need to be released from the capture facility or replaced from another water source in time, location and amount.

Rainfall Volume = Return Flow Volume + Natural Depletion

Under developed conditions, a rainwater capture facility will collect runoff from natural and developed sites. The validated relationships and factors are used to calculate the historical natural precipitation return flow (amount owed to the stream) for each precipitation event. Any amount captured for a storm event in excess of the return flow volume is the natural depletion, which can be captured for non-potable use at the pilot project without any need to be released or replaced with another source of water. The natural depletion represents the amount of precipitation that was historically consumed through ET processes on natural condition areas that when converted to developed impervious areas results in increased runoff.

The above concept of surface water owed to the stream for pre-development conditions (0% impervious) and the amount available for capture from developed condition (100% impervious) is illustrated in **Figure 1** for a 1-acre site.

Figure 1 – Pre and Post Development Runoff Example



LeonardRice
ENGINEERS, INC.

IV. Proposed Methodology for Developing Regional Factors

"REGIONALLY APPLICABLE FACTORS THAT SPONSORS CAN USE FOR SUBSTITUTE WATER SUPPLY PLANS THAT SPECIFY THE AMOUNT OF PRECIPITATION CONSUMED THROUGH EVAPOTRANSPIRATION OF PREEXISTING NATURAL VEGETATIVE COVER (37-60-115(b) (VI), C.R.S.)"

Based upon the HB-15-1016, Regional Applicable Factors (Regional Factors) are to be established upon the amount of precipitation consumed through evapotranspiration of preexisting natural vegetative cover also defined herein as the historical Natural Depletion. Historical Natural Depletion is calculated using the following governing equation:

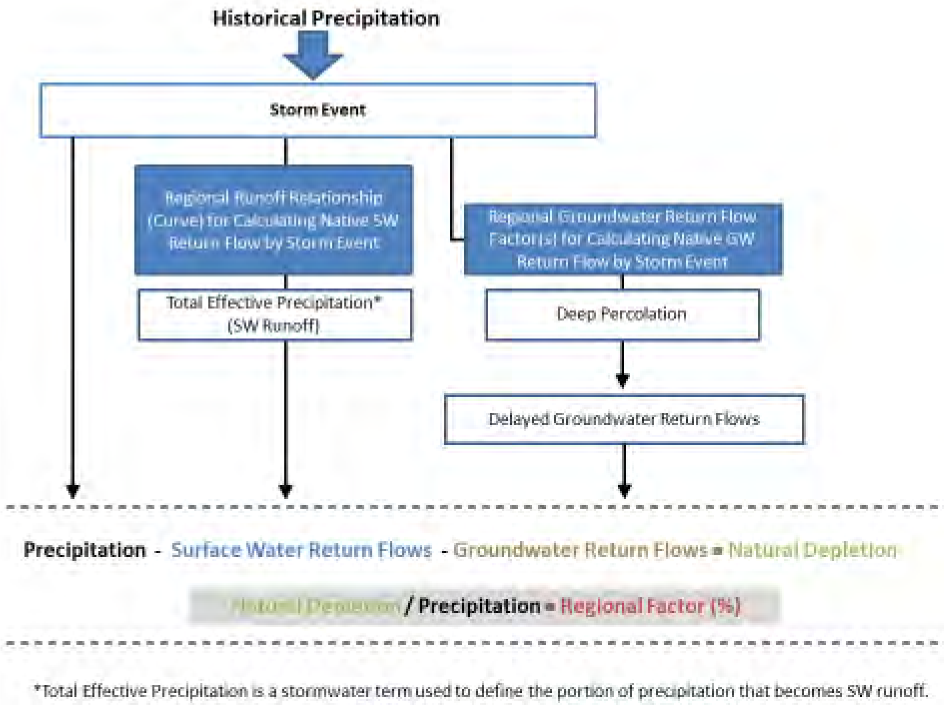
Natural Depletion = Precipitation – Precipitation Return Flows

The total precipitation less the amount that accrues to the stream system (precipitation return flows) under the pre-development conditions is the natural depletion. Regional factors are then calculated as a percent of precipitation:

Regional Factor (%) = Natural Depletion/ Precipitation

The proposed methods for quantifying precipitation return flows and natural depletions are illustrated in **Figure 2.** The proposed methods calculate surface water and groundwater returns separately. Surface water returns are calculated with regional runoff relationships (curves) for individual precipitation events and groundwater returns (deep percolation) uses a constant factor (percentage) applied to individual storm events. Natural depletions are then calculated as the amount of remaining precipitation from and individual storm event that did not return to the natural stream system.

Figure 2 – Proposed Methods



Regional Factors are simply the percent of an individual precipitation event that does not return to the natural stream system. Regional Factors, natural depletions, and precipitation return flows are a function of the hydrologic properties of the native soil types, precipitation event magnitude as well as other hydrologic conditions. It is proposed that Hydrologic Soil Groups (HSG) be used as the basis for assigning unique regional runoff relationships, groundwater return flow (deep percolation) factors, and calculating natural depletions. HSG is a designation given to a group of soils having similar runoff potential under similar storm and cover conditions. The National Resource Conservation Service (NRCS) designates HSG based upon soil properties including depth to a seasonal high water table, saturated hydraulic conductivity, and depth to a layer with a slow water transmission rate (i.e. impermeable layer). Hydrologic Soil Groups are included in NRCS soil surveys for each County in the State and available online for any user-specified project area.

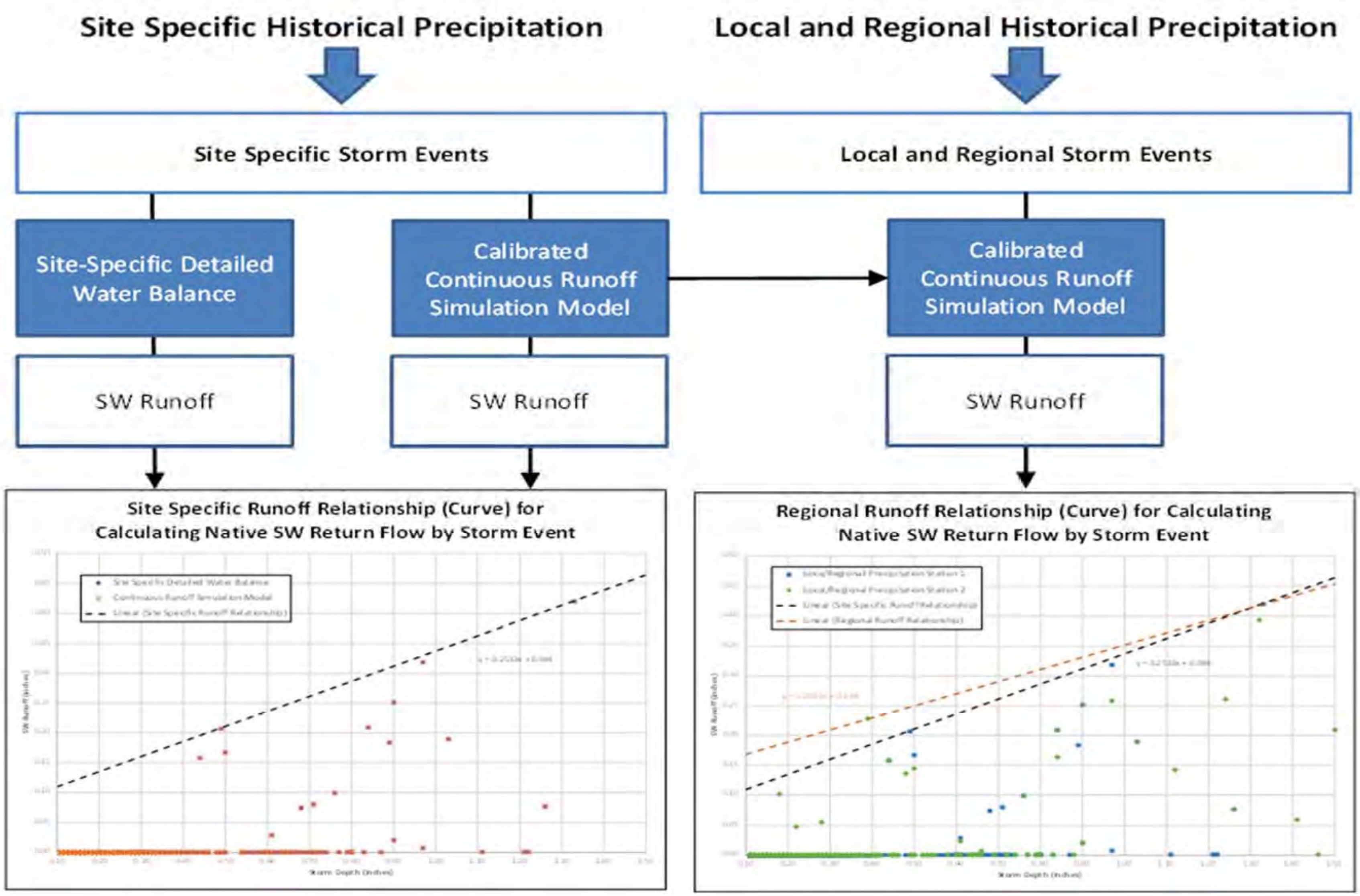
Regional Factors as defined in this approach are only applicable across regions with similar meteorological, vegetative, and hydrological conditions. The general approach and methods used to develop runoff relationships and groundwater factors are described below.

Site-Specific and Regional Surface Runoff Relationships

A runoff relationship is a line or curve showing the maximum runoff for a given storm event (in inches). **Figure 3** shows examples of linear runoff relationships of site-specific and regional runoff by precipitation events. The site-specific runoff relationship is developed based on the maximum runoff observed or simulated for each observed storm event. A line or curve is added based on the best-fit to the upper bounds of the data. The result is a conservative prediction of runoff (surface water return flows) that is equal or exceeded by simulated or observed natural runoff. As shown in **Figure 3**, the observed and simulated runoff events plot below the established site-specific runoff relationship line. To develop regional runoff relationships, additional local and regional precipitation data are added to the site-specific data. The additional precipitation-runoff data is the result of simulating runoff in a model using local and regional precipitation datasets as input. If simulated runoff from local and regional precipitation datasets exceeds the site-specific runoff relationship line, the line may be adjusted upward to include the additional data. As shown in **Figure 3** example, the runoff relationship line encompasses both the simulated and observed runoff events, but the regional line was modified from the site-specific curve to encompass new observed events. Note that during this process there may be storm event outliers simulated or observed, which may be evaluated individually based on frequency to determine if events should be covered under the runoff relationship being established.

Because runoff is sensitive to the hydrologic properties of the native soils, it is proposed that regional runoff relationships (curves) be developed for each hydrologic soil group based on these methods. If multiple native soil groups at a site are identified multiple curves may be applicable.

Figure 3 – Site-Specific and Regional Runoff Relationships for a Particular Soil Group

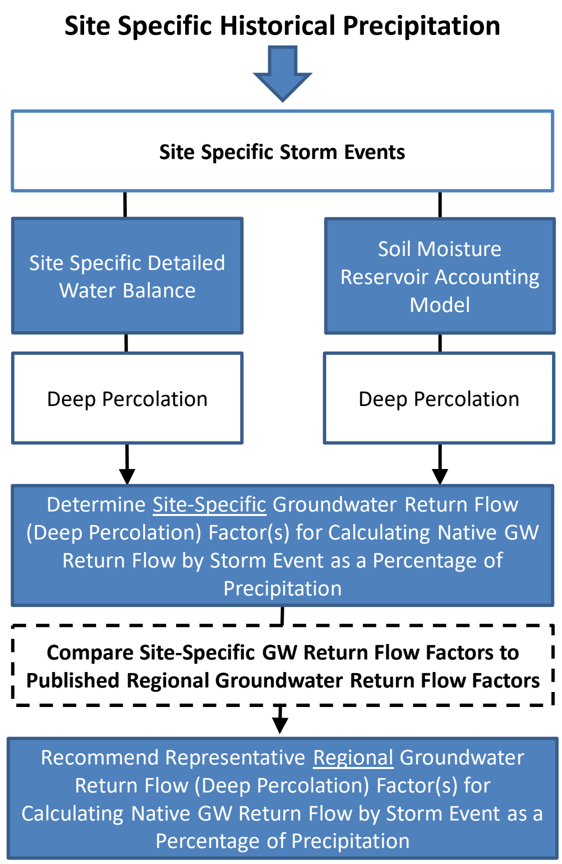


Site-Specific and Regional Groundwater Return Flow (Deep Percolation) Factors

Groundwater return flow (deep percolation) factors are the percentage of the total annual precipitation that accrues to the stream system (past the root zone) through porous underground material. Groundwater returns (deep percolation) are sensitive to storm timing, magnitude, duration, antecedent soil moisture, potential evapotranspiration timing and magnitude, and vegetation types. An investigation of variable groundwater return flow factors requires the application of relatively complex numerical modeling which is not transferable on a regional scale. Therefore, we recommend applying a constant (single) groundwater return flow (deep percolation) factor for each Hydrologic Soil Group (HSG) to each storm event. This proposed methodology for determining groundwater return flows (deep percolation) was selected because it is simple, transferable, conservative, and administrable.

It is proposed that groundwater returns (deep percolation) factors be established for each Hydrologic Soil Group (HSG) based on simulated and observed site-specific groundwater return flows (deep percolation) and published regional studies and references specific/applicable to Colorado. **Figure 4** illustrates the proposed methods for developing site-specific and regional groundwater return flow factors.

Figure 4 – Site-Specific and Regional Groundwater Return Flow (Deep Percolation) Factors



V. Steps for Developing Regional Factors

Below is a high-level summary of the five steps required for the development and application of regional factors. It is proposed that the following steps be completed for each Hydrologic Soil Group to provide a complete and representative set of regional factors for use with SWSP's. For more detailed information on individual steps or proposed technical methods please refer to the technical approach for developing regional factors section below.

Step 1 – Site-Specific Data Compilation and Site Characterization:

- *1A - Data Compilation:* Compile and validate collected field data sets from pilot project applicable to the development of regional factors (climate, precipitation, stream gage data, data from the lysimeter, etc.) and document QA/QC procedures;
- *1B - Site Characterization:* Complete site characterization of the pilot project study area summarizing soils, observed infiltration, and native watershed attributes (area, topography, geology, and vegetation).

Step 2 – Site-Specific Detailed Water Balance:

- *2A - Site-Specific Detailed Water Balance:* Develop a site-specific detailed water balance using observed climate, precipitation, lysimeter datasets and site characteristics from step 1. Quantify the site-specific observed amount of precipitation (by storm event) that, under preexisting, natural vegetation conditions, accrues to the stream system via surface and groundwater return flows (deep percolation).

Step 3 – Site-Specific and Regional Surface Runoff Relationships (see Figure 3):

- *3A -Continuous Runoff Simulation Model*: Develop and calibrate a site-specific continuous surface runoff model to simulate the site-specific detailed water budget described in Step 2A above, validating the inputs and infiltration parameters used in the model;
- *3B – Quantify Site-Specific Surface Water Return Flows and Runoff Relationships*: Plot observed runoff from step 1A and simulated runoff from steps 3A and 2A above. Develop a site-specific runoff relationship (line or curve) based on the maximum simulated or observed runoff (i.e. the upper bounds of the data) that conservatively calculates the site-specific runoff (natural surface water return flow requirement) for each precipitation event;
- *3C - Quantify Regional Surface Water Return Flows and Runoff Relationships*: Utilize readily available local and regional precipitation datasets and the calibrated continuous runoff model described from 3A and compare to the site-specific runoff relationship (line or curve) established in 3B to simulated local/regional runoff. If simulated runoff from local and regional precipitation datasets exceeds the site-specific runoff relationship (line or curve) the line may be adjusted to include additional storm event(s). Note it may be appropriate to develop design storms for frequently observed events to provide a more complete set of regional factors that are more applicable regionally or statewide. The final result is a set of regional runoff relationships for the applicable soil types that conservatively predict runoff (surface water return flows) based on storm depth.

Step 4 – Site-Specific and Regional Groundwater Return Flow (Deep Percolation) Factors

- *4A - Daily Soil Moisture Reservoir Accounting Model:* Develop a daily soil moisture reservoir (SMR) accounting model is a traditional method used for determining the amount of precipitation that enters the soil (infiltrates) and deep percolates into the groundwater system. The SMR utilizes precipitation, site characteristics step 1B, simulated ET from step 2A, and simulated runoff from step 3A. Quantify the site-specific amount of precipitation (by storm event) that, under preexisting, natural vegetation conditions, deep percolates and eventually accrues to the stream system via groundwater return flows.
- *4B - Quantify Site-Specific Groundwater Water Return Flow (Deep Percolation) and Establish Factors:* Compile and quantify annual groundwater return flows (deep percolation) from steps 1A, 2A, and 4A above and calculate site-specific groundwater return flow (deep percolation) factors as a percentage of annual precipitation. Establish a site-specific groundwater return flow (deep percolation) factor that conservatively calculates the natural groundwater return flows (deep percolation).
- *4C – Recommend Regional Groundwater Return Flow (Deep Percolation) Factors:* Compare the site-specific groundwater return flow factor (deep percolation) established in step 4B to published regional studies/references and adjust conclusions and recommendations appropriately to conservatively calculating the site-specific natural return flow requirement regionally.
- *4D - Delayed Groundwater Return Flows:* Delayed groundwater return flows will be evaluated using two separate methods. The first method will establish site-specific unit response function (URF) based on aquifer properties to determine the timing and amount of delayed groundwater return flows for the observed precipitation record. The second method assumes delayed groundwater return flows occur on a continuous basis with the aquifer at steady-state and is more applicable on a regional scale. Results from each method will be compared and a method will be selected based on practicability and defensibility.

Step 5 – Calculate Natural Depletions and Calculating Regional Factors

- *5A – Calculate Regional Natural Depletions:* Utilizing the regional runoff relationship established in step 3C and the regional groundwater return flow (deep percolation) factors established in step 4C, calculate the total precipitation return flow and natural depletion for each precipitation depth (storm depth) increment;
- *5B- Calculate Regional Factors:* Calculate regional factors for each precipitation depth (storm depth) by dividing the natural depletion by the precipitation depth (storm depth).

VI. Technical Approach for Developing Regional Factors

This section describes in more detail the proposed technical approach and methods including data sources, models, and details required for developing precipitation return flows, natural depletions, and regional factors.

Site-Specific Data Compilation and Site Characterization

The initial steps in the proposed methodology are to 1) compile, organize, review applicable natural condition time-series datasets, and; 2) characterize the natural preexisting conditions of the study site used in the pilot program.

Data compilation is simply gathering all applicable climate, precipitation, streamflow, and lysimeter datasets used in the development and calibration of models supporting the quantification of precipitation return flows and natural depletions. Prior to using the data directly, the datasets need to be reviewed, documented, and formatted for use. This may include aggregating/disaggregating datasets to a common time-step compatible with model formats.

The site characterization is a description of the preexisting natural conditions pilot study site. The site characterization is an important step because it provides the basis for many of the physical parameters used in the development and calibration of models supporting the quantification of precipitation return flows and natural depletions. The site characterization should include a description of:

- *Soils*: A detailed soil survey describing the primary soil types, hydrologic soil group(s), and available water content.
- *Field observations*: Any field observations supporting hydrologic parameters such as infiltration rates or hydraulic conductivity.
- *Vegetation*: A description of pre-existing vegetative cover, density, and growing season.
- *Watershed Attributes*: A description of the native watershed attributes including area, topography, and slope. As well as major geologic and hydrographic features of the watershed.
- *Meteorological*: A description of the precipitation patterns, frequency, and magnitude; potential evapotranspiration; and other applicable site conditions.

Site-Specific Water Balance Model

A site-specific water balance model simulates each component of the water budget for the available period of record using observed climate, precipitation, vegetation, soil, and lysimeter data sets as well as the physical site characteristics. The purpose of the detailed water balance is to; (1) quantify the site-specific amount of precipitation (by storm event) that, under pre-existing natural vegetation conditions, accrues to the stream system via surface and groundwater return flows (deep percolation), (2) validate infiltration parameters and rates, and (3) provide an estimate of ET which will be utilized in subsequent tasks. Results from the model will be used to provide the original basis for determining surface water return flow requirements by storm event using a site-specific runoff relationship (curve) and establishes the amount of precipitation that returns to the stream system via groundwater on an annual basis. HYDRUS 1-D is the model selected as the basis for the detailed water balance. Hydrus 1-D is a one-dimensional finite element model for simulating ground/atmospheric hydrologic interaction and the movement of water through porous media (soil) in saturated or unsaturated conditions. Hydrus 1-D is a widely accepted and proven method for characterizing hydrologic processes and unsaturated flow. The model period will be the available period of record.

Model Calibration

The model will be calibrated to observed soil moisture, total observed changes in water volume in the lysimeter, and measured seepage (deep percolation) from the bottom of the lysimeter. Simulated average saturated hydraulic conductivity and actual ET will be key drivers in the model calibration. Model sensitivity to other model parameters including observed runoff may also be investigated to improve calibration.

Site-Specific and Regional Surface Runoff Relationships

The Colorado Urban Hydrograph Procedure (CUHP) developed by Urban Drainage Flood Control District (UDFCD) is a widely accepted and proven method for evaluating stormwater runoff within the Denver Metro Area. For this reason, CUHP was originally selected and proposed as the method to quantify surface water return flows.

Ben Urbonas from the Urban Watersheds Research Institute (UWRI) was selected to be the peer reviewer for the development and feasibility of the technical approach used to quantify native surface water return flows and define runoff relationships. With 30+ years in stormwater master planning experience and the author or co-author on many of the stormwater tools available through the Urban Drainage Flood Control District, Ben has been a resource for this project and was important in the evaluation of available tools and methods and for quantifying precipitation (runoff). Upon Mr. Urbonas review of the original methodology and the objectives of the project and the use of CUHP he made the following observations:

1. CUHP is not a continuous model, which means the model does not account for changes in antecedent moisture conditions that may impact subsequent storm event return flows due to saturation or drying of soils.
2. CUHP uses only the Horton infiltration method to quantify precipitation runoff.
3. The characterization of stormwater runoff distribution (i.e. unit graph development) is not appropriate for the administration of precipitation harvesting on a daily basis.
4. CUHP does not provide a method for systematically defining storm events from the observed long-term precipitation record.

Although CUHP provides the necessary functionality required to evaluate rainfall-runoff processes of individual storm events for stormwater drainage and flood management purposes, it is more appropriate to utilize a continuous runoff simulation model. UWRI creates and maintains a suite of stormwater tools used throughout the stormwater community. For the purposes of this study, Mr. Urbonas recommended that Water Quality Capture Optimization and Statistical Model (WQ-COSM) be used for this project.

Water Quality Capture Optimization and Statistical Model (WQ-COSM)

Volume 3 of the Urban Storm Drainage Criteria Manual developed by the Urban Drainage Flood Control District provides criteria for stormwater runoff best management practices (BMPs) that help to reduce runoff volumes for frequently the occurring storm events and provide treatment of the water quality capture volume (WQCV). The Water Quality Capture Volume (WQCV) is the volume of runoff from frequent storm events generally defined as the 80th percentile runoff event that may be expected during an extended number period or years. However, this volume varies depending on local rainfall data and hydrologic soil conditions. The simulation and quantification of surface runoff volume from frequent storm events on a continuous basis provide a strong basis for defining site-specific and regional runoff relationships.

Water Quality Capture Optimization Statistical Model (WQ-COSM) is the proposed method for quantifying site-specific and regional surface water return flows and runoff relationships. The WQ-COSM model is traditionally used to size/optimize storage volumes (WQCV) for rain gardens or other stormwater best management practices (BMP's) that utilize temporary storage vessels based on observed precipitation records. It is an Excel spreadsheet-based computer program that uses observed precipitation data and information about the catchments hydrologic parameters to simulate runoff on a continuous basis. The WQ-COSM model allows for the use of the Rational, Horton, or Green-Ampt infiltration methods to simulate runoff for each storm event in the observed precipitation record under a variety of hydrologic soil conditions. The model includes all of the primary functions required for quantifying surface water return flows for each storm event on a continuous basis and provides a common systematic platform for developing site-specific and regional runoff relationships. The WQ-COSM model was selected for the following reasons:

- The model calculates runoff volumes for all storm duration/frequencies and intensities observed in the precipitation record, not just the design storms.
- As a continuous model, it accounts for antecedent moisture conditions and the effects of subsequent or frequently occurring storm events.
- Although Horton is the preferred method, the model offers (as mentioned earlier) three options for simulating runoff volumes on a continuous basis.
- Version 3.1 of the WQ-COSM model allows the user to define up to ten different percentages of impervious area from 0.01% (Natural Conditions) to 100%, providing the calculated runoff volumes from each.
- Version 3.1 of the WQ-COSM model supports the use of high-resolution precipitation datasets at multiple time-steps (e.g. 60-min, 15-min, 5-min, 1-min) that may be used for this analysis.
- The model uses raw unprocessed precipitation data in a standard NCDC format allowing local and regional precipitation datasets to be used directly.
- The model is easy to use requiring only precipitation data, infiltration parameters, storm separation (hours), and drying time (days) between storms to run.
- Model output includes a summary of all storm event precipitation and runoff as well as storm durations. This standard output provides all necessary information for developing both site-specific and regional runoff relationships.

Model Calibration

WQ-COSM will be used to simulate site-specific runoff for the available period of record using the Horton infiltration method. The site-specific model will be calibrated to match simulated surface water return flows (runoff) from the detailed water budget (Hydrus 1-D). Average saturated hydraulic conductivity from the Hydrus 1-D model will be used as a starting point for calibrating the initial infiltration used in the Horton Infiltration Model. Model sensitivity to other model parameters will also be investigated to improve calibration. Surface water return flows by storm event from the model will be plotted as the basis for determining the site-specific runoff relationship (curve).

Model Validation/Regionalization

Readily available local and regional precipitation datasets along the Front Range will be used to confirm the validity of the site-specific runoff relationship and determine if the site-specific runoff relationship is transferable on a regional scale. Precipitation data from up to ten stations will be used to simulate runoff utilizing the same input site-specific hydrologic parameters. If simulated runoff from local and regional precipitation datasets exceed the site-specific runoff relationship the curve will be adjusted to include the storm event(s). The result will be a validated regional runoff relationship (curve). Note that individual storm events may be evaluated based on their frequency of occurrence to determine if events should be included or excluded.

Regional Native GW Return Flows (Deep Percolation)

The proposed methods for developing regional factors utilize regional runoff relationships (curves) and groundwater return flow (deep percolation) factors (percentages) applied to individual storm events to determine precipitation return flows (the amount owed to the natural stream system).

Daily Soil Moisture Reservoir Accounting Model

A daily soil moisture reservoir (SMR) accounting model is a traditional method used for determining the amount of precipitation that enters the soil (infiltrates) and deep percolates into the groundwater system. Using the published NRCS soils available water content (AWC) and rooting depth a soil moisture reservoir volume can be defined for a unit area. Inflows into the SMR are based on observed precipitation (P) and outflows are based on simulated ET (from Hydrus 1-D) (ET) and simulated runoff (Q_{sw}) (from WQ-COSM).

The Excel-based continuous soil moisture accounting model then tracks daily changes in storage of the SMR resulting inflows and outflows using the following equation:

$$= \quad - \quad - \quad _{sw} + \Delta$$

Deep percolation events occur only when the SMR max capacity is exceeded.

Model Validation

The site-specific detailed water balance and daily SMR accounting model results will be compared to the observed deep percolation from the lysimeter annually as a percentage of precipitation. Published values of native regional groundwater return flows (deep percolation) will then be used to confirm the reasonableness of deep percolation estimates for individual soil types or hydrologic soil groups. Based upon site-specific observed and simulated results and published information a method for calculating regional groundwater return flows (deep percolation) will be recommended.

Delayed Groundwater Return flows

Many locations throughout the region have little to no local groundwater tables connected to the nearby stream alluvium. In such situations, water that deep percolates may not accrue to the stream system. However, to make this approach applicable regionally and to be conservative to the stream system, quantified natural deep percolation is assumed connected and available to downstream water users.

Two methods will be used to evaluate delayed groundwater return flows: 1) The first method will establish a site-specific unit response function (URF) based on aquifer properties to determine the timing and amount of delayed groundwater return flows for the observed precipitation record. 2) The second method assumes delayed groundwater return flows occur on a continuous basis with the aquifer at steady-state and is applicable on a regional scale at locations where there is a significant delay between infiltration and accrual to the stream. Results from each method will be compared and an appropriate method will be selected based on practicability and defensibility. These methods are described in more detail below:

Method # 1: Site-Specific Unit Response Function

Accounting for the change in groundwater return flows to the stream from natural to developed conditions requires an estimate of the lag time for the deep percolation of precipitation to travel through the local aquifer and reach the stream. The lag time is often expressed as a Unit Response Function (URF) that expresses the groundwater return flows in each month as a percentage of the initial month of deep percolation. For a given location, the URF is a function of several site-specific factors including the subsurface geology and hydrogeology, the distance to the stream or other accretion points, and the distance to the aquifer boundary. Due to the site-specific nature of these factors, estimating URFs should be evaluated on a site-specific basis. The Glover (1954) method has been used extensively in Colorado for well-depletion lagging, groundwater return flow lagging, and other purposes and is widely used groundwater return flow accounting in Colorado. For precipitation harvesting projects monthly URFs computed using the Glover Method provides a reasonable basis for evaluating groundwater return flow timing.

Method # 2: Continuous Return Flows

The observed precipitation record and URF from the first method will be used to quantify the continuous amount of delayed groundwater return flows required utilizing the Glover method described above. The observed precipitation record will be repeated for a fifty-year period to determine the continuous return flow requirement to the stream at steady-state. This method may provide a more conservative estimate that protects downstream water users while being more applicable on a regional scale.

Calculate Natural Depletions and Regional Factors

Calculating natural depletions and regional factors is the last step in the proposed methodology. Below is an example using the established regional runoff relationship and conservative recommendations for regional groundwater return flow (deep percolation) factors from previous tasks to calculate surface water and groundwater return flows, natural depletions, and regional factors. It is proposed that surface water and groundwater return flows (deep percolation), natural depletions, and regional factors be calculated for each precipitation depth increment (0.01-inch increments).

Example of a storm depth increment of 0.80 inches:

1. Surface return flows for native conditions for each precipitation depth (storm depth) increment are to be calculated individually using the established regional runoff relationship from previous tasks. The regional runoff relationship presented below is the mathematical equation from **Figure 3** above for a straight line (i.e. linear) relationship between surface water returns and storm depth for a specific hydrologic soil group.

   This regional runoff relationship example from **Figure 3** uses a standard linear equation defined as y = mx + b, where:

   SW Return Flow (y) =m * Storm Depth (x) + b

   Storm Depth = 0.80 inches

   SW Return Flow (y) = (0.2533 * 0.80 inches) + 0.084

   Surface Water Return Flow = 0.29 inches (36%)

2. Groundwater return flows for native conditions for each precipitation depth (storm depth) increment are to be calculated individually using the established conservative recommendations for regional groundwater return flow (deep percolation) factors from previous tasks.

GW Return Flow = Precipitation Depth * Regional Groundwater Return Flow (Deep Perc) Factor

Regional Groundwater Return Flow (Deep Perc) Factor = 3%

GW Return Flow = 0.80 inches * 3%

GW Return Flow = 0.024 inches

3. Precipitation Return Flows and Natural Depletion are to be calculated for each precipitation depth (storm depth) increment individually using the following equations:

   Precipitation Return Flows = SW Return Flow + GW Return Flow

   Surface Water Return Flow = 0.29 inches
   GW Return Flow = 0.024 inches

Precipitation Return Flows = 0.29 inches + 0.024 inches = 0.314 inches

Precipitation Return Flows = 0.314 inches

Natural Depletion = Precipitation Depth – Precipitation Return Flows

Natural Depletion = 0.80 inches - 0.314 inches

Natural Depletion = 0.486 inches

4. Regional factors for each precipitation depth (storm depth) are to be calculated individually by dividing the natural depletion by the precipitation depth (storm depth).

Regional Factor (%) = Natural Depletion/ Precipitation Depth

Regional Factor (%) = 0.486 inches/0.80 inches = 0.6075 or 60.8 %

Regional Factor = 60.8 % for a 0.80 inch precipitation event

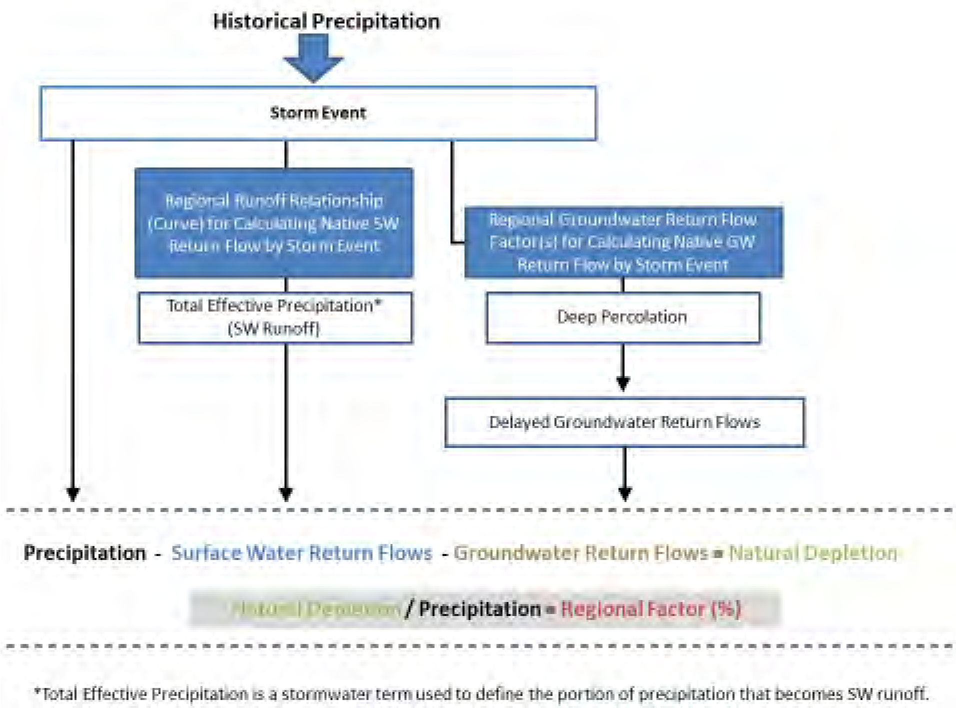
VII. Application of Regional Runoff Relationships and Groundwater Factors

Precipitation harvesting will be administered like an augmentation plan on a daily basis with the point of administration at the stormwater facility or cistern. The amount stored or diverted for use without replacement is limited to the amount of historical natural depletion.

Real-time measured precipitation at or near the site will be used to define storm events. The total storm depths of each storm event will then be used to determine the amount of historical natural depletion and the amount owed to the stream from surface returns based on established regional runoff relationships and groundwater factors. Groundwater return flows (deep percolation) will be calculated using either; (1) a delayed unit response functions and tracked on a continuous basis or (2) applied instantaneously assuming steady-state. All surface and delayed groundwater owed to the stream shall be returned to the stream as regulated stormwater or with another legal replacement water source pursuant to an SWSP supporting or augmentation plan. Daily administrative-accounting will be required to track storm events, return flow requirements, and the total precipitation harvested available for use.

Figure 5 illustrates the application of regional runoff relationships and groundwater return flow (deep percolation) factors for determining precipitation return flow requirements and natural depletion.

Figure 5 – Application of Proposed Methodology



The physical regional extent that Factors are applicable is not evaluated in this methodology. Further investigations need to be conducted to define the physical size and characteristics of each defined region where Regional factors are applicable.

References

Leonard Rice Engineers, Inc. 2015. House Bill 15-1016, Proposed Regionally Applicable Methodology and Lessons Learned, Sterling Ranch Precipitation Harvesting Pilot Program, Douglas County, Colorado. Prepared for Dominion Water and Sanitation District.

Appendix 3
(Task 3)

DRAFT Memorandum

To:	Tracy Kosloff, Colorado Division of Water Resources
From:	Mark Mitisek, Leonard Rice Engineers, Inc.
Copy:	Sarah Stone, Dominion Water & Sanitation District
Reviewed by:	Patrick O'Brien and Greg Roush, Leonard Rice Engineers, Inc.
Date:	December 28, 2018
Project:	Colorado Water Plan Grant – Regional Factor Development for Precipitation Harvesting
Subject:	Task 3A –Site-Specific Data Compilation

Site-Specific Data Compilation

Data compilation is simply gathering all applicable climate, precipitation, streamflow, and lysimeter datasets used in the development and calibration of models supporting the quantification of precipitation return flows and natural depletions. Prior to using the data directly, the datasets need to be reviewed, documented, and formatted for use. This includes aggregating/disaggregating datasets to a common time-step compatible with model formats. This memorandum summarizes the following primary tasks completed for compiling site-specific data collected from the natural conditions monitoring program at Sterling Ranch:

- Compile and validate site-specific time series datasets from the pilot project applicable to the development of regional factors (precipitation, stream gage data, data from the lysimeter, etc.);
- Perform QA/QC on each dataset and document the process used to review each data set used as input or for calibration purposes.
- Format and organize datasets for use with the site-specific detailed water balance (Hydrus 1-D), continuous simulation runoff model (WQ-COSM), and the soil moisture reservoir accounting models.

Natural Conditions Monitoring Program

Site-specific data collection for the Pilot Program at Sterling Ranch began in March of 2010 with the installation of the Sterling Rach climate station. Since that time a significant amount of natural conditions field data has been collected to support the water budget including climate, precipitation, streamflow, and lysimeter datasets. Described below are the various measurement devices installed on-site at Sterling Ranch that collected data as a part of the natural conditions monitoring program. Also included is a summary of the data review processes (QA/QC), missing periods of record, and final formatted data sets (as separate electronic files). The final datasets from each sensor that are applicable to the quantification of natural precipitation return flows or natural depletions are provided. A description and tabulation of these data sets is summarized below.

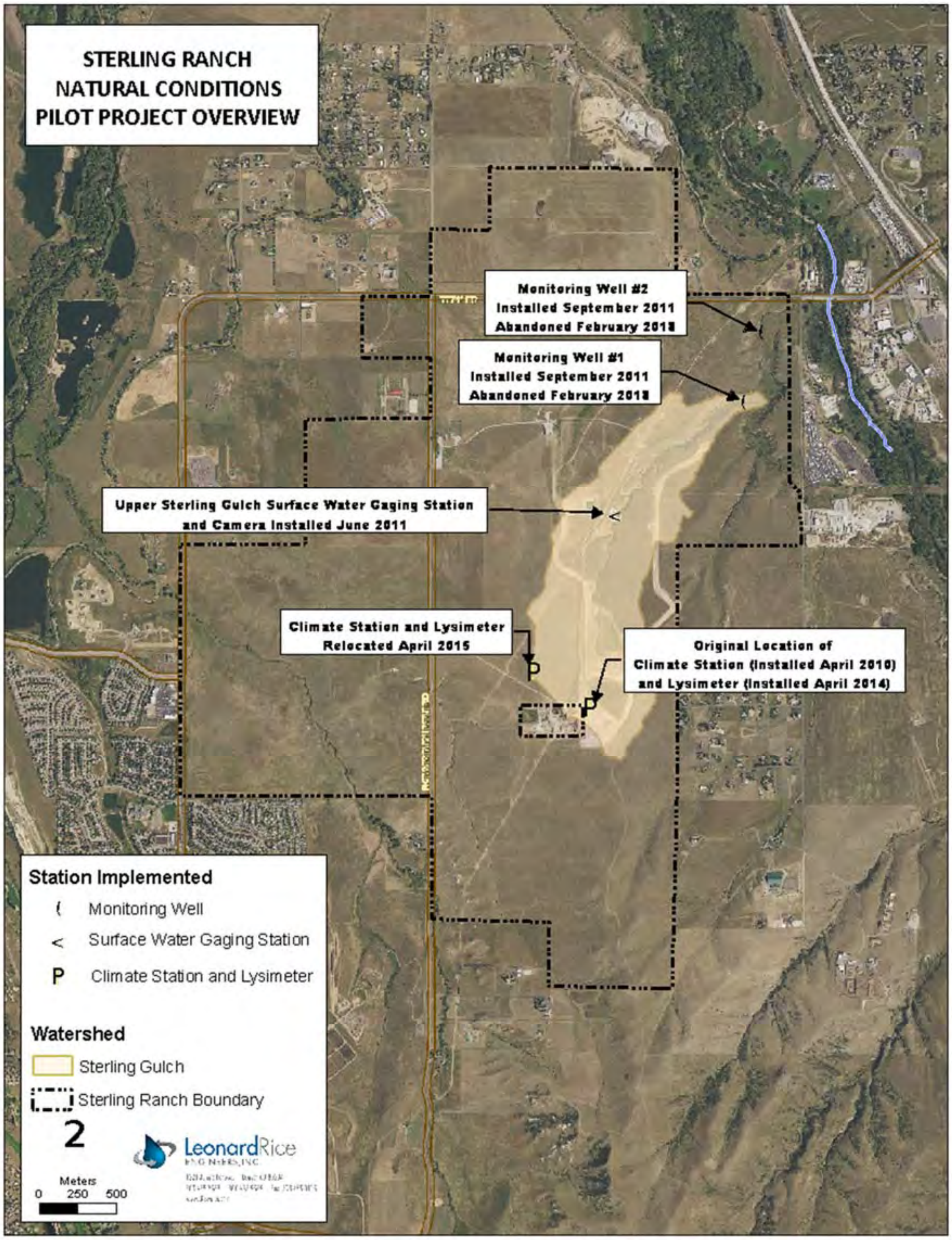


Figure 1 – Sterling Gulch Basin Map

Precipitation and Climate Datasets

All measurement devices and sensors are found at the Sterling Ranch Climate Station enclosure, with the exception of the surface flow measurement station which is found within Sterling Gulch. All measurements at the Climate Station are collected in a Campbell Scientific CR1000 data logger, telemetered, compiled by OneRain Inc.

In April 2015, the entire Climate Station was relocated to a different representative site on Sterling Ranch (Figure 2). At that time all measurement devices and sensors were tested and re-calibrated to ensure data consistency.

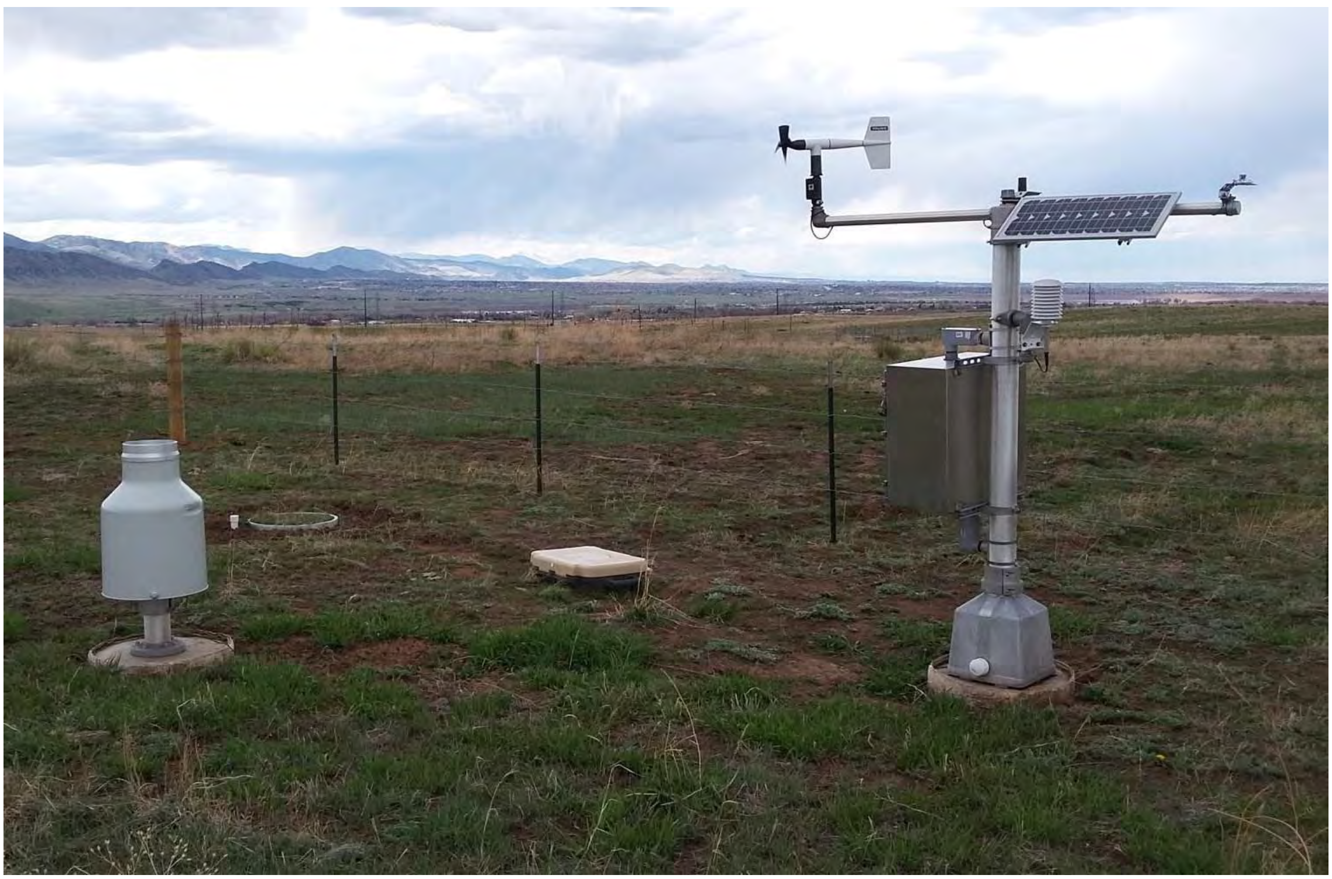


Figure 2 – Sterling Ranch Climate Station (April 2016)

Sensor Descriptions

Below is a description of each climate sensor:

Precipitation

Incremental precipitation in inches is measured by an OTT Pluvio weighing precipitation gauge. The precipitation gage was installed on the site and began collecting data on March 29, 2010. The precipitation gauge is located at the Sterling Ranch Climate Station and reports incremental data in regular 1-hour intervals, and down to the minute whenever precipitation is detected.

Temperature & Relative Humidity

Both temperature in degrees Fahrenheit and relative humidity as a percent are measured by a Campbell Scientific HMP45C-L combined sensor. The combined sensor was installed on the site and began collecting data on March 29, 2010. The combined sensor is located at the Sterling Ranch Climate Station and reports data at 15-minute intervals.

Solar Radiation

Incoming solar radiation in MJ/m^2 is measured by a LI-COR LI200x-L silicon pyranometer. The pyranometer was installed on the site and began collecting data on March 29, 2010. The pyranometer is located at the Sterling Ranch Climate Station and reports data at 15-minute intervals.

Wind Speed

Wind speed in mi/hr is measured by an R.M Young 05103-L wind sensor installed at WMO standard of 2 meters. The wind sensor was installed on the site and began collecting data on March 29, 2010. The wind sensor is located at the Sterling Ranch Climate Station and reports data at 15-minute intervals.

Missing Data Periods

The climate station data was unavailable for all sensors during three separate periods spanning longer than 1 day. The data unavailability was due to installation and integration of lysimeter, battery /solar panel issues, or telemetry outages. The extended missing periods are:

- 3/7/11 to 3/31/11
- 3/24/14 to 4/9/14 (installation of lysimeter)
- 11/26/15 to 12/3/15

In order to produce a daily model input file without data gaps, these missing days were filled using the average of the associated day of the month from the remainder of the study period. For example, the missing day of 3/7/11 was filled using the average from day 3/7 from all other years of the study period. This filling method was chosen to best represent average seasonal effects present during those time periods. The length of these daily data gaps made interpolation not feasible, and no nearby climate stations had all the required parameters to fill from during these data gaps. The parameters filled using this method were the meteorological inputs to the model (temperature, relative humidity, wind speed, and solar radiation).

Data QA/QC

All data generated from the Sterling Ranch Climate and Precipitation Stations were subjected to review and QA/QC procedures. Where applicable, data filling methods were applied. These review procedures are described below for the following datasets:

- Precipitation
- Temperature
- Relative Humidity
- Solar Radiation
- Wind speed

Precipitation QA/QC

Incremental precipitation measurements were summed to even 5-minute timestamps to serve as the baseline dataset. Timestamps between incremental precipitation measurements were set to 0. Unit conversions were made and checked where applicable to accommodate model input files.

Precipitation was summed to daily values for modeling and analysis. Possible outlier values were checked against a set of nearby Urban Drainage Flood Control (UDFCD) and NOAA climate stations to confirm the timing and magnitude of large precipitation events.

Temperature QA/QC

Raw temperature measurements were compiled on a standard 15- minute interval to serve as the baseline dataset. Temperature measurements were averaged to daily values, and minimum and maximum daily temperatures were selected for modeling and analysis. For the period of 4/22/2015 through 8/2/2016, the temperature measurements at Sterling Ranch were deemed to be invalid due to equipment malfunction after the climate station was relocated. The sensor was replaced on 8/2/16 and returned to working properly. Data from 4/22/2015 through 8/1/2016 was removed and replaced with temperature data from the Highlands Ranch WTP (2710) climate station maintained by Urban Drainage Flood Control District. This station is a public station located 5.5 miles northeast of the Sterling Gulch Climate Station. The temperature data was compared during overlapping periods and determined to be representative of the site. Unit conversions were made and checked where applicable to accommodate model input files.

Relative Humidity QA/QC

Raw relative humidity measurements were compiled on a standard 15-minute interval to serve as the baseline dataset. Relative humidity measurements were averaged to daily values for modeling and analysis. Unit conversions were made and checked where applicable to accommodate model input files.

Solar Radiation QA/QC

Raw solar radiation measurements were compiled on a standard 15-minute interval to serve as the baseline dataset. Solar radiation measurements were averaged to daily values for modeling and analysis. Unit conversions were made and checked where applicable to accommodate model input files. Upon review, the sensor malfunction became detectable in the raw data in May 2016 continuing until July 2018 when the sensor was replaced. With no representative solar radiation stations nearby, the 15-minute data was filled using average daily and seasonal patterns from the previously observed record. This data filling method resulted in reasonable daily and seasonal patterns of solar radiation.

Wind Speed QA/QC

Raw Wind speed measurements were compiled on a standard 15-minute interval to serve as the baseline dataset. Wind speed measurements were averaged to daily values for modeling and analysis. Unit conversions were made and checked where applicable to accommodate model input files.

Climate Data Outlier Detection

The software program REF-ET[1] was used to further perform QA/QC on the meteorological model input datasets. While the REF-ET program is designed for calculating reference crop evapotranspiration values, it has a built-in QA/QC program that provides graphical representations of the meteorological input data. This program was used to check the following datasets:

- Precipitation (in)
- Average Temperature (deg C)
- Minimum Temperature (deg C)
- Max Temperature (deg C)
- Average Relative Humidity (%)
- Average Wind speed (km/day)
- Average solar radiation (MJ/M^2*day)

The results from this program determined that our meteorological input datasets contained no significant outliers and that any recommended adjustments to our post-processed solar radiation data would prove insignificant. Therefore, our meteorological datasets (post-processed as described in the above sections) were deemed adequate for model input purposes.

Final Datasets

Table 1 below summarizes the final Sterling Ranch Precipitation and Climate datasets compiled for this effort. The table includes parameter name (file name), units, start and end dates, percent missing, and time steps of each dataset.

Table 1 - Precipitation and Climate Datasets

Parameter Name	Units (raw)	Units (Final)	Start Date	End Date	Percent Missing	Raw data Time Step	Final Time Step
Precipitation - Increment	in	in and cm	3/29/2010	5/31/2018	N/A	Intermittent/Event based	5, 15, and 60 Minute
Relative Humidity	%	%	3/29/2010	5/31/2018	1.8%	15 min	Daily
Solar Radiation	MJ/m^2	MJ/m^2*day	3/29/2010	5/31/2018	2.2%	15 min	Daily
Wind - Avg Velocity	mi/hr	km/day	3/29/2010	5/31/2018	1.8%	15 min	Daily
Air Temperature - Sterling Ranch	Deg F	Deg C	3/29/2010	5/31/2018	1.7%	15 min	Daily

Lysimeter Dataset

A single weighing lysimeter was installed on the site and began collecting data on April 11, 2014. The 24 inches diameter by 42 inches deep lysimeter was designed to represent native soil and vegetation conditions at Sterling Ranch with average rooting depths representative of mid-prairie native grasses. The lysimeter is equipped with three 500 lb load cells, four soil moisture sensors, and a tensiometer controlled vacuum system and tipping bucket. The parameters provided include four separate soil moisture measurements in percent saturation (10-inch depth, 20-inch depth, 10-inch depth within the core, 20-inch depth within the core), water depth change (inches), and incremental deep percolation volume measurements (mL). Data collected by these sensors will be used in calibration of the detailed water balance model. **Figure 1** shows the original and current location of the lysimeter next to the Sterling Ranch Climate Station. **Figure 3** is a picture and a general schematic of the Sterling Ranch Lysimeter.

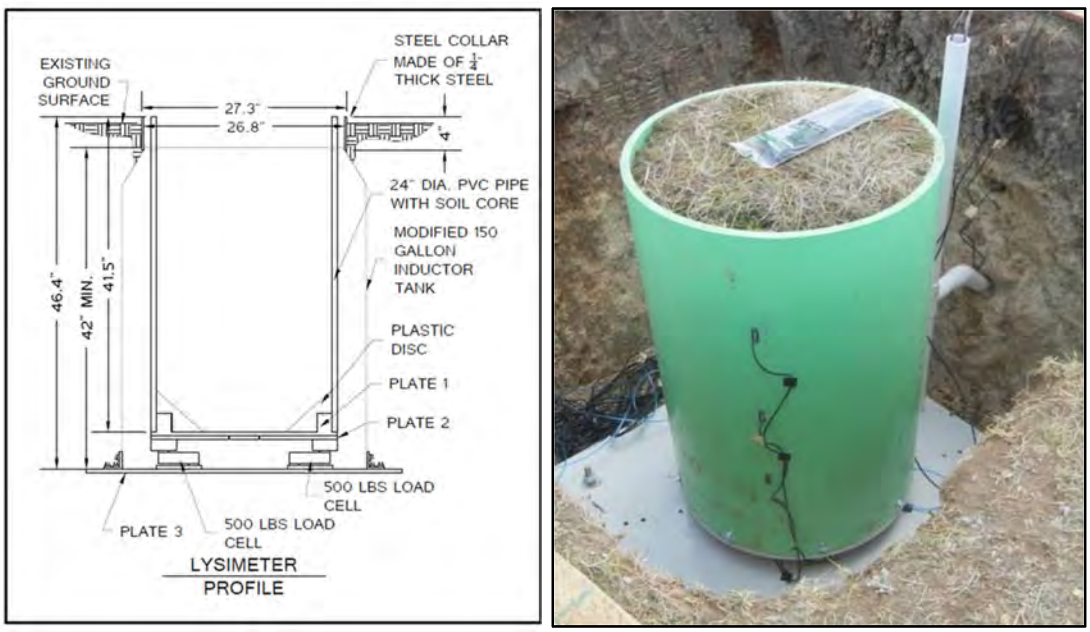


Figure 3 – Sterling Ranch Lysimeter

Sensor Descriptions

Below is a description of each lysimeter sensor:

Soil Moisture Sensors (10 and 20 inches)

Four Decagon (ECH2O) 5TM soil moisture probes measuring percent (%) saturation of the soil moisture were installed with the lysimeter and began collecting data on April 12, 2014. Two of the soil moisture probes were installed inside the lysimeter at 10 and 20 inches below the surface. The other two soil moisture probes were installed outside the lysimeter in the natural soil column at 10 and 20 inches below the surface. Data from each sensor is reported 15-minute intervals. The purpose of the dual soil moisture probes inside and outside the lysimeter core is confirm relative soil moisture conditions within the lysimeter are being maintained.

Water Depth Change

Water depth change is the net change in water content (inches) of the lysimeter core and is determined based on the change in weight (lbs) over the area of the lysimeter. Three load-cells are used to report the change in weight every 15-minutes. Water depth change measures both inflows from precipitation (increase in weight/inches) as well as outflows from evapotranspiration or deep percolation (decrease in weight/inches). Although the lysimeter began collecting changes of weight on April 12, 2014, the correct programmatic changes and calibration of the load cells in aggregate began providing accurate measurement of water depth changes beginning April 29, 2015.

Deep Percolation (Vacuum Increment)

The lysimeter is equipped with a tensiometer controlled vacuum system that measures the outflow of water (i.e. deep percolation) from the bottom of the lysimeter based on natural soil conditions. The vacuum system consists of a ceramic plate located at the base of the lysimeter; a pump used to regulate the vacuum applied to the ceramic plate; a tensiometer used to measure the current pressure of the native soil outside the lysimeter and inform the pump how much vacuum to apply; and a miniature tipping bucket (4 mL/tip) used to sample the volume (i.e. deep percolation) of water collected by the ceramic plate. This entire system is automated measuring deep percolation (vacuum increments) only when a deep percolation event occurs.

Representative Data Periods

The lysimeter was installed and began reporting data on April 12, 2014, at its original location just east of the Roxborough WTF then relocated 4,600 feet northwest to its current location on April 29, 2015. The lysimeter and climate station were moved from the original site due to construction activity associated with the Roxborough WTF upgrade. Operationally, the first year of data collection occurred for all sensors. However, due to program errors, the reported changes in the weight of the lysimeter core resulted in errant values. Only the soil moisture probes and deep percolation provided valid data during the 2014-2015 operational year.

With the move of the lysimeter to its new location the load-cells were re-calibrated and the vacuum system was re-installed. All program errors were resolved and all of the sensors began recording valid data starting April 29, 2015.

Data QA/QC

Soil Moisture QA/QC

The raw soil moisture measurements are not a direct model input and are only used for model calibration purposes. The raw unaltered, un-compiled datasets were reviewed for consistency to validate data collected and confirm data trends. To validate this dataset the observed precipitation record at the Sterling Ranch precipitation station was compared to the soil moisture sensor data to confirm the timing and magnitude of observed soil moisture patterns. In addition, the soil moisture sensors at different depths were compared to confirm observed soil moisture closer to the surface (10-inches) was lower and varied more in magnitude than soil moisture observed at depth (20-inches).

Water Depth Change QA/QC

The raw water depth change measurements are not a direct model input and are only used for model calibration purposes. The raw unaltered, un-compiled datasets were reviewed for consistency to validate data collected and confirm data trends. To validate this dataset the observed precipitation record at the Sterling Ranch precipitation station was compared to the water depth change. All increases in water depth changes (i.e. inflows) were compared to observed precipitation event frequency, duration, and magnitude. Based upon this review it was determined the best representative period of record occurs from June 2015 through May 2017. It is recommended that this period is used as the calibration period. If data is used outside of this period further review, QA/QC, and data validation of the dataset is required.

Deep Percolation (Vacuum Increment) QA/QC

The raw deep percolation measurements are not a direct model input and are only used for model calibration purposes. The raw unaltered, un-compiled datasets were reviewed for consistency to validate data collected and confirm data trends. To validate this dataset the observed precipitation record at the Sterling Ranch precipitation station was compared to the deep percolation dataset to confirm timing and magnitude of events.

Final Datasets

Table 2 below summarizes the final Sterling Ranch Lysimeter datasets compiled for this effort. The table includes parameter name (file name), units, start and end dates, percent missing, and time steps of each dataset.

Table 2 - Sterling Ranch Lysimeter Datasets

Parameter Name	Units (raw)	Units (Final)	Start Date	End Date	Percent Missing	Raw data Time Step	Final Time Step
Soil Moisture - 10 inches	%	%	4/12/2014	5/31/2018	0.9%	15 min	15 min
Soil Moisture - 20 inches	%	%	4/12/2014	5/31/2018	0.9%	15 min	15 min
Soil Moisture - Core - 10 inches	%	%	4/12/2014	5/31/2018	0.9%	15 min	15 min
Soil Moisture - Core - 20 inches	%	%	4/12/2014	5/31/2018	0.9%	15 min	15 min
Water Depth Change	in	in	4/29/2015*	5/31/2018	0.8%	15 min	15 min
Vacuum (Deep Perc) - Increment	mL	in	4/12/2014	5/31/2018	N/A	Intermittent/Event based	Daily

* Data prior to 5/30/2015 and after to 06/01/2017 was not validated.

Surface Water Flow Dataset

The surface water station for Sterling Ranch is installed within the upper portion of Sterling Gulch and began collecting data on June 23, 2011. **Figure 1** shows the location of the surface water station. The surface water station includes a 9-inch Parshall Flume, shaft encoder water level sensor (SDR), and continuous data logger. Data is manually collected from the data logger monthly during the months of March to October.

Missing Data Periods

The available period of record compiled for the Sterling Ranch surface water station is June 23, 2011, to May 31, 2018. During the operational period from March to October, there were a total of 79 missing days for the period of record (78/1693 = 4.6%). These missing periods were the result of data logger program errors and data overwrites. Below is a list of date ranges with missing data:

- 9/9/2011-9/24/2011 (16-days)
- 6/8/2012-6/12/2012 (5-days)
- 10/24/2013-10/31/2013 (8-days)
- 9/12/2014-10/30/2014 (49-days)

Data QA/QC

Observed flow data (cfs) at the Sterling Gulch flume were computed from stage measurements recorded within the stilling well at the flume. Raw data collection occurred primarily at 5-minute increments throughout the study period, with some periods producing hourly or 15-minute data. Prior to compiling the average flow (cfs) to the common hourly increment, the following QA/QC procedures were completed:

- The raw data files were reviewed for consistency and all missing data were filled with zeroes.
- During the months of March through October, the observed flow events were compared to the observed precipitation record to confirm corresponding storms.
- The final compiled datasets were also plotted for consistency and determining surface water event outliers. Based on the plot it was observed that July 12, 2014, exceeded the max stage measurable by the flume. As documented by the 2015 annual report the July 12, 2014 surface water event overtopped the flume and was not accurately recorded. For posterity, this data was not removed from the raw data files.

Final Dataset

Table 3 below summarizes the final Sterling Ranch Surface Water Flow dataset compiled for this effort. The table includes parameter name (file name), units, start and end dates, percent missing, and time steps of each dataset.

Table 3 - Sterling Ranch Surface Water Flow Dataset

Parameter Name	Units (raw)	Units (Final)	Start Date	End Date	Percent Missing	Raw data Time Step	Final Time Step
Flow - Sterling Gulch Flume	cfs	acre-feet	6/23/2011	5/31/2018	4.6%	15 min	Daily

Groundwater Datasets

Two groundwater monitoring wells located within Sterling Gulch were completed in September 2011 (see **Figure 1**). Groundwater level data from each well were collected on a monthly basis during the operational period of March through October. During this period of record, only one measurable groundwater event (Mid-July 2014 corresponding to the July 12, 2014 event) was observed. With no detectable alluvial groundwater level information, these datasets were not compiled or used in subsequent tasks.

Evapotranspiration Dataset

Evaporation and transpiration were continuously modeled using HYDRUS-1D using the standard Penman-Monteith equation utilizing the 15-minute meteorological data described above. For more information on the development of this dataset see the Task 4A Detailed Water Balance memorandum.

Compilation of Observed Datasets

Tables 1-3 described above summarize the datasets compiled from the Sterling Ranch natural conditions monitoring program that is used in the subsequent tasks to support the development of site-specific and regional factors for precipitation harvesting. Included with this memorandum is a flash drive of the final compiled datasets. The parameter names listed are the file names, and the modeled time steps and final units described above.

References

[1] Allen, Richard G. “REF-ET.” 4.1, University of Idaho, 2016, www.uidaho.edu/cals/kimberly-research-and-extension-center/research/water-resources/ref-et-software

DRAFT Memorandum

To: Tracy Kosloff, Colorado Division of Water Resources

From: Joel Barber P.E., Leonard Rice Engineers, Inc.

Copy: Sarah Stone, Dominion Water & Sanitation District

Reviewed by: Mark Mitisek and Greg Roush, Leonard Rice Engineers, Inc.

Date: December 28, 2018

Project: Colorado Water Plan Grant – Regional Factor Development for Precipitation Harvesting

Subject: Task 3B- Site Characterization

Site Characterization

The Sterling Gulch drainage basin is approximately 364 acre drainage located in the foothills south west of Denver, CO. The size of the drainage above the Upper Sterling Gulch Flume is approximately 223.2 acres. Sterling Gulch is an intermittent stream which carries water only in response to individual storm events. The gulch drains into Plum Creek, which is a tributary of the South Platte River. The following is an outline of the geology, soils characterization, vegetation description, and topography of the drainage.

Geology and Soils

Surficial deposits in the area are Pleistocene Solocum Alluvium (Bryant, 1981). Geotechnical investigations of the drainage were conducted by A.G. Wassenaar Inc. in 2013. The investigations consisted of geotechnical borings and soil sampling. The drainage was found to have 2 to 35 feet of unconsolidated sand, sandy clay, clay, and gravel overlying sandstone and claystone bedrock of the Denver formation. Topsoil was characterized as approximately 8 inches of sandy clay. Slightly sandy clay to very sandy clay was the most commonly identified soil in the borings, with a lesser amount of sand and gravel.

Figure 1 is a map of the Sterling Gulch study area with the United States Department of Agriculture (USDA) web soil survey map of the drainage with hydrologic soil groups shown in the background. There are four hydrologic soil groups, A, B, C, and D. The hydrologic soil group defines a soil's ability to infiltrate water, with soil group A having the fastest infiltration rate and group D the slowest. In general, the soil groups correlate directly to gradation with group A having the coarsest texture and group D the finest. Group C soils cover 72 % of the drainage and Group B soils cover 28% of the drainage. Group C soils cover the upper (southern) portion of the drainage, while the lower parts of the drainage and much of the drainage channel are covered with Group B soils. Group C soils are predominantly fine-grained materials (predominantly sandy clay loams) with low infiltration potential, an expected saturated hydraulic conductivity of approximately 0.4 ft/day to 1.2 ft/day. Group B soils are fine to moderately coarse-grained (predominantly silt loam or loams) and have a moderate infiltration potential, an expected saturated hydraulic conductivity of approximately 1.2 ft/day to 4 ft/day (USDA, 2019). The USDA Web Soil Survey (WSS) provides an estimate of saturated hydraulic conductivity of mapped soils. The geometric mean of the WSS saturated hydraulic conductivity (k_{sat}) of the mapped B and C soils in the study area is 0.51 ft/day.

Soil samples from the double ring infiltration testing, discussed in further detail later in this memo, are composed of predominantly sandy clay loam, with variable amounts of fine to coarse sand and organics.

These samples correspond with the geotechnical soil descriptions of topsoil in the A.G. Wassenaar Inc., 2013 report. The field soil description along with the WSS mapping indicates that the surficial soils in the drainage are predominately hydrologic soil Group C materials.

The claystone and sandstone bedrock underlying the surficial soils is likely less permeable than the overlying unconsolidated deposits. Therefore the bedrock likely acts as a relatively impermeable barrier to infiltration. Groundwater that recharges the alluvial aquifer likely does not significantly infiltrate into the underlying bedrock and instead flows along the bedrock surface towards the base of the drainage.

There is no apparent static water table in the majority of the unconsolidated deposits with a potentially thin saturated thickness of groundwater at the bottom of the drainage. A.G. Wassenaar Inc. advanced 56 geotechnical test borings for the Sterling Ranch development. The borings are located throughout the bottom half of Sterling Gulch as well as in neighboring drainages. Approximately 21 of the 56 borings were advanced in the lower half of the Sterling Gulch basin. The borings encountered 2 to 35 feet of dry sandy clay, clay, sand, and gravel overlying sandstone and claystone bedrock. The A.G. geotechnical borings were all dry during drilling, but water was found in a single open borehole a month after drilling.

Vegetation and Growing Season

LRE conducted a visual vegetation survey of the basin during infiltration testing. Sparse vegetation covers the majority of the drainage basin area with grasses dominating as the primary vegetation type with diffuse short shrubs throughout. Denser vegetation with smaller trees and bushes is located along the drainage.

Grass height was measured at two locations. Vegetation at both sites surveyed consisted of several grass species of varying heights, colors, and physical characteristics. At the first site, the tallest grass height observed was 17 inches. The shortest grass height observed was 2.5 inches. The average height of all grasses measured was approximately 8 inches. At the second site, the tallest grass height observed was 9.5 inches. The shortest grass height observed was 2.5 inches. The average height of all grasses measured was approximately 6 inches.

The growing season of the native grasses is temperature dependent and varies annually. The growing season of grasses is commonly defined as the period in which the mean daily average temperature is greater than 45 degrees Fahrenheit (USDA, 1967). Using the on the on-site climate station for the years 2010 to 2018 we found that the growing season to range from late April through early October for the native grasses. We additionally evaluated the pattern of transient changes in lysimeter water content to confirm the interpreted growing season from the temperature data. The growing season may be evaluated from the transducer data by looking at the rate of water withdrawal from the lysimeter core. The lysimeter data, in general, agrees with a growing season of late April to early October with some minor annual variations.

Infiltration Testing

LRE conducted mini disk infiltration testing at the lysimeter core area and double ring infiltrometer testing at eight locations within Sterling Gulch. Mini disk infiltrometer testing was conducted at 7 location around the lysimeter core. The results of these tests are assumed to be representative of the infiltration capacity of the material in the lysimeter core. A summary of the testing results is presented in **Table 1**. Assuming a sandy clay loam soil the estimated average saturated hydraulic conductivity (k_{sat}) of the material in the lysimeter core is 0.95 ft/day. Although the core was taken from a region mapped as soil group B, the measured permeability of the soil from mini disk infiltrometer testing indicates the soil has a permeability in the range of soil group C (NRCS, 2007).

Double ring infiltrometer testing is a method for estimating the infiltration rate and k_{sat} of near-surface soils. The locations of the double ring infiltrometer tests are shown in **Figure 2**. The steady state infiltration rates from double ring infiltrometers are not equivalent to the saturated hydraulic conductivity (k_{sat}) of the surficial soils unless steady state infiltration with the water table is achieved. We estimated k_{sat} using the relationship presented in Reynolds and Elrick, 1990. Because a static water table is not present, steady state infiltration with the water table could not be achieved. Therefore, the infiltration rates provided in **Table 2** are greater than that of the material's estimated $k_{sat.}$

Testing was conducted following ASTM D3385 standardized methods for eight selected locations with varying WSS mapped soils. The results of the infiltration testing are presented in **Table 2**, which summarizes the steady state infiltration data at each location and the resulting k_{sat} values used to support subsequent modeling efforts.

Table 1: Summary of Mini Disk Infiltrometer Testing Results

Mini Disk Test ID	Interpreted Ksat (ft/day)
pt 37	0.65
pt 38	0.55
pt 39	0.15
pt 40	1.62
pt 41	1.08
pt 42	0.74
pt 43	1.83
Average	**0.95**

Table 2: Summary of Double Ring Infiltrometer Testing Results

Location ID	Steady State Infiltration Rate (in/hr)[1]	Interpreted Ksat (ft/day)[2]	Interpreted Ksat (cm/s)
I-1	0.75	0.66	0.014
I-2	1.11	1.04	0.022
I-3	0.29	0.27	0.0057
I-4	0.75	0.66	0.014
I-5	1.53	1.32	0.028
I-6	1.13	1.04	0.022
I-7	2.07	1.80	0.038
I-8	1.29	1.18	0.025
Mean	**1.1**	**0.99**	**0.021**

1. Steady state infiltration is defined as the constant infiltration rate after a 4-hour infiltration test.
2. Reynolds and Elrick, 1990.

Conclusions

We characterized the drainage basin surficial soils using published soils mapping from the USDA Web Soil Survey (WSS), geotechnical investigations, and infiltration testing. Visual inspection of the surficial soils matches the WSS mapping. The surficial soils are predominantly sandy clay loam with varying degrees of sand. The soils are predominantly hydrologic soil group C. Field measurements of infiltration rates from ring infiltrometers testing was found to range from 0.29 to 2.07 ft/day with an average of 1.1 ft/day. Interpreted k_{sat} from the ring infiltrometer testing was found to range from 0.27 to 1.80 ft/day with an average of 0.99 ft/day. These tests were conducted at locations mapped as group B and group C soils. The USDA WSS soils describe the soils to have a saturated hydraulic conductivity (k_{sat}) of 0.51 ft/day (the geometric mean of the B and C soils that are present), which is within the range of the interpreted values from the ring infiltrometer testing. The surficial soils in the basins are generally poorly draining soils with a low infiltration potential.

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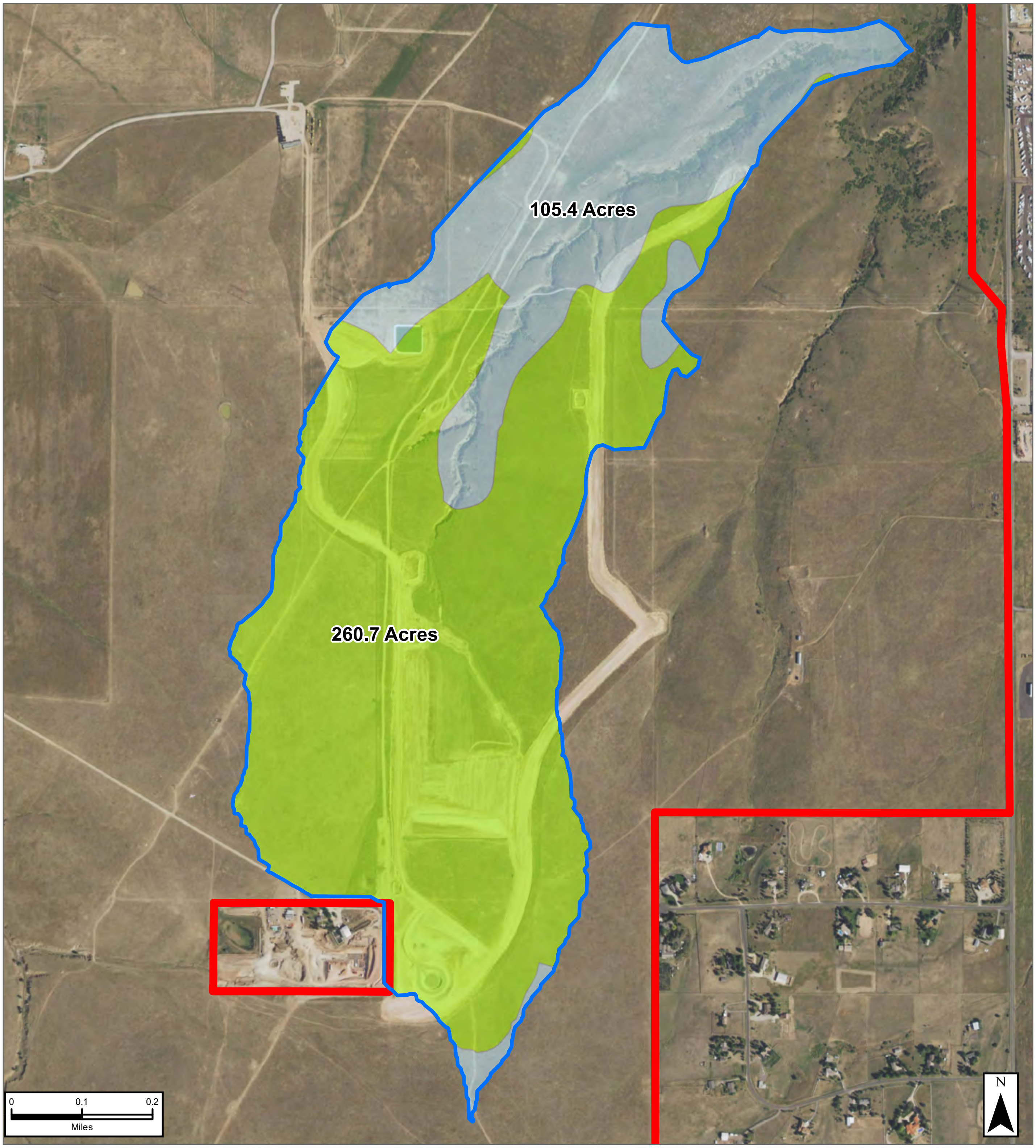

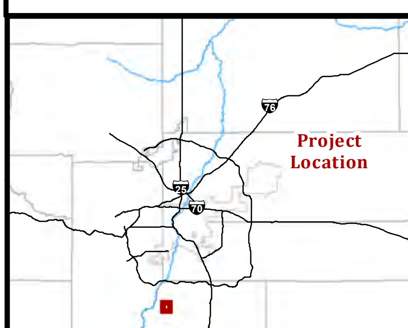

Legend

Watershed Boundary

Sterling Ranch Boundary

Sterling Gulch NRCS Hydrologic Soil Groups

B

C

This product is for reference purposes only and is not to be construed as a legal document or survey instrument.

FIGURE 1
NRCS WEB SOIL SURVEY
HYDROLOGIC SOIL GROUPS

LeonardRice ENGINEERS, INC

December 2018

Appendix 4
(Task 4)

DRAFT Memorandum

To:	Tracy Kosloff, Colorado Division of Water Resources
From:	Joel Barber P.E. , Leonard Rice Engineers, Inc.
Copy to:	Sarah Stone, Dominion Water and Sanitation District
Reviewed by:	Mark Mitisek and Greg Roush, Leonard Rice Engineers, Inc.
Date:	December 28, 2018
Project:	Colorado Water Plan Grant – Regional Factor Development for Precipitation Harvesting
Subject:	Task 4A – Site-Specific Water Balance Model

Purpose

The purpose of this memorandum is to outline the methods, assumptions, results, and conclusions of a water balance model of the Sterling Ranch drainage basin with the objective of simulating the soil moisture water balance components evaporation, transpiration, deep percolation, and runoff. The model was developed to assist in the development of regional factors for precipitation harvesting along the Colorado Front Range. The objectives of the model are to:

1. quantify the site-specific amount of precipitation (by storm event) that, under pre-existing natural vegetation conditions, accrues to the stream system via surface and groundwater return flows,
2. validate infiltration parameters and rates, and
3. provide estimates of evaporation and transpiration.

The 1-D soil moisture water balance model was developed using HYDRUS 1-D and calibrated to infiltration, soil moisture, and water balance observations in a lysimeter located in the Sterling Ranch drainage basin. A climate station is located adjacent to the lysimeter and was used to define the surface/atmospheric boundary condition in the model. We used the calibrated model to estimate the drainage basin wide water balance in response to storm events including estimates of deep percolation, runoff, evaporation, and transpiration. The results of the soil water balance model is a simulation of the percentages of recorded precipitation that historically under natural conditions evaporated, transpired, recharged groundwater, and ran off. The simulated total evaporation and transpiration as a percent of precipitation directly relates to the precipitation harvesting factor used to compute augmentation requirements.

Hydrogeologic Conceptual Model

LRE developed a HYDRUS 1-D model to calculate the soil moisture water balance components evaporation, transpiration, runoff, and deep percolation. Under the drainage basins natural condition, after a storm event precipitation enters storage in the vadose zone unless either; (1) the available storage is full or (2) the rate of precipitation is in excess of the rate at which it can enter the vadose zone, which in either case runoff occurs. Once the water is in storage in the soil column, it may than be removed via evaporation and transpiration (as a combination referred to as the ET component of the water balance). If the available storage in the soil column is full the water will flow downward and past the root zone as deep percolation. Beyond the scope of this model, deep percolation is assumed to recharge the alluvial groundwater and flow towards the South

Platte River alluvial aquifer. Over long periods of time it can be assumed that net change in storage is approximately zero and therefore 100% of the precipitation will evaporate, transpire, runoff, or recharge the groundwater.

Assumptions

The following are assumed in this analysis;

- All model properties, including soil, vegetation, and climate parameters are homogenous vertically within the simulated soil column and laterally across the Sterling Ranch basin.
- The effects of overland flow is not considered in the 1-D model and runoff is assumed to instantaneously reach the stream channel.
- Deep percolation beyond 3.75 feet below ground surface leaves the model and assumed to recharge the aquifer
- Although there are simulated evaporation and transpiration losses to grasses, there are no phreatophytes in the basin able to pull water from the groundwater.
- Grass is assumed to be the primary vegetation on the property and the influence from other vegetation is not considered.

Model Construction

The water balance model was conducted with HYDRUS 1-D version 4.16.0110, a one-dimensional flow model for simulating unsaturated and saturated flow (Simunek, 2008). HYDRUS 1-D is a commonly used and industry accepted model for simulating soil water balance in natural conditions including variably saturated flow through porous media, vapor flow, root water uptake, and atmosphere/surface interactions.

Two models were developed as follows:

1. Calibration Model: The purpose of the calibration model is to calibrate the model to observations at the lysimeter and to demonstrate the model accuracy relative to the observations.
2. Basin Wide Model: The purpose of the basin wide model is to simulate historical natural depletions on a basin scale. The simulated natural depletions are then used to develop regional factors.

Model Geometry

We simulated a 3.75 ft thick soil column which is representative of the lysimeter core and equivalent rooting zone depth of Western Wheatgrass. The model is discretized into 200 elements that are finer near the surface (0.00045 inches) and get exponentially larger with depth to a maximum of 0.452 inches. **Figure 1** is a graphical representation of the model.

Time Discretization

The calibration model was run for a duration of 2618 days representative of a period from April, 2010 to June, 2017. The basin wide model was run for a period of 2982 days representative of a period from April, 2010 through May, 2018. The model was run with dynamic time steps that could vary between $1x10^{-5}$ and 5 minutes.

Boundary Conditions

The top boundary condition of the model is an atmospheric boundary allowing for ponding and surface water runoff. Precipitation is input to the model from the rain gauge in 5 minute intervals for the duration of the model period. The precipitation data is modeled at a fine resolution to more accurately simulate the effect of storm duration on the calculated water balance. The max allowable ponding on the surface before runoff occurs was set to 1 inch and 0.05 inches for the calibration and basin wide simulation respectively. The 1-inch allowable ponding was assumed to simulate the extended lip around the lysimeter that prevents water from running off the lysimeter top. The allowable 0.05 inches of ponding was allowed to simulated small depression storage and was selected based on professional judgment and experience. Potential evaporation and transpiration at the surface was calculated using the Penman Monteith method with a direct input of solar radiation. Effective radiation was calculated assuming a direct input of emissivity. The emissivity of the ground surface (i.e. the ability of the ground to absorb sunlight) was estimated based on published literature and modified during model calibration as discussed later in this memorandum. The input parameters for the atmospheric boundary condition are outlined in **Table 1**, with the selected parameters and assumptions for selecting the parameter.

The bottom of the model is a free drainage boundary condition to simulate deep percolation beyond the root zone.

Table 1: Atmospheric boundary condition inputs.

Parameter	Source	Value
Solar Radiation	On site meteorological station	Transient daily average
Maximum Temperature		Transient daily maximum
Minimum Temperature		Transient daily minimum
Humidity		Transient daily average
Wind Speed		Transient daily average
Precipitation		Transient 5-minute data
Grass Height	Field Survey	Constant 6 inches[3]
Albedo	Typical values for grass fields[1]	Constant 0.2
Root Depth	Typical values for wheatgrass[2]	Constant 45 inches (3.75 ft)
Emissivity	Model calibration	0.4

1. Dingman, 2008
2. Foxx et al, 1984
3. See **Attachment 1**

Leaf area index (LAI) was estimated as a function of grass height using the methods outlined in Allen et al 1996 and as shown below;

$$. \quad 0.5 * \quad 5.5 + 1.5 * \qquad (\;)$$

Where h is the grass height. The LAI was defined as a function of time to represent the growing season. During the late fall, winter, and early spring the grass is dormant and the LAI is set to 0. During the summer months as well as the late spring and early fall the LAI was set to a positive value. The transient LAI with time during the year is shown on **Figure 2**. The start and end of the growing season was defined based on the average first and last frost from *Plant Maps*. The LAI pattern shown on **Figure 2** is assumed to repeat annually regardless of annual changes in the start and end of the growing season.

Root water uptake is modeled using the Feddes function. Plant specific Feddes properties were selected from the built-in library of properties in Hydrus and assuming grass.

Variably Saturated Flow Model

The unsaturated soil hydraulic properties were modeled using the van Genuchten – Mualem equation. Hysteresis was not considered for numerical stability of the model. The soil hydraulic parameters were selected based on the built-in library of soil properties in HYDRUS and assuming a sandy clay loam. Field observation in the basin indicated that a sandy clay loam is representative of the near surface soils. Observations from the installation of the lysimeter as well as geotechnical test holes advanced in the basin (A.G. Wessener, 2013) indicate that there is vertical heterogeneity in the top 5 feet of the deposits. This vertical heterogeneity was not discretized in the model, but instead we assumed the average simulated soil properties were representative of the bulk soil column.

For the calibration model, the saturated hydraulic conductivity (k_s) of the soil was set as 0.95 ft/day based on the average interpreted k_s from seven mini disk infiltrometer tests conducted in the vicinity of the lysimeter core. For the basin wide simulation, the k_s of the soil was selected to be 0.99 ft/day based on the average hydraulic conductivity interpreted from 8 double ring infiltrometer tests conducted in the basin. See **Attachment 1** for a summary of the infiltration testing.

Model Calibration

The model was calibrated to observed soil moisture in the lysimeter at depths of 10 inches and 20 inches, total observed changes in water volume in the lysimeter, and measured seepage from the bottom of the lysimeter. For a detailed description of the lysimeter and the quality assurance and control conducted on the lysimeter observation data see Task 3A – *Site Specific Data Compilation*.

Emissivity was the only parameter modified during the calibration. The critical minimum allowable matric suction of the soil was modified for numeric stability as recommended in the Hydrus manual though was not directly modified as a calibration parameter. The calibrated emissivity of the ground surface was 0.4, which is slightly higher than the recommended value of 0.34 in HYDRUS 1-D. This slightly higher emissivity is within the range that would be expected for a natural surface.

Figure 3 is the simulated water content in the soil column compared to the observed soil column water content for a selected calibration period **Figure 3**. We calibrated the model to multiple periods of lysimeter data between June 2015 and May 2017. This calibration period presented in Figure 3 is a period which the lysimeter scale had been calibrated and where there were few to no identified errors in the readings from the QA/QC review of the lysimeter data (See Task 3A – *Site Specific Data Compilation*). Other calibration periods were used to further confirm the model results to observed data. The model closely simulated the timing and magnitude of changes in the water content in the soil column. The modeled and observed response to a storm event on April 28th and April 29th is the source of discrepancy in the model and measured water content. This difference is caused by an error in the lysimeter and does not represent an error in the calibration. The storm event has an observed magnitude of 0.5 inches, but the lysimeter measures a two inch increase in stored water. It is not possible for more water to enter storage than precipitated, therefore the measured spike in stored water in response to this storm event is in error. The modeled change in storage matches more closely the change in storage that would be expected from a 0.5 inch magnitude storm event.

The simulated water content at depths of 10 inches and 20 inches compared to measured water content values in the lysimeter is presented on **Figure 4**. Water content in the lysimeter is measured by two ECH2O 5TM soil moisture probes installed at depths of 10 inches and 20 inches below the top of the lysimeter. The simulated water content at 10 and 20 inches is generally 5% to 10% higher than observed and magnitude of moisture content spikes in response to storm events tends to be higher than observed. This difference may be a result of the soil moisture probes not being calibrated to the site specific soils. The instrument manual indicates that the un-calibrated results may vary by approximately 3%, but a literature review of the accuracy of soil moisture probes indicates it may be greater than the instrument manual indicates (Genjegunte, 2012). Additionally the higher observed moisture content, particularly in the magnitude of the moisture spikes, as well as that the model simulated greater changes in moisture content at the 20 inch probe, indicates the model simulates water penetrating deeper into the soil column than observed.

The simulated and observed deep percolation is presented in **Table 2** and **Figure 5**. The simulated deep percolation is 17% lower than observed. The error in the simulated deep percolation compared to the observed is 0.3% of the whole water balance, which is acceptable. Additionally it is important to note that; (1) the edges of the lysimeter were not sealed and water likely leaks preferentially around the edges along the soil lysimeter wall interface, and (2) suction is applied on the base of the lysimeter to extract the deep percolation and this suction is not simulated in the model. These two facts could explain the small error in the observed versus simulated deep percolation.

Table 2: Modeled versus observed deep percolation.

Year	Modeled Deep Percolation (in)	Observed Deep Percolation (in)
2010	0.00	-
2011	0.00	-
2012	0.00	-
2013	0.00	-
2014	0.00	0.00
2015	2.26	2.16
2016	0.01	0.53
2017	0.00	0.04
2018	0.00	0.00
Total	2.27	2.73

Basin Wide Soil Water Balance Results

The soil moisture balance on the basin scale was calculated by extrapolating the 1-D, or unit, water balance simulation across the basin. These results assume the average permeability of the surficial soils are representative of soil group C as discussed in *Task 3A*. The results of this analysis are applicable to other basins composed of surficial soils with a comparable permeability. The hydrologic parameters assumed in the analysis are representative of both soil groups. Total volumes of each component of the water balance were calculated by multiplying the simulated unit flux by the area of the basin upstream of the flume. All input parameters used in the calibration simulation were selected for the basin simulation except for the hydraulic conductivity of the soil and the allowable ponding. The hydraulic conductivity of the soil was set to 0.99 ft/day based on the site infiltration testing and the allowable ponding was set to 0.05 inches. For details on the site infiltration testing see Task 3B – *Site Characterization*.

The simulated water balance is presented on **Figure 6** and **Figure 7** and in **Table 3** for the modeling period for April 2010 through May 2018. Deep percolation, evaporation, and transpiration observations are not available therefore only simulated runoff values can be compared to observations at the Sterling Gulch flume. The simulated runoff plotted against the observed runoff is presented on **Figure 8** and tabulated in **Table 4**. The simulated runoff is approximately 129% greater than observed and is therefore conservative with regard to precipitation harvesting by overestimating the amount of runoff.

Table 3: Modeled Sterling Gulch soil moisture water balance for a modeling period from April 2010 through May 2018.

Water Balance Component	Modeled (in)	Modeled (acre-ft)[1]	Factor of Precipitation (%)
Precipitation	135.9	2527	100%
Runoff	3.5	65	3%
Evaporation	67.6	1257	50%
Transpiration	62.6	1164	46%
Deep Percolation	2.3	42	2%

1. Assumes a 223.2 acre drainage basin.

Table 4: Modeled Sterling Gulch basin runoff versus observed runoff.

Year	Modeled Runoff (Acre-Ft)	Observed Runoff (Acre-Ft)
2010	12.78	N/A
2011	3.48	0.14
2012	0.00	0.06
2013	1.87	1.41
2014	27.95	22.41*
2015	13.52	2.16
2016	0.49	1.99
2017	2.67	0.05
2018	1.89	0.00
Total	64.6	28.2

*we assumed the runoff to be 20 acre-ft greater than observed based an analytical calculations for storms that overtopped the weir. See Task 3B – *Site Specific Data Compilation* for more details.

Discussion and Conclusion

LRE used HYDRUS 1-D to model the basin water balance components runoff, evaporation, transpiration, and deep percolation for use in developing precipitation harvesting factors. The model was calibrated to observed deep percolation and soil water balance data from an on-site lysimeter and observed runoff in the drainage. Input data was taken from the onsite climate station, field infiltration testing, and field observations of the vegetation.

LRE calculated that over the 8-year modeling period 95% of recorded precipitation evaporates or transpires, 2% accrues to the stream by groundwater return flows, and 3% accrues to the stream by surface runoff, as shown on **Figure 7** and in **Table 3**. The calibrated model estimates downward soil moisture flux and deep percolation is 17% less than observed which is 0.3% of the total water balance. The difference in simulated and observed deep percolation is, based on our professional judgment and common modeling techniques, within an acceptable margin of error. Our simulated groundwater recharge rates (2%) are comparable to published literature from the South Platte Decision Support System Groundwater Flow Model (3%) from the Rio Grande Decision Support System Model (3%), and in the Republican River Basin groundwater flow model (2%) (Brown and Caldwell, 2017; Republican River Compact, 2003).

The simulated surface runoff is 129% greater than observed. The overestimate of runoff is potentially due to depression ponding and overland flow losses. Depression ponding and overland flow are 2-D effects that reduce actual surface water returns and are not considered in the 1-D Hydrus model. Additionally snow fall is not simulated in the Hydrus model. If snow melt was considered it would reduce the simulated surface water returns that are currently simulated during spring snowfall events. These results indicate the model is conservative with regard to simulated surface water returns.

We calculated that approximately 50% of precipitation evaporates and 46% of precipitation transpires. There are no direct measurements of ET available to compare the simulated ET to, but because the simulated runoff is greater than observed the simulated ET is likely less than actual ET. The overall error of simulated ET is estimated to be less than 1% of the total water budget and is within acceptable modeling error. The error is potentially from uncertainty in evaporation from depression ponds and ET from overland flow that is not considered in the 1-D analysis. Evaporation and transpiration was calculated in time steps of 5 minutes or less and the time series data is available upon request.

Limitations

The variably saturated flow model presented in this memorandum was developed for the explicit purpose of estimating the soil-water balance components of the Sterling Ranch basin and assisting in the development of precipitation harvesting factors. The model is not intended for use beyond this application. In addition, the accuracy of the model is limited by the site observations and simplifying assumptions described herein. The actual soil water balance is likely to vary from the simulation presented.

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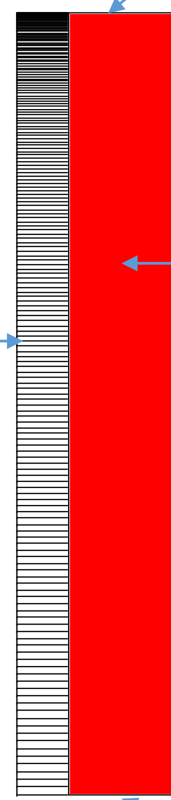

Note:
Definition of the vegetation allows for removal of water stored in the soil column by transpiration but is defined as part of the atmospheric boundary.

DATE: 1/14/2019

AUTHOR: JDB

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Figure 1
Hydrus Model Geometry and Boundary Conditions

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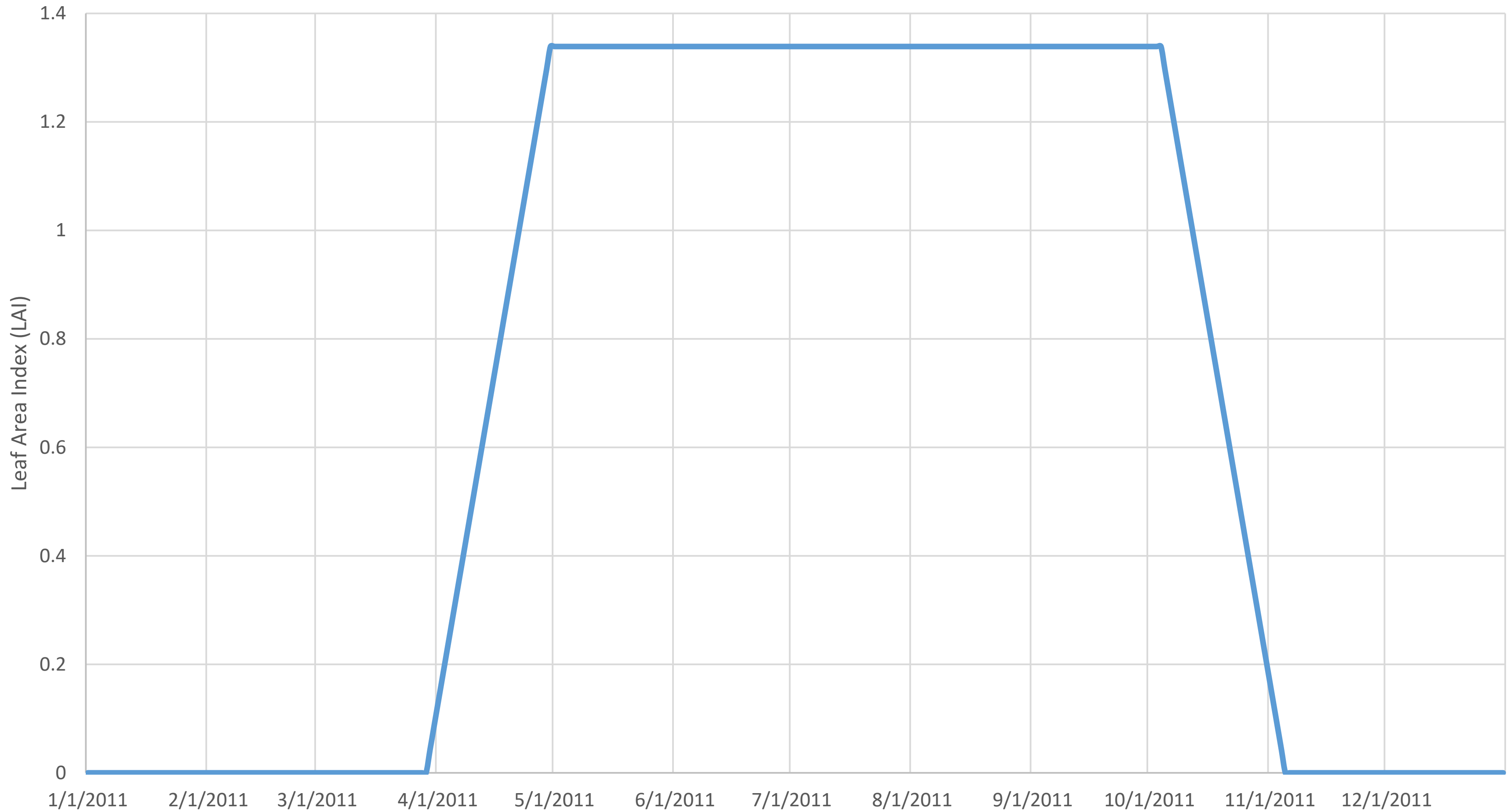

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Figure 2
Modeled Annual LAI

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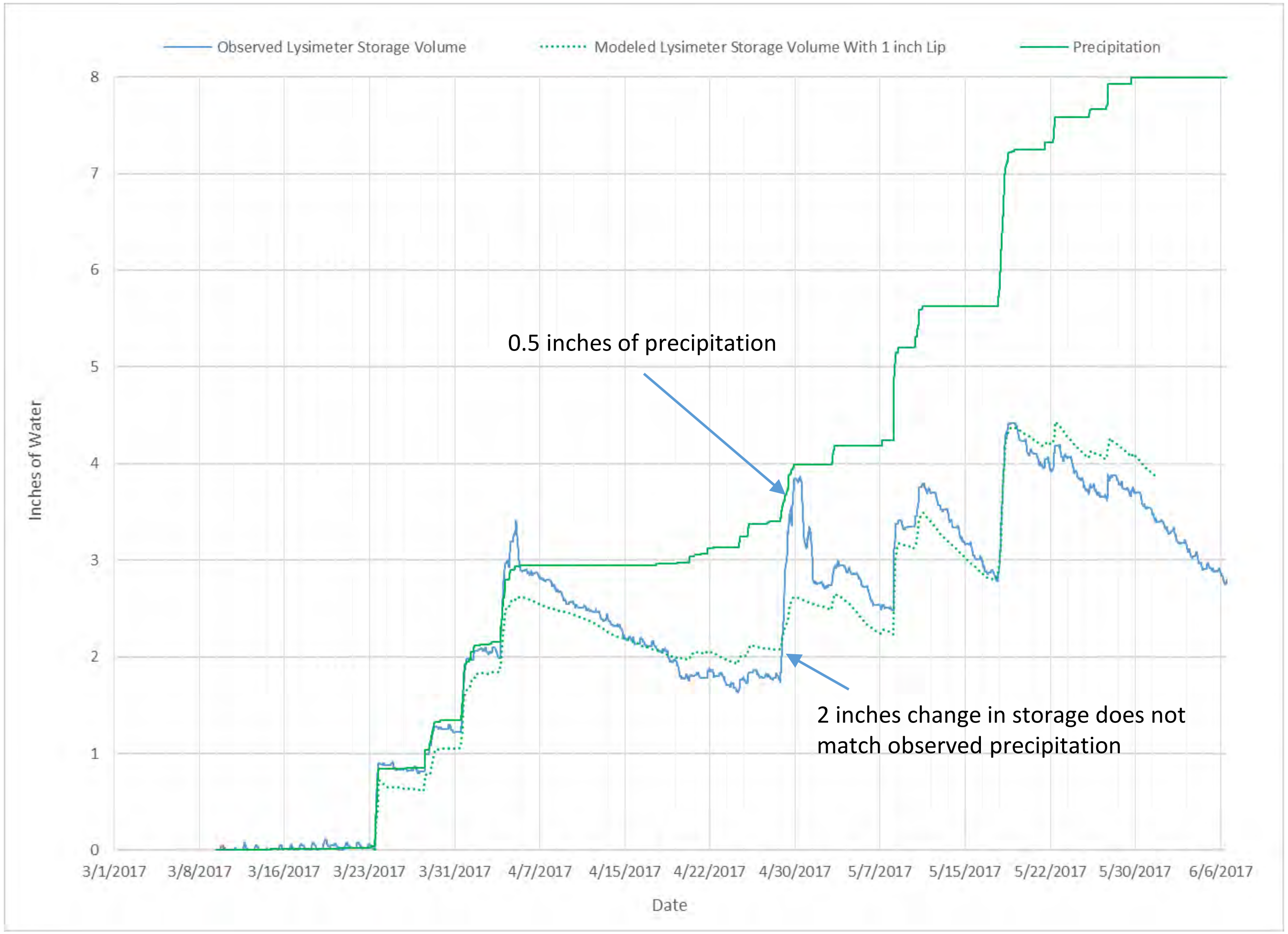

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Figure 3
Observed Versus Simulated Storage in the Lysimeter

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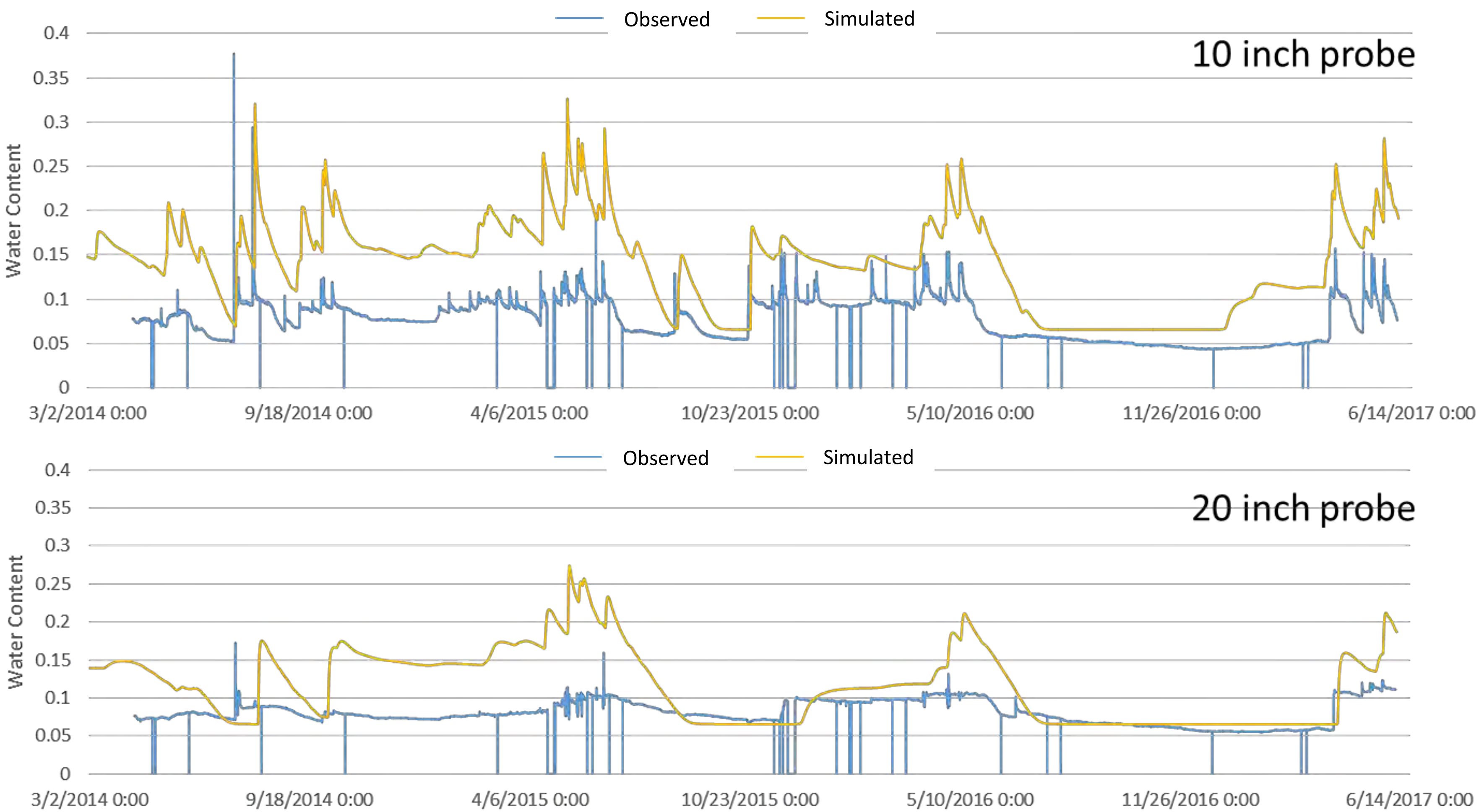

DATE: 8/2/2018 AUTHOR: JDB CHECKED BY:	Figure 4 Observed Versus Simulated Soil Moisture In Lysimeter	LeonardRice ENGINEERS, INC. 1221 Auraria Parkway | Denver, CO 80204 303-455-9589 | 800-453-9589 | Fax: 303-455-0115 www.LREwater.com

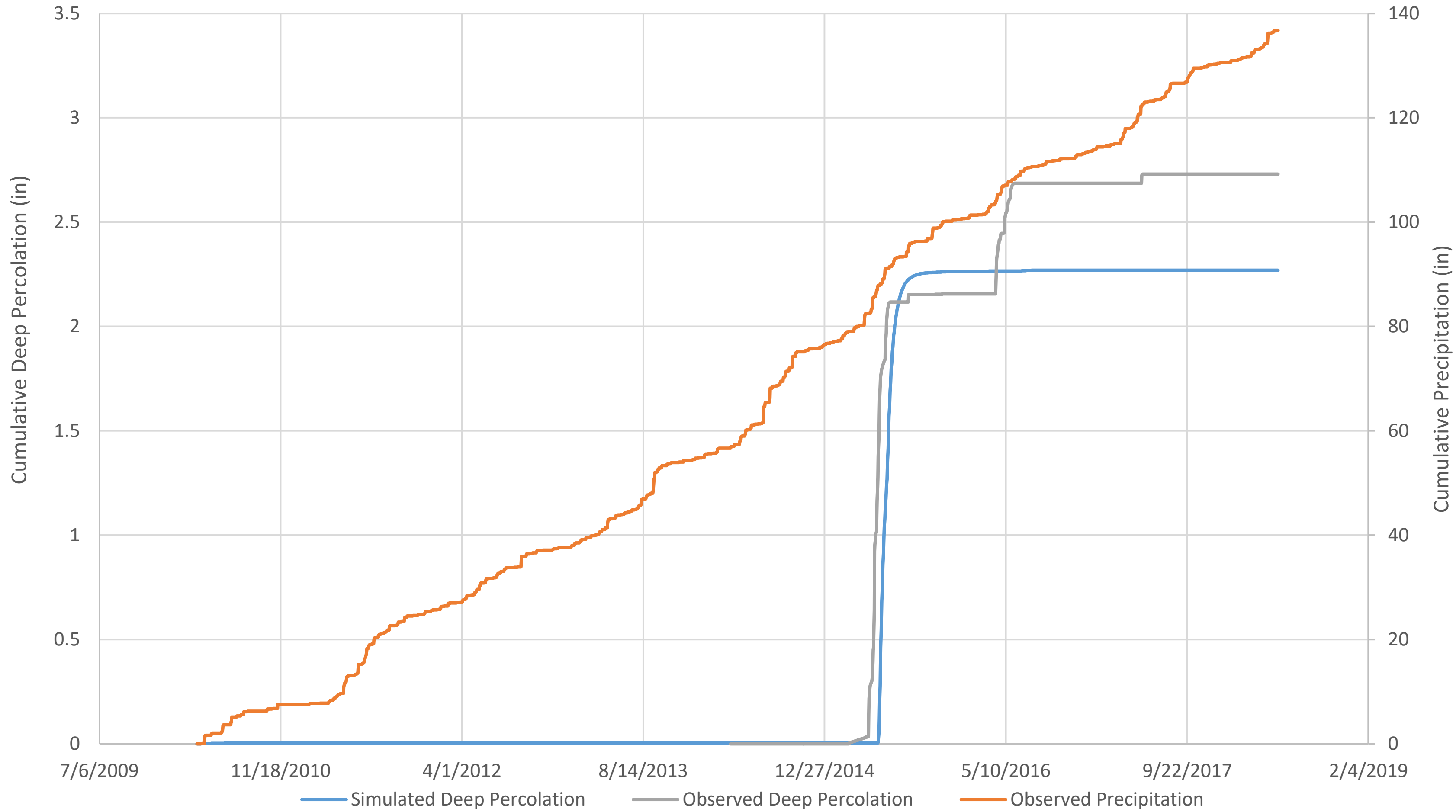

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Figure 5
Observed Versus Simulated
Deep Percolation in Lysimeter

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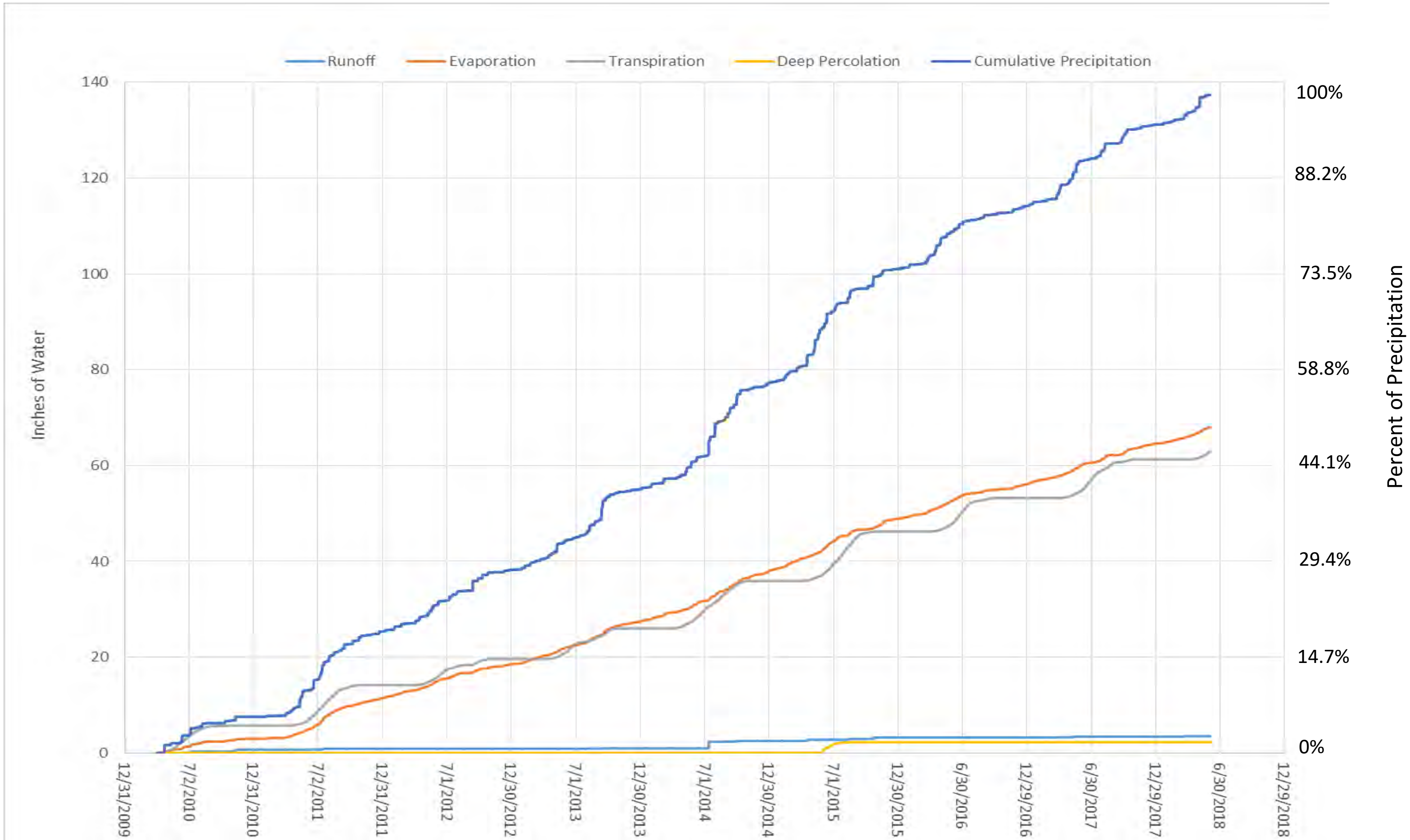

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Figure 6
Modeled Soil Water Balance

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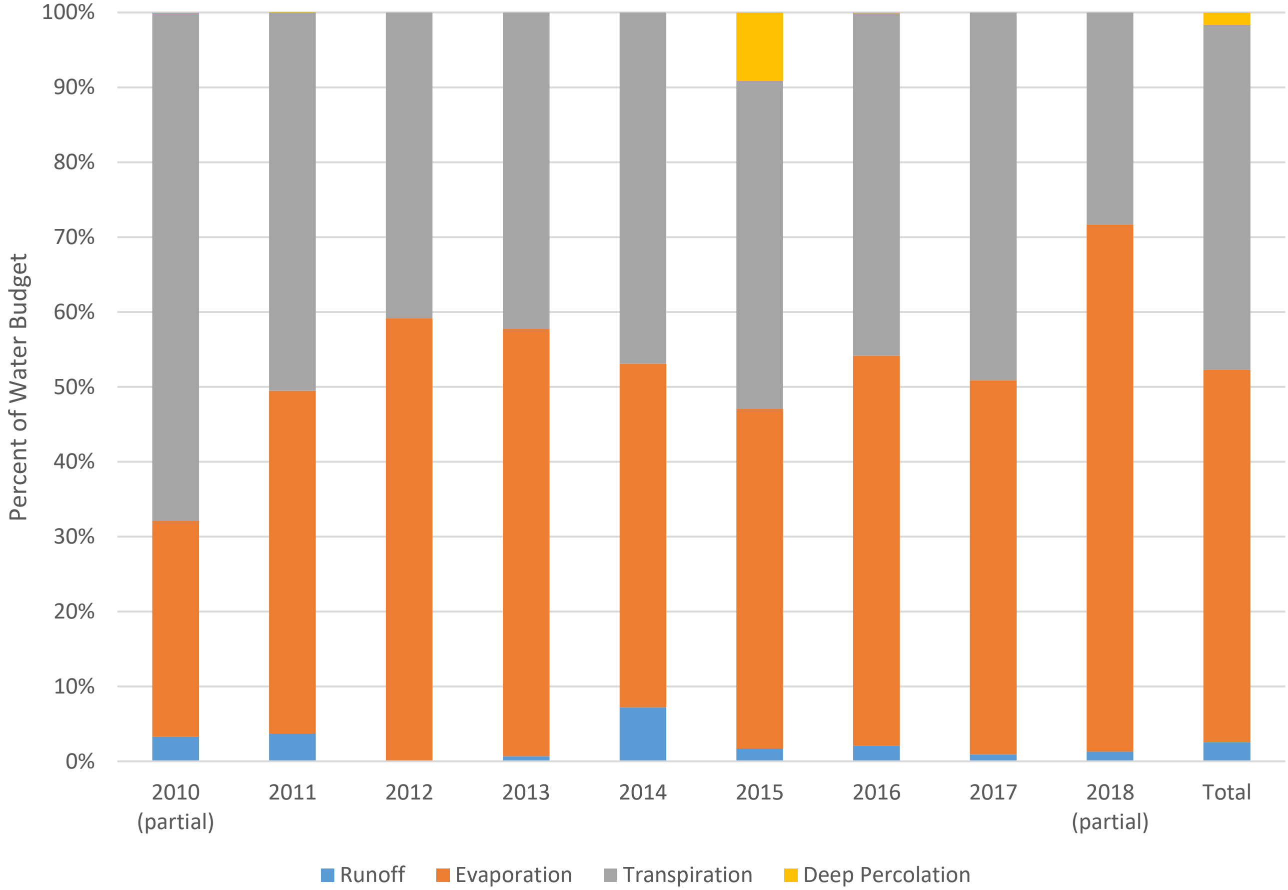

Note: Data normalized to filter out very small annual changes in storage so that water budget sums to exactly 100%.

DATE: 1/14/2019

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Figure 7
Annual an Average Water Balance

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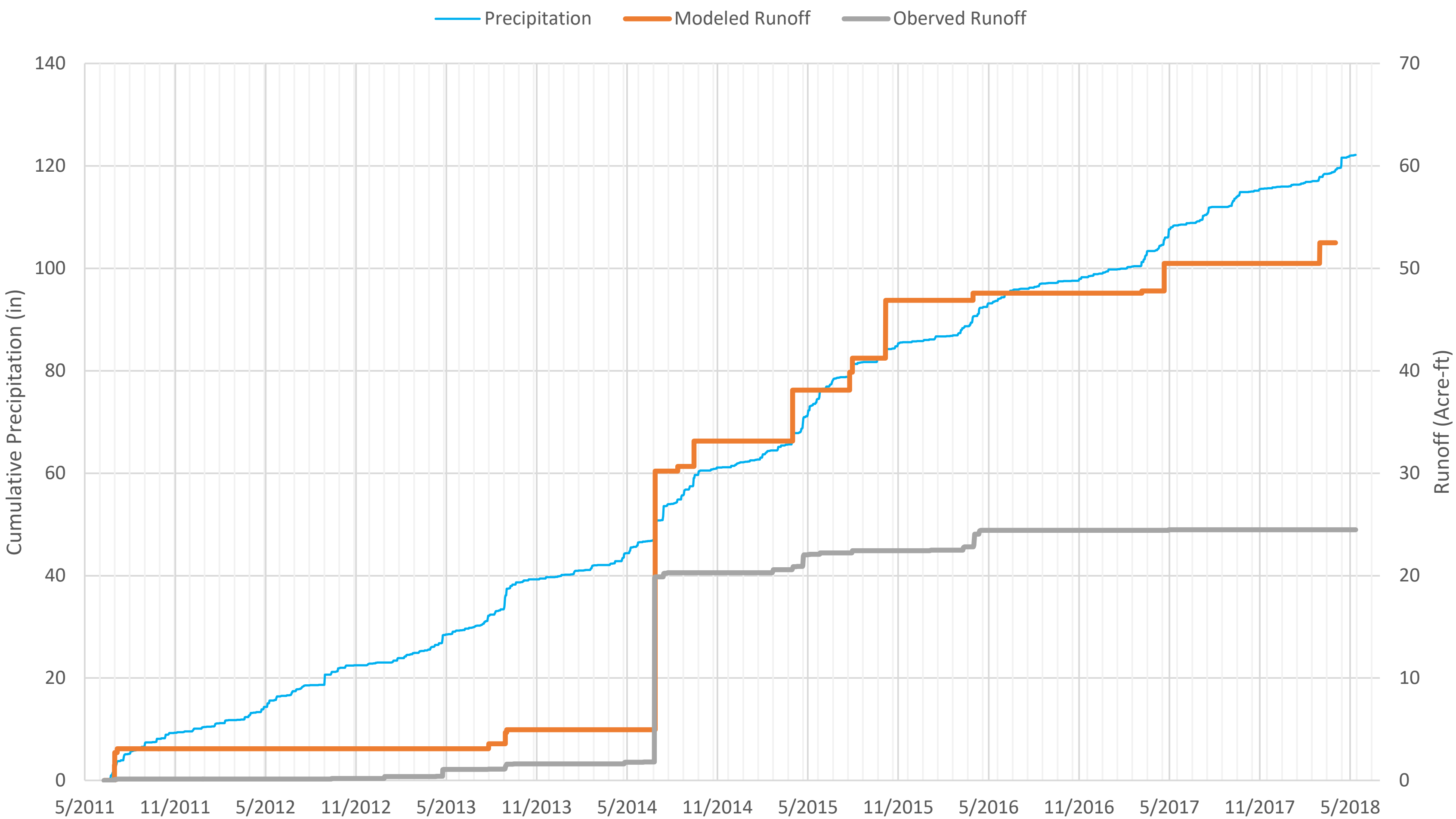

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Figure 8
Modeled Versus Observed
Runoff

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DRAFT - Memorandum

To:	Tracy Kosloff, Colorado Division of Water Resources
From:	Mark Mitisek, Leonard Rice Engineers, Inc.
Copy to:	Sarah Stone, Dominion Water and Sanitation District
Reviewed by:	Joel Barber and Greg Roush, Leonard Rice Engineers, Inc.
Date:	February 6, 2019
Project:	Colorado Water Plan Grant – Regional Factor Development for Precipitation Harvesting
Subject:	Task 4B – Site-Specific and Regional Surface Water Return Flows

Task Summary

The development of site-specific and regional runoff relationships provides a practical and conservative solution to quantifying surface return flows owed to the stream under pre-existing natural conditions. The use of these relationships in a Substitute Water Supply Plan (SWSP) provides the applicant with a simple method for administering precipitation harvesting while protecting downstream vested water rights. This task focuses on the development and support of site-specific and regional runoff relationships for hydrologic soil group C. This memorandum documents the development and application of a calibrated continuous runoff simulation model to:

- Quantify site-specific runoff (surface water return flows) at Sterling Ranch for each observed storm depth;
- Test the site-specific runoff relationship using readily available local and regional precipitation datasets to determine if the relationship is transferable on a local and regional scale.

This memorandum also documents the approach used to:

- Establish a site-specific runoff relationship (line or curve) that conservatively calculates the site-specific runoff (natural surface water return flow requirement) for all storm depths from 0 to 2.0 inches;
- Compare the basin total site-specific runoff (surface water return flows) simulated at Sterling Ranch to the observed runoff;
- Develop a regional runoff relationship (line or curve) that conservatively calculates the regional runoff (natural surface water return flow requirement) for all storm depths from 0 to 2.0 inches.

The information presented in this memorandum builds on the following task:

- Task 3A - Site-Specific Data Compilation
- Task 3B - Site Characterization
- Task 4A - Site-Specific Water Balance Model
- Task 4C - Site-Specific and Regional Deep Percolation

Please refer to these memorandums for additional information.

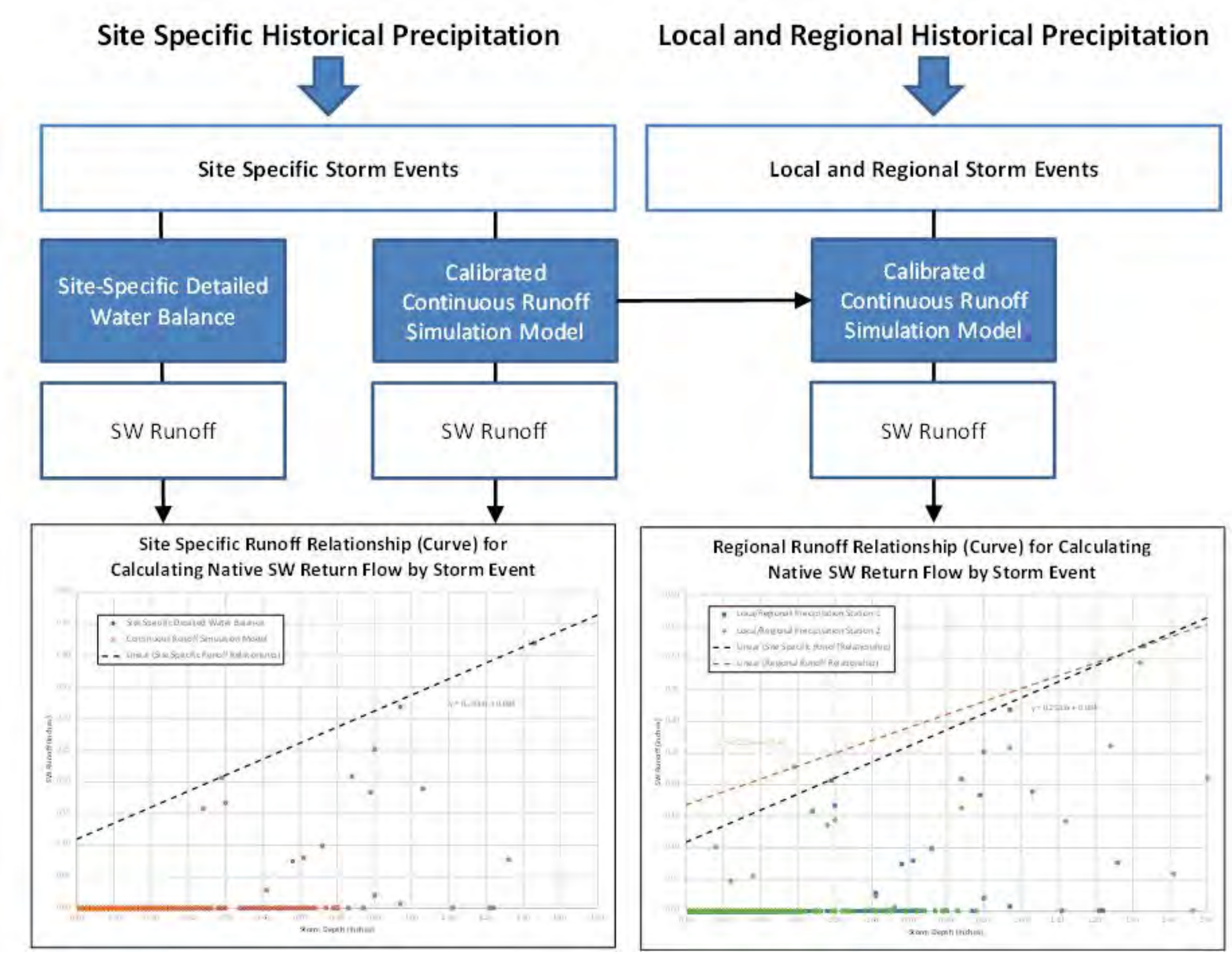
Approach for Developing Site-Specific and Regional Surface Runoff Relationships

A runoff relationship is a line or curve showing the maximum runoff (surface water return flow) for a given storm event (in inches) for a specific Hydrologic Soil Group. **Figure 1** shows an example of linear runoff relationships of site-specific and regional runoff by storm event. The site-specific runoff relationship is developed based on the maximum runoff simulated for each observed storm event. A line or curve is added and adjusted to fit to the upper bounds of the data. The result is a conservative prediction of runoff (surface water return flows) that is equal to or greater than the simulated or observed natural runoff. As shown in **Figure 1**, the observed and simulated runoff events plot below the established site-specific runoff relationship line.

To develop regional runoff relationships, the calibrated continuous runoff simulation model is used with local and regional precipitation datasets to simulate regional and local runoff. If simulated runoff from local and regional precipitation datasets exceeds the site-specific runoff relationship line, the line may be adjusted further to include additional storm event(s). As shown on **Figure 1**, the runoff relationship line encompasses both the simulated and observed runoff events, but the regional line was modified from the site-specific curve to encompass new observed events. Note that during this process there may be storm event outliers simulated or observed, which may be evaluated individually based on frequency to determine if events should be covered under the runoff relationship being established.

Because runoff is sensitive to the hydrologic properties of the native soils, regional runoff relationships (curves) are to be developed for each hydrologic soil group based on these methods. The runoff relationships developed and evaluated in this memorandum are only representative of hydrologic soil group C.

Figure 1 – Site-Specific and Regional Runoff Relationships Example



Continuous Runoff Simulation Model

Water Quality Capture Optimization Statistical Model (WQ-COSM) was selected for quantifying site-specific and regional surface water return flows and establishing runoff relationships. WQ-COSM is an Excel spreadsheet-based continuous simulation model that uses observed precipitation data and information about the catchment's hydrologic parameters to simulate runoff on a continuous basis. The WQ-COSM model uses the Rational, Horton, or Green-Ampt infiltration methods to simulate runoff for each storm event in the observed precipitation record for a defined hydrologic soil condition. The model includes all of the primary functions required for quantifying surface water return flows for each storm event and provides a common systematic platform for developing both site-specific and regional runoff relationships. The following sections describes the approach for development and calibration of a site-specific WQ-COSM representative of hydrologic soil group C, and the adjustments required to support site-specific and regional runoff relationships.

Model Development

As a part of this effort the WQ-COSM Excel spread-sheet was updated (Version 3.1) by Urban Waters Research Institute (UWRI) to allow for the use of high resolution precipitation datasets at multiple timesteps (e.g. 60-min, 15-min, 5-min, 1-min) and an impervious area percentage of 0% (0.01%) to represent pre-existing natural conditions. Previously, the model only simulated daily or hourly for impervious percentages of >= 1%. The WQ-COSM User's Manual (Attachment A) provides a clear description of the model, steps for developing the model, and a summary of all input parameters for various sites and soils conditions and infiltration methods. For the purposes of this study the Horton infiltration method was selected as the most universally applicable infiltration method supported by the stormwater community. For the Horton infiltration method/runoff model the following WQ-COSM inputs parameters are required:

Rainfall Processing Parameters:

5-Minute Continuous Precipitation Dataset (inches): *The Sterling Ranch Climate Station 5-minute precipitation dataset compiled in Task 3A – Data Compilation was formatted using the standard National Climate Data Center (NCDC) format for use in the model. All observed precipitation from March 29, 2010 to May 31, 2018 is included. Timesteps without precipitation are not required for the simulation and are recommended to be removed.*

Drying Separation Period for New Storms (hours): *WQ-COSM utilizes a separation period to define individual storm events from the precipitation record. For the purposes of this study a separation period of 3-hours was used to define storm events. This means that the observation of precipitation must be separated by three consecutive hours of no observed precipitation to be defined as a new storm event with a discrete storm depth.*

Minimum Storm Depth Needed for Runoff (inches): *The program allows for the filtering-out of "trace" amounts of precipitation as being not relevant to the surface runoff process. In this Study, the minimum storm depth of >=0.11 inches were selected for simulation in WQ-COSM. Storms less than 0.11 inches are not expected to produce runoff from undeveloped watersheds and are not included in the continuous simulations of rainfall/runoff.*

Runoff Processing Parameters:

Catchment Imperviousness (%): *WQ-COSM allows up to ten impervious percentages to be evaluated simultaneously. However, for the purposes of this study only 0.01% (~0%) was used to represent natural pre-existing conditions.*

Storm Runoff Outlier Exclusion (%): *Upon simulation of runoff from the observed storm events the WQ-COSM allows users to exclude storm runoff events to be evaluated for water quality capture volumes using a set upper percentile of runoff. Storms that exceed the percentile (outliers) are excluded from the reporting. Although this parameter is useful for evaluating water quality capture volumes it was not used for this analysis.*

Drying Period (Days): *The drying period in days is the time required for the catchment to recover its initial infiltration rate and its depression storage capacity. Suggested drying periods for various soil types are found in Table A5 in the WQ-COSM User's Manual (Attachment 1). At Sterling Ranch average drying time of 2.5 days was observed at the lysimeter, which was represented in the model using the 3-days, which is the middle of the recommended range for semi-arid regions and the minimum drying period WQ-COSM input.*

Horton Parameters:

Horton Infiltration Parameters: *To determine the infiltration rate using Horton the user must define the initial and final infiltration rates (in/hr) as well as the infiltration decay coefficient (1/hr). These values are site-specific and depend on the soil and vegetative cover complex. Soil type is the most important factor in determining the infiltration rate. Table A2 and A3 in the WQ-COSM User's Manual (Attachment 1) describe the default parameters representative for each soil type. Note that Horton initial infiltration rates are highly sensitive and the primary parameter used for calibration.*

Depression Storage (inches): *Depression storage refers to precipitation that is collected and held in small depressions and does not runoff. This water eventually infiltrates or is evaporated. WQ-COSM allows the user to define values of depression storage for pervious and impervious areas. However, for the purposes of this study only pervious depressions storage is required to represent natural pre-existing conditions. Table A4 in the WQ-COSM User's Manual (Attachment 1) can be used as a guide in estimating the amount of depression losses to be used.*

The WQ-COSM model developed for Sterling Ranch represents the hydrologic soil group C. The input parameters were selected using recommended values presented in the WQ-COSM guide as well as supported by site-specific observed infiltration rates and drying-times. Using the approach and input parameters summarized above, the WQ-COSM was used to simulate site-specific runoff for the available period of record using Horton infiltration method.

Model Results/Output

WQ-COSM is an Excel spreadsheet/VBA model that is executed by clicking the "Run WQ-COSM" button on the Input Summary worksheet. Upon execution of the model there are two output worksheets populated which are used in this analysis. Below is a description of each:

Storm Data: *The Storm Data worksheet shows the processed continuous rainfall data and identifies the individual storm that each precipitation increment is associated with. The individual storms are determined by the user provided Dry Period separation time (hours). The individual storms exclude small non-runoff producing storms as defined by the user. The runoff volume (inches) and runoff rate (cfs) associated with each incremental precipitation depth is also shown on this worksheet. The incremental storm depths and runoff summarized in this worksheet allow storm events to be summarized on a daily basis.*

All Storms Summary: *The All Storms Summary worksheet shows all runoff producing storms. Instead of showing all of the incremental depths like the Storm Data worksheet does, the All Storms Summary worksheet sums the incremental rainfall and runoff depths within each storm to provide the total rainfall and runoff for each storm event. The All Storms Summary worksheet also includes the storm start and end date/time, storm duration (hours), and storm separation time. This is the primary output used in this analysis to evaluate the relationship between individual storm events (storm depth) and runoff providing the basis for developing site-specific and regional runoff relationships.*

Model Calibration

The site-specific WQ-COSM for Hydrologic Soil Group C was calibrated to match simulated surface water return flows (runoff) from the detailed water balance (Hydrus 1-D) presented in Task 4A – Site-Specific Water Balance Memo. It was determined early on that calibrating WQ-COSM to individual storm events simulated by the detailed water balance (Hydrus 1-D) would result in hundreds of model runs with specific intensities, durations, frequencies, and drying times. None of which is practical or applicable on a regional scale. Therefore the calibration of WQ-COSM focused on total runoff and pattern of runoff for the period.

Calibration was completed by varying the initial infiltration rate until the linear relationship between storm depth and runoff was the same as the relationship simulated by the detailed water balance model. It was found that an initial infiltration rate of 2.775 inches/hr provides a matching relationship for Hydrologic Soil Group C for storm events observed March through October. **Figure 2** below shows the final WQ-COSM input parameters used.

Figure 2 – WQ-COSM Input Parameters

Input Parameters Summary Sheet
WQ-COSM v3.1 (November 2018)

Project I.D. and Rainfall Processing Parameters

NOAA Precipitation Data Filepath & Name:	..\..\Datasets\SterlingRanch_ClimateStation\precip_5min_Formatted_NoZeroes.csv				
Precipitation Data Station Name:	**Sterling Ranch Climate Station**				
Project/Study Location:	**Sterling Ranch Runoff Modeling**				
Dry Period Separation for New Storm:	3	hours	NOAA Precipitation Unit Time:		
Minimum Storm Depth Needed for Runoff:	0.11	in		5	min

Runoff Processing Parameters

Catchment Imperviousness:	0%	10%	20%	30%	40%
(At least one imperviousness value required, others are optional)	50%	60%	70%	80%	90%

Storm Runoff Outlier Exclusion (Upper % Outlier):	99.0%	
Drying Period:	3	days
Runoff Model:	Horton	

Horton

Initial Infiltration Rate:	2.775	in/hr
Final Infiltration Rate:	0.09	in/hr
Infiltration Decay Coefficient:	3.00	1/hr
Pervious Depression Storage:	0.35	in
Impervious Depression Storage:	0.10	in

The **Figure 3** below shows the simulated runoff (surface water return flows) from the detailed water balance (Hydrus 1-D) and the calibrated WQ-COSM for Hydrologic Soil Group C at Sterling Ranch. The plot confirms that the linear relationship between simulated runoff and storm depth are the same and the WQ-COSM is calibrated. The following linear relationship is the starting point for establishing the site-specific runoff relationship.

$$y = 0.0342x - 0.0066 \qquad \text{(equation 1)}$$

x = Storm Depth (inches)
y= SW Runoff (Return Flow)
0.0066 = Y-intercept
0.0342 = Slope

The final WQ-COSM calibration is also confirmed by the cumulative runoff and total for the period compared to the detailed water balance (Hydrus 1-D) in **Figure 7** below. The figure shows the timing and magnitude of surface runoff events are similar and the total cumulative runoff are nearly the same.

Site-Specific Runoff Relationship Adjustments

The linear relationship shown in **Figure 3** is the mathematical "best-fit" line for all simulated storm events. However, there are multiple runoff events that are above the line, so this relationship should not be used directly to conservatively calculate surface return flows for all storm events. To account for runoff from as many observed storm events as possible further adjustments are required. Below is a description of the five adjustments:

Slope Adjustment Factor – Slope determines the steepness or angle of the linear relationship between the adjustment factor scales the slope up (+ factor) or down (- factor).

Y-Intercept (inches) - The y-intercept is the point on the y-axis that the linear relationship crosses representing the minimum runoff owed to the stream.

Minimum Storm (inches) – The minimum storm depth (x) resulting in simulated runoff.

Groundwater Return Flow Factor (%) – Groundwater return flow factors are the percentage of a storm event that accrues to the stream system via groundwater return flows. The groundwater return flow factor for Hydrologic Group C = 3% (Task 4C – Site-Specific and Regional Deep Percolation). The groundwater return flow factor must be included to determine the maximum depletion.

Maximum Depletion – The maximum depletion is the amount of precipitation that can physically enter the soil and/or be evaporated or transpired for any storm event. This is cap is generally only applied to large storm events.

Table 1 summarizes each of the recommended adjustments to the site-specific linear runoff relationship (equation 1).

Table 1 – Site-Specific Runoff Relationship Adjustments

Slope Adjustment Factor	Y-Intercept (inches)	Minimum Storm (inches)	GW Return Flow Factor (%)	Max Depletion (inches)
1.95	0.09	0.25	3%	1.35

After completion of adjustments to the site-specific linear runoff relationship it is recommended that the final site-specific runoff relationship be expressed as an exponential function to smooth the transition and remove the inflection point associated with the set maximum depletion. Below are the final adjusted linear and exponential relationships.

$$y = 0.0667x + 0.09 \quad \text{(equation 2)}$$

$$y = 0.0698e^{1.0728x} \quad \text{(equation 3)}$$

Site-Specific Runoff Relationship

Figure 4 is a plot that shows the final site-specific linear and exponential runoff relationships for Sterling Ranch representative of hydrologic soil group C. These relationships capture nearly all (linear = 100% and exponential = 99.6%) of the simulated storm events at Sterling Ranch. The figure also shows the point at which the maximum natural depletion of 1.35 inches is reached for both the linear and exponential relationships. This is the point where physically no additional precipitation can enter the soil and/or be evaporated or transpired for any storm event.

As you can see in **Figure 4** the use of and exponential function smooths the transition associated with a set maximum depletion resulting in a better representation of runoff from storm depths >0.55 inches. The graphs also shows the range of runoff for each storm depth with some storms resulting in higher runoff than others. This has to do with the intensity, duration, and frequency of rainfall and whether infiltration capacity is reduced or full. By using the upper bounds of the simulated storms as the basis of the site-specific runoff relationship it captures a wide range of storm conditions.

Site-Specific Administrative Runoff Relationship

Administrative runoff is the defined surface water return flow requirement in percent for each incremental storm depth (inches). The administrative runoff relationship was developed for direct use in administrative accounting and the evaluation of the applicability of the site-specific runoff relationship regionally. The administrative runoff relationship is based upon the exponential site-specific runoff relationship (equation 3) applied to all incremental storm depths from 0.0 inches to 5.0 inches. The result is a site-specific administrative runoff relationship of runoff (inches and %) for every storm depth (Table 2). **Figure 5 and 6** show the final site-specific administrative runoff relationship on a volume (inches) and percentage basis.

Site-Specific Runoff on a Basin Scale

To compare the simulated and administered runoff (based on Table 2) to the observed runoff at the Sterling Ranch the simulated and administered runoff were multiplied by the development area of 223.2 acres and summarized daily. The cumulative daily runoff (March through October) was calculated for each dataset. **Figure 7** shows the cumulative simulated runoff from the detailed water balance (Hydrus 1-D), WQ-COSM, the administrative runoff, and the actual observed runoff from the Sterling Gulch flume for each pilot project year. On a cumulative volume basis the administrative runoff far exceeds the simulated and observed runoff at Sterling Ranch showing the site-specific administrative runoff relationship is very conservative and protective to downstream vested water rights.

Regional Runoff Relationship Validation

Readily available local and regional precipitation datasets along the Front Range of Colorado were used to confirm the validity of the site-specific administrative runoff relationship established and determine if the relationship is transferable on a local and regional scale. **Table 3** summarizes the stations selected. **Figure 8** is a map showing the spatial distribution of the precipitation stations selected. These stations were selected based upon on location and proximity to urban areas, the available period-of-record, and the resolution of available precipitation datasets (i.e. only stations with 5-minute data were selected).

Table 3 – Local Regional Precipitation Stations

Station ID	Station Name	City/Town	Start Date	End Date	Source
6011	Sterling Ranch	Sterling Ranch	4/1/2010	5/31/2018	Dominion/OneRain
2710	Highlands Ranch WTP	Highlands Ranch	11/19/2009	6/19/2018	UDFCD/OneRain
2750	Castle Rock	Castle Rock	11/19/2009	6/19/2018	UDFCD/OneRain
10028	Diamond Hill	Denver	12/19/2008	12/8/2018	UDFCD/OneRain
4360	Justice Center	Boulder	1/20/2011	12/8/2018	UDFCD/OneRain
2730	Salisbury Park	Parker	12/19/2008	12/8/2018	UDFCD/OneRain
700	Tollgate At 6th	Aurora	12/19/2008	12/8/2018	UDFCD/OneRain
384908104453301	South Academy Blvd	Colorado Springs	4/1/2011	12/19/2018	USGS (Colorado Springs Engineering)
394028104565501	Harvard Gulch at University Park	Denver	5/6/2009	12/19/2018	USGS (UDFCD)
6708690	West Plum Creek	Sedalia	4/2/2015	12/19/2018	USGS (Town of Castle Rock)

Sources: UDFCD/OneRain = https://udfcd.onerain.com/map/?view=3f0489de-3933-42b2-bea1-b3e00c03947e
USGS = https://co.water.usgs.gov/infodata/COPrecip/index.html

A continuous runoff simulation model was developed for each station using the calibrated WQ-COSM input parameters shown in **Figure 2** above and local and regional precipitation datasets. The point of this effort was to include additional local rainfall datasets in the WQ-COSM model to determine if unexpected results would occur after additional simulations. Results were processed for each station individually showing the WQ-COSM simulated runoff for each storm event compared to the site-specific administrative runoff relationship from **Table 2**. **Attachment 2** summarizes the simulated runoff relationships at each station during the months of March through October. The summary tables include volume and counts of simulated runoff, storm events, and administrative runoff broken out for storm events (<=0.25 inches, >= 0.25 or <= 1.0 inch, and >1.0 inch). The summaries also show the volume and count of simulated runoff above and below the line established by the site-specific administrative runoff relationship.

Results

Table 4 through Table 7 summarize the results from **Attachment 2** of total volume and counts of storm events, simulated runoff volume, and storm event volume for all observed storm events at Sterling Ranch and at each local or regional station (March-October). The tables show the count or volume of events or runoff that are above or below the line established by the site-specific administrative runoff relationship. Below is a summary of key statistics from each table:

- **Total Storm Event Summary (Table 4)** - From the ten stations evaluated (including Sterling Ranch) a total of 2,229 storm events were observed. Of 2,229 storm events observed 97.6%

(2,176) storm events are below the line established by the site-specific administrative runoff relationship.

- **Total Storm Event Volume (Table 5)** - From the ten stations evaluated (including Sterling Ranch) the total storm event volume observed was 843.3 inches. Of the 843.3 inches of total storm event volume observed 98.8% (833.32 inches) is below the line established by the site-specific administrative runoff relationship.

- **Total WQ-COSM Simulated Runoff Volume (Table 6)** - The site-specific administrative runoff relationship captures 78.5% (36.6 inches) of simulated runoff volume from observed storm events for all stations (including Sterling Ranch). The 21.5% (9.98 inches) of runoff volume that is not captured by this relationship is primarily (72.2%, 7.21 inches) the result of larger magnitude (>1 inch) and/or sequential storm events with insufficient drying times.

- **Total Administrative Runoff Volume (Table 7)** – By comparing the total WQ-COSM simulated runoff volume (to the total administrative runoff volume from the site-specific administrative runoff relationship for the ten stations evaluated (including Sterling Ranch) the net impact to the river can be determined. Table 7 shows 3.0 times (138.14 inches/46.58 inches) more volume benefit to the river by using the site-specific administrative runoff relationship.

Conclusions and Recommendations

Below are the conclusions and recommendations based on the results from this analysis:

- The site-specific administrative runoff relationship developed is representative 97.6% of observed storm events and 98.8% of the total storm event volume. Therefore the site-specific administrative runoff relationship is applicable regionally for conservatively quantifying surface water return flows required to the stream system. The site-specific administrative runoff relationship can be used directly to support Substitute Water Supply Plans (SWSP) for conservatively quantifying the native pre-existing surface water return flows required for individual storm events.

- Because the site-specific administrative runoff relationship is applied to all storm events individually and return flow obligations are calculated for all events > 0.25 inches the cumulative returns (i.e. replacements) far exceed any shortages associated with these type sequential storm events. **Figure 7** shows a plot of cumulative simulated, observed, and administrative runoff (i.e. the regional runoff relationship) at Sterling Ranch. The figure shows that the cumulative runoff (surface returns) is 12.8X (25.63 AF/329.08 AF) greater than the observed runoff, and 7.1X (46.29 AF/329.08 AF) greater than the simulated runoff. Therefore the use of the site-specific administrative runoff relationship regionally for the administration of precipitation harvesting is more than sufficient for protecting downstream vested water rights from a volumetric perspective.

- As established in Task 2, surface water runoff is defined as the maximum amount of potential runoff from a storm event at the soil before conveyance losses or channel routing. The simulated surface runoff shown in the tables in figures are at the soil before conveyance losses or channel routing. The result is a conservative representation of surface water runoff.

- The site-specific administrative runoff relationship captures 78.5% of all simulated runoff volume from observed storm events from all stations (including Sterling Ranch). The 21.5% of runoff volume that is not captured by this relationship is primarily the result of larger magnitude (>1 inch) and/or sequential storm events with insufficient drying times.

- Several of the storm events not captured by the site-specific administrative runoff relationship are associated with the September 2013 flood event impacting the majority of the Front Range. These extreme events are infrequent and highly variable. Additional investigation is recommended to determine the frequency of individual storm events to determine if the event should be covered under the established site-specific administrative runoff relationship.

- The timing, magnitude, duration, and frequency of sequential events are highly variable. A less conservative adjustment of the site-specific administrative runoff relationship is only justified if paired with the simulated result from WQ-COSM. The only way to account for timing and volume of sequential events systematically from all stations is to run WQ-COSM. If the simulated runoff from WQ-COSM exceeds the adjusted site-specific administrative runoff relationship the applicant would need to replace the simulated amount. From an accounting perspective this additional step would insure all events are being accounted for in timing and amount.

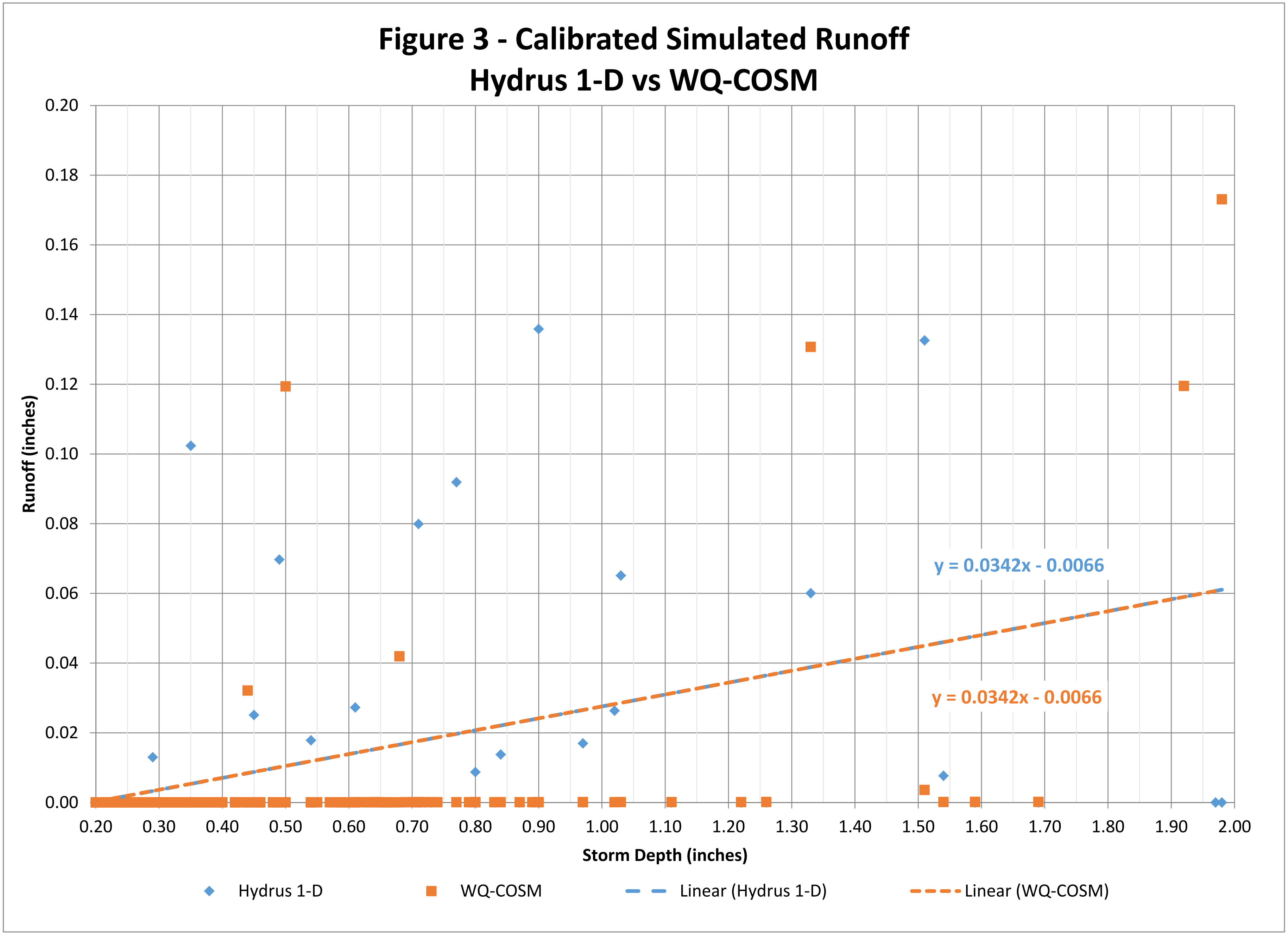


Figure 3 - Calibrated Simulated Runoff
Hydrus 1-D vs WQ-COSM
Runoff (inches)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70 1.80 1.90 2.00
Storm Depth (inches)
y = 0.0342x - 0.0066
y = 0.0342x - 0.0066
Hydrus 1-D
WQ-COSM
Linear (Hydrus 1-D)
Linear (WQ-COSM)

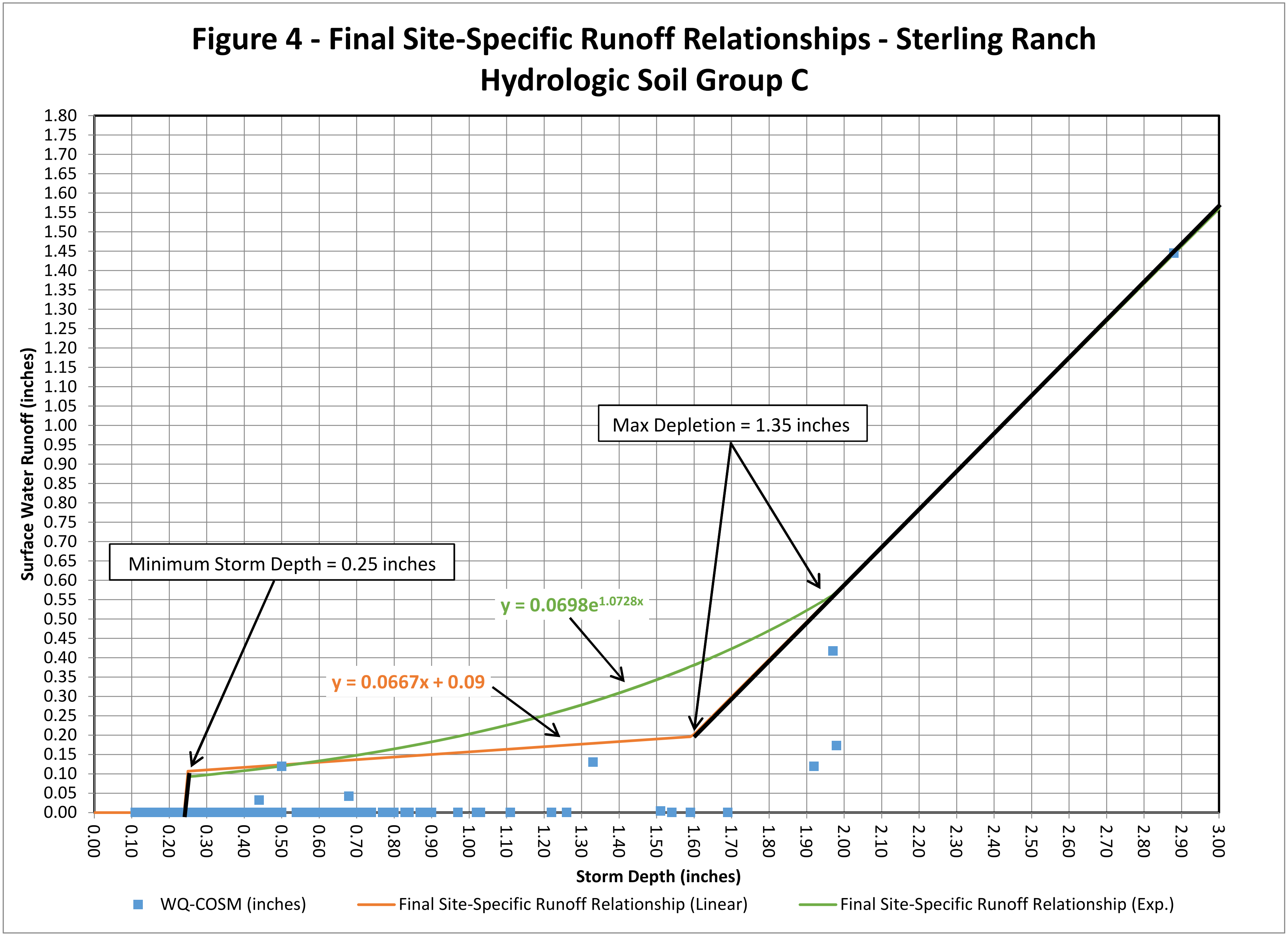


Figure 4 - Final Site-Specific Runoff Relationships - Sterling Ranch
Hydrologic Soil Group C
Surface Water Runoff (inches)
Storm Depth (inches)
1.80
1.75
1.70
1.65
1.60
1.55
1.50
1.45
1.40
1.35
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20
2.30
2.40
2.50
2.60
2.70
2.80
2.90
3.00
Max Depletion = 1.35 inches
Minimum Storm Depth = 0.25 inches
y = 0.0698e^1.0728x
y = 0.0667x + 0.09
WQ-COSM (inches)
Final Site-Specific Runoff Relationship (Linear)
Final Site-Specific Runoff Relationship (Exp.)

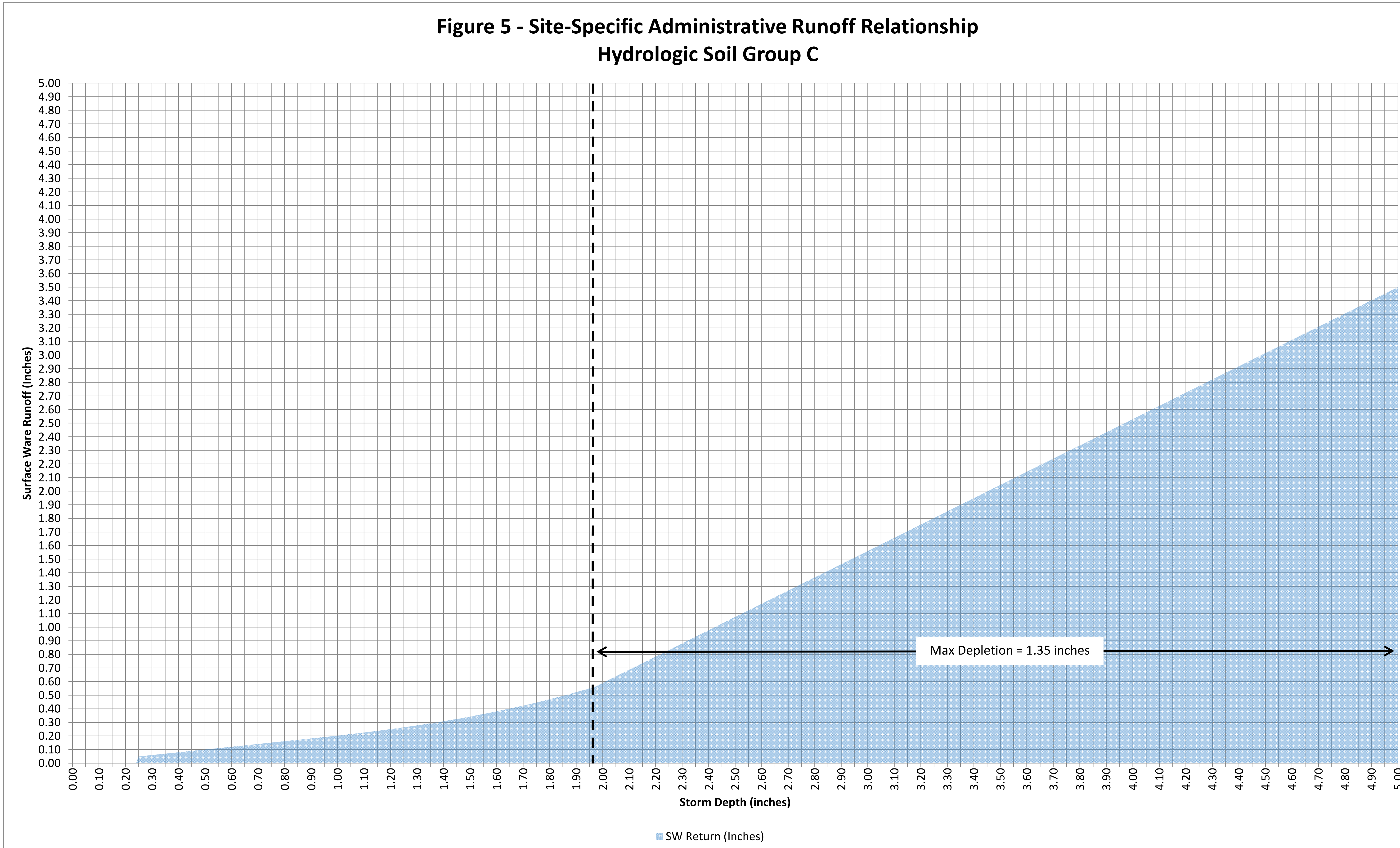
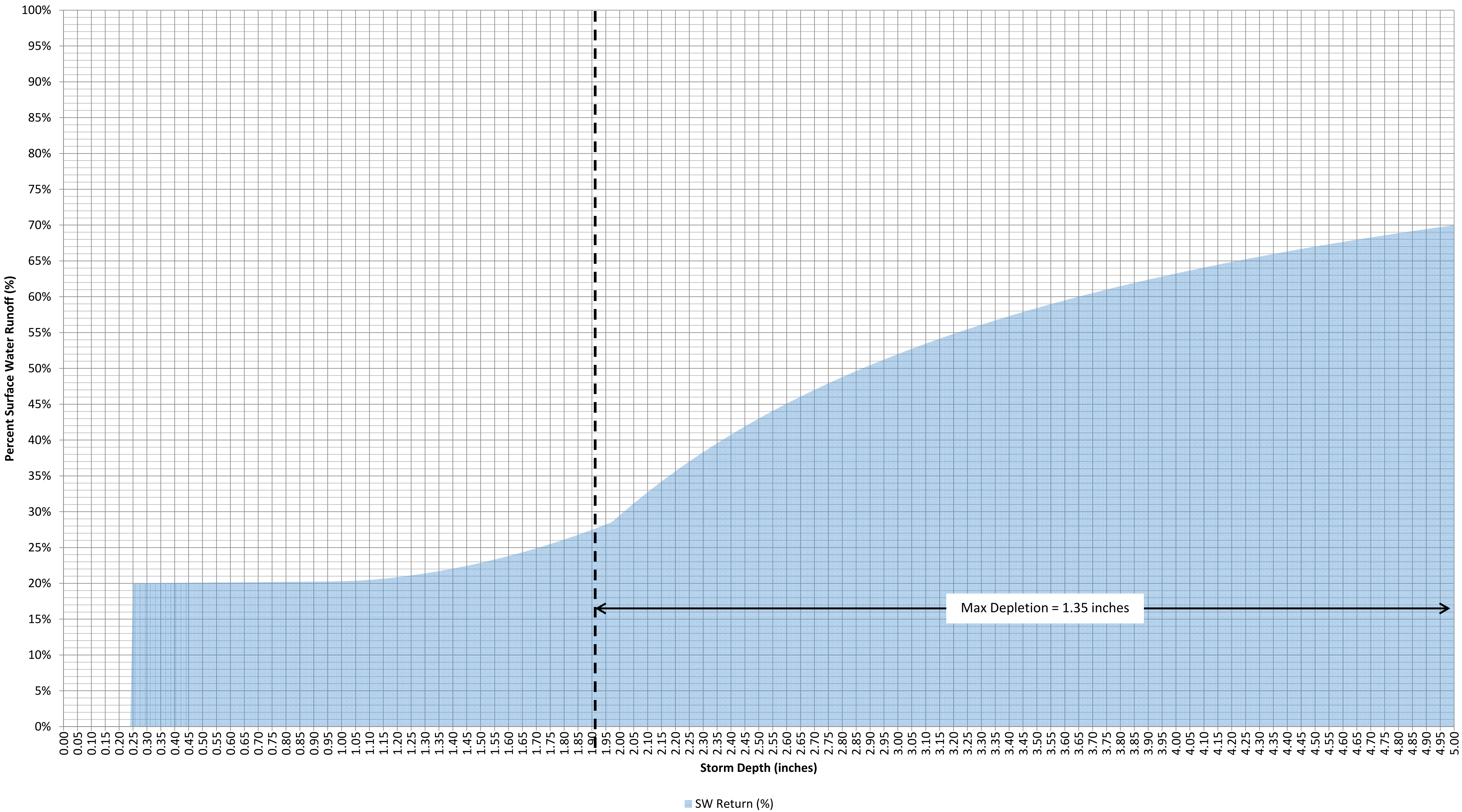


Figure 5 - Site-Specific Administrative Runoff Relationship
Hydrologic Soil Group C
Surface Ware Runoff (Inches)
Storm Depth (inches)
Max Depletion = 1.35 inches
SW Return (Inches)

Figure 6 - Site-Specific Administrative Runoff Relationship
Hydrologic Soil Group C



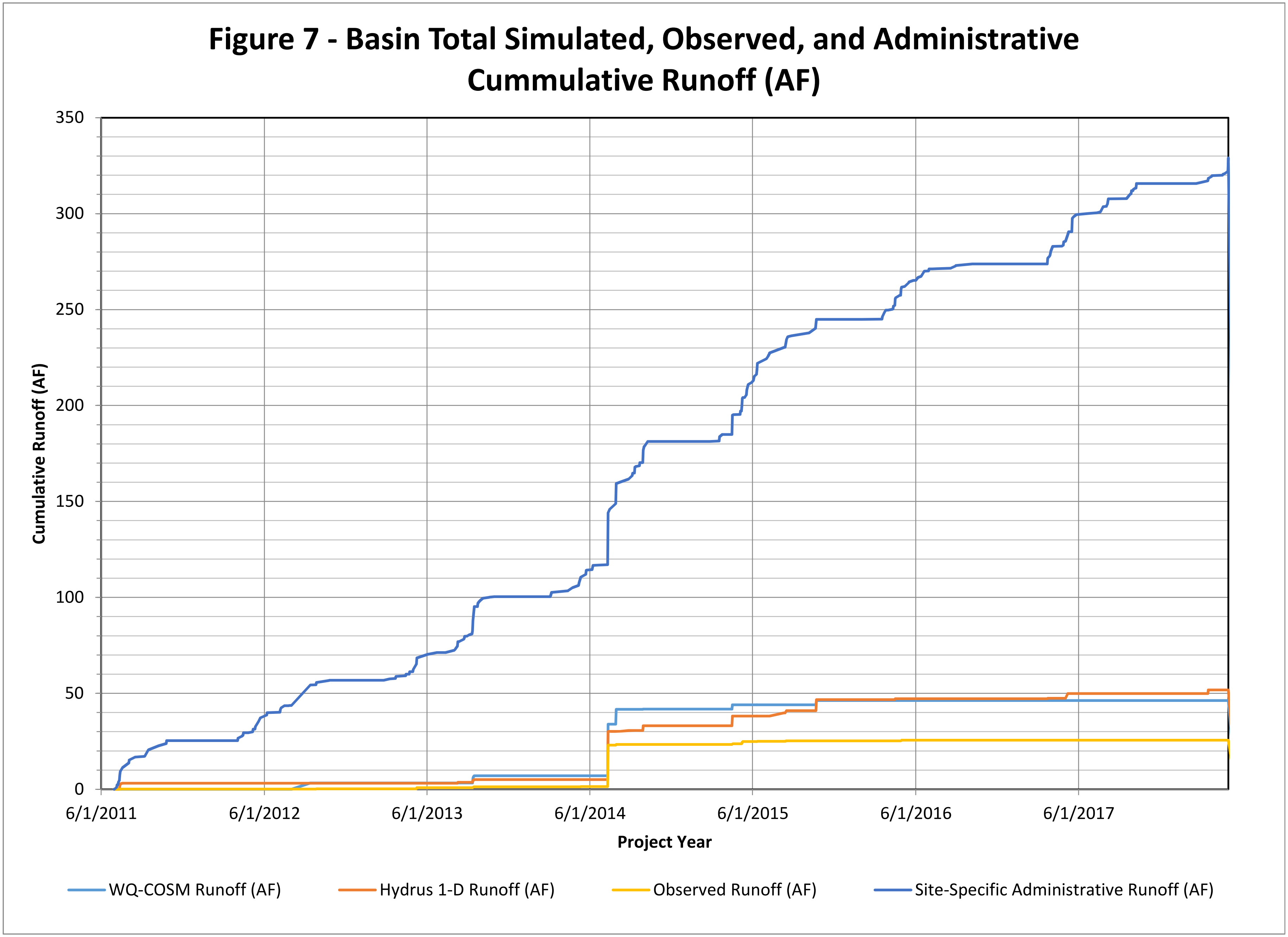
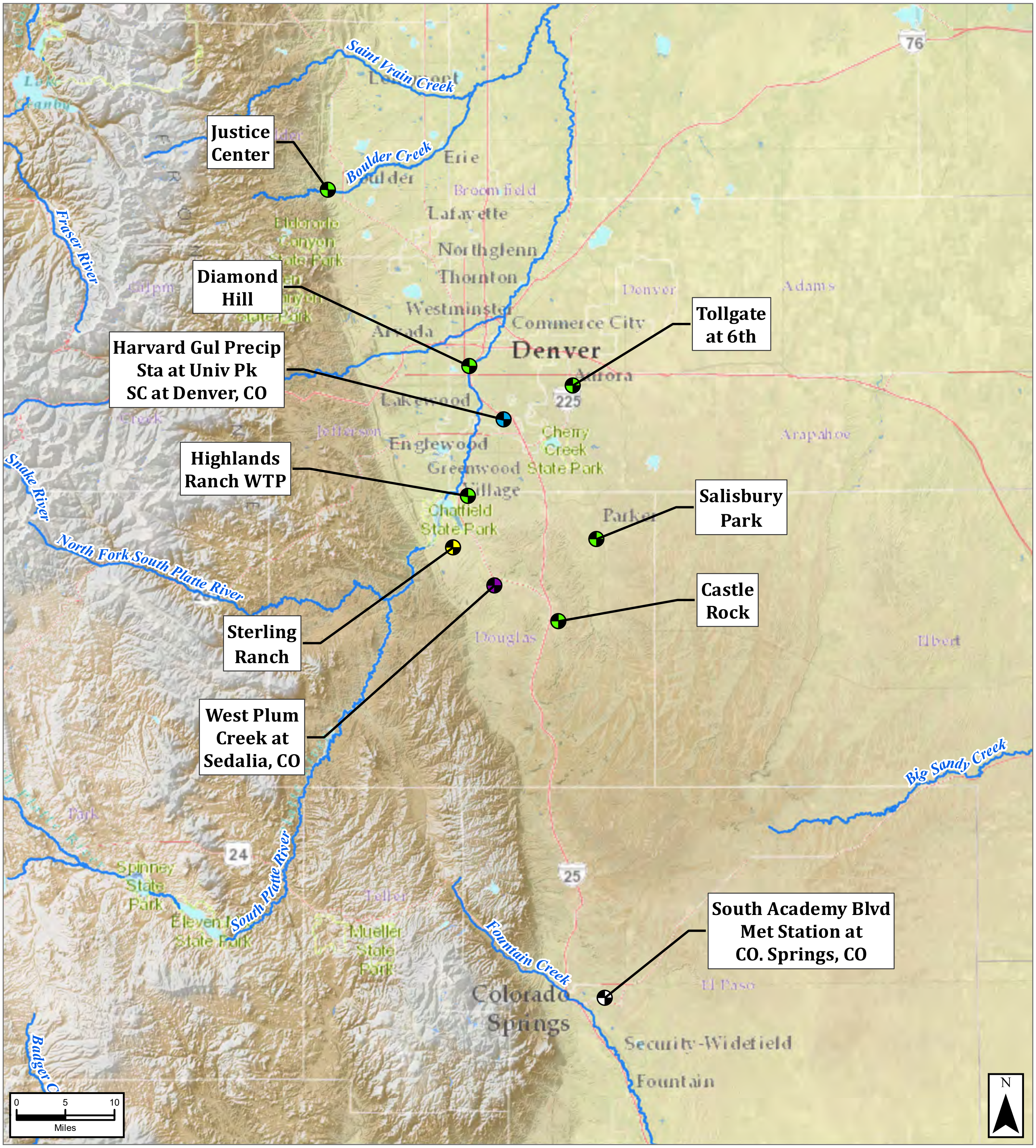
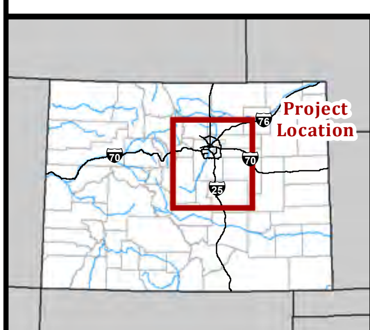


Figure 7 - Basin Total Simulated, Observed, and Administrative Cummulative Runoff (AF)
350
300
250
200
150
100
50
0
Cumulative Runoff (AF)
6/1/2011
6/1/2012
6/1/2013
6/1/2014
6/1/2015
6/1/2016
6/1/2017
Project Year
WQ-COSM Runoff (AF)
Hydrus 1-D Runoff (AF)
Observed Runoff (AF)
Site-Specific Administrative Runoff (AF)





Legend

- Dominion Water & Sanitation District
- Urban Drainage Flood Control District
- USGS (Colorado Springs Engineering and Emergency Management)
- USGS (Town of Castle Rock)
- USGS (UDFCD)

This product is for reference purposes only and is not to be construed as a legal document or survey instrument.

FIGURE 8
LOCAL AND REGIONAL PRECIPITATION STATIONS

LeonardRice ENGINEERS, INC

1207DOM02
12/22/2018

Path: U:\1207DOM_Dominion\02_Rainwater\04_SW3 Potential Funding - CWP Grant\Task4 - Site Specific and Regional Factor Development\WQ-COSM\Datasets\GIS\StationMap.mxd

Table 2 - Site-Specific Administrative Runoff Relationship (Sterling Ranch)
Hydrologic Soil Group C

Storm Depth (inches)	SW Return (Inches)	SW Return (%)
0.00	0.00	0.00%
0.01	0.00	0.00%
0.02	0.00	0.00%
0.03	0.00	0.00%
0.04	0.00	0.00%
0.05	0.00	0.00%
0.06	0.00	0.00%
0.07	0.00	0.00%
0.08	0.00	0.00%
0.09	0.00	0.00%
0.10	0.00	0.00%
0.11	0.00	0.00%
0.12	0.00	0.00%
0.13	0.00	0.00%
0.14	0.00	0.00%
0.15	0.00	0.00%
0.16	0.00	0.00%
0.17	0.00	0.00%
0.18	0.00	0.00%
0.19	0.00	0.00%
0.20	0.00	0.00%
0.21	0.00	0.00%
0.22	0.00	0.00%
0.23	0.00	0.00%
0.24	0.00	0.00%
0.25	0.05	20.00%
0.26	0.05	20.00%
0.27	0.05	20.01%
0.28	0.06	20.01%
0.29	0.06	20.01%
0.30	0.06	20.02%
0.31	0.06	20.02%
0.32	0.06	20.03%
0.33	0.07	20.03%
0.34	0.07	20.03%
0.35	0.07	20.04%
0.36	0.07	20.04%

Storm Depth (inches)	SW Return (Inches)	SW Return (%)
0.37	0.07	20.04%
0.38	0.08	20.05%
0.39	0.08	20.05%
0.40	0.08	20.06%
0.41	0.08	20.06%
0.42	0.08	20.06%
0.43	0.09	20.07%
0.44	0.09	20.07%
0.45	0.09	20.07%
0.46	0.09	20.08%
0.47	0.09	20.08%
0.48	0.10	20.09%
0.49	0.10	20.09%
0.50	0.10	20.09%
0.51	0.10	20.10%
0.52	0.10	20.10%
0.53	0.11	20.10%
0.54	0.11	20.11%
0.55	0.11	20.11%
0.56	0.11	20.12%
0.57	0.11	20.12%
0.58	0.12	20.12%
0.59	0.12	20.13%
0.60	0.12	20.13%
0.61	0.12	20.13%
0.62	0.12	20.14%
0.63	0.13	20.14%
0.64	0.13	20.15%
0.65	0.13	20.15%
0.66	0.13	20.15%
0.67	0.14	20.16%
0.68	0.14	20.16%
0.69	0.14	20.16%
0.70	0.14	20.17%
0.71	0.14	20.17%
0.72	0.15	20.18%
0.73	0.15	20.18%
0.74	0.15	20.18%
0.75	0.15	20.19%
0.76	0.15	20.19%

Storm Depth (inches)	SW Return (Inches)	SW Return (%)
0.77	0.16	20.19%
0.78	0.16	20.20%
0.79	0.16	20.20%
0.80	0.16	20.21%
0.81	0.16	20.21%
0.82	0.17	20.21%
0.83	0.17	20.22%
0.84	0.17	20.22%
0.85	0.17	20.22%
0.86	0.17	20.23%
0.87	0.18	20.23%
0.88	0.18	20.24%
0.89	0.18	20.24%
0.90	0.18	20.24%
0.91	0.18	20.25%
0.92	0.19	20.25%
0.93	0.19	20.25%
0.94	0.19	20.26%
0.95	0.19	20.26%
0.96	0.19	20.27%
0.97	0.20	20.27%
0.98	0.20	20.27%
0.99	0.20	20.28%
1.00	0.20	20.29%
1.01	0.21	20.30%
1.02	0.21	20.31%
1.03	0.21	20.33%
1.04	0.21	20.35%
1.05	0.21	20.36%
1.06	0.22	20.39%
1.07	0.22	20.41%
1.08	0.22	20.43%
1.09	0.22	20.46%
1.10	0.23	20.49%
1.11	0.23	20.52%
1.12	0.23	20.55%
1.13	0.23	20.58%
1.14	0.24	20.62%
1.15	0.24	20.65%
1.16	0.24	20.69%

Storm Depth (inches)	SW Return (Inches)	SW Return (%)
1.17	0.24	20.73%
1.18	0.25	20.77%
1.19	0.25	20.81%
1.20	0.25	20.86%
1.21	0.25	20.90%
1.22	0.26	20.95%
1.23	0.26	21.00%
1.24	0.26	21.05%
1.25	0.26	21.10%
1.26	0.27	21.16%
1.27	0.27	21.21%
1.28	0.27	21.27%
1.29	0.28	21.33%
1.30	0.28	21.39%
1.31	0.28	21.45%
1.32	0.28	21.51%
1.33	0.29	21.57%
1.34	0.29	21.64%
1.35	0.29	21.70%
1.36	0.30	21.77%
1.37	0.30	21.84%
1.38	0.30	21.91%
1.39	0.31	21.98%
1.40	0.31	22.06%
1.41	0.31	22.13%
1.42	0.32	22.21%
1.43	0.32	22.29%
1.44	0.32	22.36%
1.45	0.33	22.44%
1.46	0.33	22.53%
1.47	0.33	22.61%
1.48	0.34	22.69%
1.49	0.34	22.78%
1.50	0.34	22.87%
1.51	0.35	22.95%
1.52	0.35	23.04%
1.53	0.35	23.13%
1.54	0.36	23.23%
1.55	0.36	23.32%
1.56	0.37	23.42%

Storm Depth (inches)	SW Return (Inches)	SW Return (%)
1.57	0.37	23.51%
1.58	0.37	23.61%
1.59	0.38	23.71%
1.60	0.38	23.81%
1.61	0.38	23.91%
1.62	0.39	24.01%
1.63	0.39	24.12%
1.64	0.40	24.23%
1.65	0.40	24.33%
1.66	0.41	24.44%
1.67	0.41	24.55%
1.68	0.41	24.66%
1.69	0.42	24.78%
1.70	0.42	24.89%
1.71	0.43	25.01%
1.72	0.43	25.12%
1.73	0.44	25.24%
1.74	0.44	25.36%
1.75	0.45	25.48%
1.76	0.45	25.60%
1.77	0.46	25.73%
1.78	0.46	25.85%
1.79	0.47	25.98%
1.80	0.47	26.11%
1.81	0.47	26.24%
1.82	0.48	26.37%
1.83	0.49	26.50%
1.84	0.49	26.64%
1.85	0.50	26.77%
1.86	0.50	26.91%
1.87	0.51	27.05%
1.88	0.51	27.19%
1.89	0.52	27.33%
1.90	0.52	27.47%
1.91	0.53	27.62%
1.92	0.53	27.76%
1.93	0.54	27.91%
1.94	0.54	28.06%
1.95	0.55	28.21%
1.96	0.56	28.36%

Storm Depth (inches)	SW Return (Inches)	SW Return (%)
1.97	0.56	28.52%
1.98	0.57	28.82%
1.99	0.58	29.16%
2.00	0.59	29.50%
2.01	0.60	29.84%
2.02	0.61	30.17%
2.03	0.62	30.50%
2.04	0.63	30.82%
2.05	0.64	31.15%
2.06	0.65	31.47%
2.07	0.66	31.78%
2.08	0.67	32.10%
2.09	0.68	32.41%
2.10	0.69	32.71%
2.11	0.70	33.02%
2.12	0.71	33.32%
2.13	0.72	33.62%
2.14	0.73	33.92%
2.15	0.74	34.21%
2.16	0.75	34.50%
2.17	0.75	34.79%
2.18	0.76	35.07%
2.19	0.77	35.36%
2.20	0.78	35.64%
2.21	0.79	35.91%
2.22	0.80	36.19%
2.23	0.81	36.46%
2.24	0.82	36.73%
2.25	0.83	37.00%
2.26	0.84	37.27%
2.27	0.85	37.53%
2.28	0.86	37.79%
2.29	0.87	38.05%
2.30	0.88	38.30%
2.31	0.89	38.56%
2.32	0.90	38.81%
2.33	0.91	39.06%
2.34	0.92	39.31%
2.35	0.93	39.55%
2.36	0.94	39.80%

Storm Depth (inches)	SW Return (Inches)	SW Return (%)
2.37	0.95	40.04%
2.38	0.96	40.28%
2.39	0.97	40.51%
2.40	0.98	40.75%
2.41	0.99	40.98%
2.42	1.00	41.21%
2.43	1.01	41.44%
2.44	1.02	41.67%
2.45	1.03	41.90%
2.46	1.04	42.12%
2.47	1.05	42.34%
2.48	1.06	42.56%
2.49	1.07	42.78%
2.50	1.08	43.00%
2.51	1.08	43.22%
2.52	1.09	43.43%
2.53	1.10	43.64%
2.54	1.11	43.85%
2.55	1.12	44.06%
2.56	1.13	44.27%
2.57	1.14	44.47%
2.58	1.15	44.67%
2.59	1.16	44.88%
2.60	1.17	45.08%
2.61	1.18	45.28%
2.62	1.19	45.47%
2.63	1.20	45.67%
2.64	1.21	45.86%
2.65	1.22	46.06%
2.66	1.23	46.25%
2.67	1.24	46.44%
2.68	1.25	46.63%
2.69	1.26	46.81%
2.70	1.27	47.00%
2.71	1.28	47.18%
2.72	1.29	47.37%
2.73	1.30	47.55%
2.74	1.31	47.73%
2.75	1.32	47.91%
2.76	1.33	48.09%

Storm Depth (inches)	SW Return (Inches)	SW Return (%)
2.77	1.34	48.26%
2.78	1.35	48.44%
2.79	1.36	48.61%
2.80	1.37	48.79%
2.81	1.38	48.96%
2.82	1.39	49.13%
2.83	1.40	49.30%
2.84	1.40	49.46%
2.85	1.41	49.63%
2.86	1.42	49.80%
2.87	1.43	49.96%
2.88	1.44	50.13%
2.89	1.45	50.29%
2.90	1.46	50.45%
2.91	1.47	50.61%
2.92	1.48	50.77%
2.93	1.49	50.92%
2.94	1.50	51.08%
2.95	1.51	51.24%
2.96	1.52	51.39%
2.97	1.53	51.55%
2.98	1.54	51.70%
2.99	1.55	51.85%
3.00	1.56	52.00%
3.01	1.57	52.15%
3.02	1.58	52.30%
3.03	1.59	52.45%
3.04	1.60	52.59%
3.05	1.61	52.74%
3.06	1.62	52.88%
3.07	1.63	53.03%
3.08	1.64	53.17%
3.09	1.65	53.31%
3.10	1.66	53.45%
3.11	1.67	53.59%
3.12	1.68	53.73%
3.13	1.69	53.87%
3.14	1.70	54.01%
3.15	1.71	54.14%
3.16	1.72	54.28%

Storm Depth (inches)	SW Return (Inches)	SW Return (%)
3.17	1.72	54.41%
3.18	1.73	54.55%
3.19	1.74	54.68%
3.20	1.75	54.81%
3.21	1.76	54.94%
3.22	1.77	55.07%
3.23	1.78	55.20%
3.24	1.79	55.33%
3.25	1.80	55.46%
3.26	1.81	55.59%
3.27	1.82	55.72%
3.28	1.83	55.84%
3.29	1.84	55.97%
3.30	1.85	56.09%
3.31	1.86	56.21%
3.32	1.87	56.34%
3.33	1.88	56.46%
3.34	1.89	56.58%
3.35	1.90	56.70%
3.36	1.91	56.82%
3.37	1.92	56.94%
3.38	1.93	57.06%
3.39	1.94	57.18%
3.40	1.95	57.29%
3.41	1.96	57.41%
3.42	1.97	57.53%
3.43	1.98	57.64%
3.44	1.99	57.76%
3.45	2.00	57.87%
3.46	2.01	57.98%
3.47	2.02	58.10%
3.48	2.03	58.21%
3.49	2.04	58.32%
3.50	2.05	58.43%
3.51	2.05	58.54%
3.52	2.06	58.65%
3.53	2.07	58.76%
3.54	2.08	58.86%
3.55	2.09	58.97%
3.56	2.10	59.08%

Storm Depth (inches)	SW Return (Inches)	SW Return (%)
3.57	2.11	59.18%
3.58	2.12	59.29%
3.59	2.13	59.40%
3.60	2.14	59.50%
3.61	2.15	59.60%
3.62	2.16	59.71%
3.63	2.17	59.81%
3.64	2.18	59.91%
3.65	2.19	60.01%
3.66	2.20	60.11%
3.67	2.21	60.22%
3.68	2.22	60.32%
3.69	2.23	60.41%
3.70	2.24	60.51%
3.71	2.25	60.61%
3.72	2.26	60.71%
3.73	2.27	60.81%
3.74	2.28	60.90%
3.75	2.29	61.00%
3.76	2.30	61.10%
3.77	2.31	61.19%
3.78	2.32	61.29%
3.79	2.33	61.38%
3.80	2.34	61.47%
3.81	2.35	61.57%
3.82	2.36	61.66%
3.83	2.37	61.75%
3.84	2.37	61.84%
3.85	2.38	61.94%
3.86	2.39	62.03%
3.87	2.40	62.12%
3.88	2.41	62.21%
3.89	2.42	62.30%
3.90	2.43	62.38%
3.91	2.44	62.47%
3.92	2.45	62.56%
3.93	2.46	62.65%
3.94	2.47	62.74%
3.95	2.48	62.82%
3.96	2.49	62.91%

Storm Depth (inches)	SW Return (Inches)	SW Return (%)
3.97	2.50	62.99%
3.98	2.51	63.08%
3.99	2.52	63.17%
4.00	2.53	63.25%
4.01	2.54	63.33%
4.02	2.55	63.42%
4.03	2.56	63.50%
4.04	2.57	63.58%
4.05	2.58	63.67%
4.06	2.59	63.75%
4.07	2.60	63.83%
4.08	2.61	63.91%
4.09	2.62	63.99%
4.10	2.63	64.07%
4.11	2.64	64.15%
4.12	2.65	64.23%
4.13	2.66	64.31%
4.14	2.67	64.39%
4.15	2.68	64.47%
4.16	2.69	64.55%
4.17	2.69	64.63%
4.18	2.70	64.70%
4.19	2.71	64.78%
4.20	2.72	64.86%
4.21	2.73	64.93%
4.22	2.74	65.01%
4.23	2.75	65.09%
4.24	2.76	65.16%
4.25	2.77	65.24%
4.26	2.78	65.31%
4.27	2.79	65.38%
4.28	2.80	65.46%
4.29	2.81	65.53%
4.30	2.82	65.60%
4.31	2.83	65.68%
4.32	2.84	65.75%
4.33	2.85	65.82%
4.34	2.86	65.89%
4.35	2.87	65.97%
4.36	2.88	66.04%

Storm Depth (inches)	SW Return (Inches)	SW Return (%)
4.37	2.89	66.11%
4.38	2.90	66.18%
4.39	2.91	66.25%
4.40	2.92	66.32%
4.41	2.93	66.39%
4.42	2.94	66.46%
4.43	2.95	66.53%
4.44	2.96	66.59%
4.45	2.97	66.66%
4.46	2.98	66.73%
4.47	2.99	66.80%
4.48	3.00	66.87%
4.49	3.01	66.93%
4.50	3.02	67.00%
4.51	3.02	67.07%
4.52	3.03	67.13%
4.53	3.04	67.20%
4.54	3.05	67.26%
4.55	3.06	67.33%
4.56	3.07	67.39%
4.57	3.08	67.46%
4.58	3.09	67.52%
4.59	3.10	67.59%
4.60	3.11	67.65%
4.61	3.12	67.72%
4.62	3.13	67.78%
4.63	3.14	67.84%
4.64	3.15	67.91%
4.65	3.16	67.97%
4.66	3.17	68.03%
4.67	3.18	68.09%
4.68	3.19	68.15%
4.69	3.20	68.22%
4.70	3.21	68.28%
4.71	3.22	68.34%
4.72	3.23	68.40%
4.73	3.24	68.46%
4.74	3.25	68.52%
4.75	3.26	68.58%
4.76	3.27	68.64%

Storm Depth (inches)	SW Return (Inches)	SW Return (%)
4.77	3.28	68.70%
4.78	3.29	68.76%
4.79	3.30	68.82%
4.80	3.31	68.88%
4.81	3.32	68.93%
4.82	3.33	68.99%
4.83	3.34	69.05%
4.84	3.34	69.11%
4.85	3.35	69.16%
4.86	3.36	69.22%
4.87	3.37	69.28%
4.88	3.38	69.34%
4.89	3.39	69.39%
4.90	3.40	69.45%
4.91	3.41	69.51%
4.92	3.42	69.56%
4.93	3.43	69.62%
4.94	3.44	69.67%
4.95	3.45	69.73%
4.96	3.46	69.78%
4.97	3.47	69.84%
4.98	3.48	69.89%
4.99	3.49	69.95%
5.00	3.50	70.00%

Table 4 - Total Storm Event Summary

Station Name	Total Storm Count	Total Storms Above Line		Total Storms Below Line	
		Count	%	Count	%
Sterling Ranch	240	1	0.4%	239	99.6%
Highlands Ranch WTP	257	5	1.9%	252	98.1%
Castle Rock	208	4	1.9%	204	98.1%
Diamond Hill	264	4	1.5%	260	98.5%
Justice Center	259	7	2.7%	252	97.3%
Salisbury Park	226	2	0.9%	224	99.1%
Tollgate At 6th	256	6	2.3%	250	97.7%
South Academy Blvd	224	16	7.1%	208	92.9%
Harvard Gulch at University Park	203	5	2.5%	198	97.5%
West Plum Creek	92	3	3.3%	89	96.7%
Total	2229	53	2.4%	2176	97.6%

Table 5 - Total Storm Event Volume Summary (inches)

Station Name	Total Storm Event Volume	Total Storm Event Volume Above Line		Total Storm Event Volume Below Line	
		Volume	%	Volume	%
Sterling Ranch	99.51	0.02	0.0%	99.49	100.0%
Highlands Ranch WTP	81.4	0.41	0.5%	80.99	99.5%
Castle Rock	75.92	1.41	1.9%	74.51	98.1%
Diamond Hill	95.13	0.53	0.6%	94.6	99.4%
Justice Center	101.66	1.72	1.7%	99.94	98.3%
Salisbury Park	75.61	0.79	1.0%	74.82	99.0%
Tollgate At 6th	91.46	1.47	1.6%	89.99	98.4%
South Academy Blvd	108.48	2.05	1.9%	106.43	98.1%
Harvard Gulch at University Park	82.15	1.04	1.3%	81.11	98.7%
West Plum Creek	31.98	0.54	1.7%	31.44	98.3%
Total	843.3	9.98	1.2%	833.32	98.8%

Table 6 - Total WQ-COSM Simulated Runoff Volume Summary (inches)

Station Name	Total Runoff Volume	Total Runoff Volume Above Line		Total Runoff Volume Below Line	
		Volume	%	Volume	%
Sterling Ranch	2.49	0.02	0.8%	2.47	99.2%
Highlands Ranch WTP	1.92	0.41	21.4%	1.51	78.6%
Castle Rock	5.78	1.41	24.4%	4.37	75.6%
Diamond Hill	3.15	0.53	16.8%	2.62	83.2%
Justice Center	6.85	1.72	25.1%	5.13	74.9%
Salisbury Park	1.64	0.79	48.2%	0.85	51.8%
Tollgate At 6th	5.11	1.47	28.8%	3.64	71.2%
South Academy Blvd	14.41	2.05	14.2%	12.36	85.8%
Harvard Gulch at University Park	3.2	1.04	32.5%	2.16	67.5%
West Plum Creek	2.03	0.54	26.6%	1.49	73.4%
Total	46.58	9.98	21.4%	36.6	78.6%

Table 7 - Total Administrative Runoff Volume Summary (inches)

Station Name	Total WQ-COSM Simulated Runoff Volume	Total Administrative Volume	Total WQ-COSM Simulated Runoff Volume Above Line	Net Impact to the River	
				WQ-COSM Simulated Volume	Administrative Volume
Sterling Ranch	2.49	18.28	0.02	2.49	18.26
Highlands Ranch WTP	1.92	11.67	0.41	1.92	11.26
Castle Rock	5.78	12.94	1.41	5.78	11.53
Diamond Hill	3.15	15.75	0.53	3.15	15.22
Justice Center	6.85	18.97	1.72	6.85	17.25
Salisbury Park	1.64	11.34	0.79	1.64	10.55
Tollgate At 6th	5.11	15.47	1.47	5.11	14
South Academy Blvd	14.41	24.45	2.05	14.41	22.4
Harvard Gulch at University Park	3.2	14.34	1.04	3.2	13.3
West Plum Creek	2.03	4.91	0.54	2.03	4.37
Total	46.58	148.12	9.98	46.58	138.14

Attachment 1

WQ-COSM User's Manual

USER'S MANUAL

Water Quality Capture Optimization and Statistics Model (WQ-COSM) v3.0

January 2017 Edition

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Table of Contents

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Introduction

Water Quality Capture Optimization Statistical Model (WQ-COSM) is an Excel spreadsheet based computer program that uses recorded precipitation data from the National Climatic Data Center (NCDC) and information about the catchment's hydrologic parameters to help the user determine the water quality capture volume (WQCV) and the maximized WQCV for any type of stormwater treatment facility (i.e., structural Best Management Practice (BMP)) that captures runoff in temporary storage basin (vessel) for mitigating of hydrologic changes caused by urbanization and also treats its water quality through sedimentation, biological uptake of pollutants and/or filtration/infiltration.

This program replaces previous versions including a Windows-based WQ-COSM program and a DOS based program called PondRisk (ref.: Guo, James C.Y. (1986). *PONDRISK Computer Model for Determination of Maximized Detention Volume*, Dept. of Civil Engineering, U. of Colorado Denver, Denver, Colorado). The Excel spreadsheet version of WQ-COSM provides a modern user interface with easily accessible tabular results and adds additional functionality that was not available in PondRisk. WQ-COSM computes runoff using continuous runoff simulation using either the Rational Method, Horton's infiltration method or Green-Ampt infiltration method and calculates the WQCV based on the runoff simulation.

WQCV is an integral part of any BMP that removes significant portions of pollutants from the majority of runoff events and helps mitigate the hydrologic changes caused by urbanization. These BMPs differ from flow-through BMPs that do not have a WQCV and do not mitigate the effects of increased stormwater runoff peaks and volumes that result from urbanization. Flow-through BMPs are primarily used to remove gross pollutants consisting of floating trash and coarse sediment, but for the most part, do not remove fine sediment and associated pollutants, bacteria, and dissolved constituents in significant amounts. A WQCV is a part of the following types of BMPs:

- Total storage for an Extended Detention Basin (i.e., dry) basin (EDB)
- Surcharge storage above the permanent pool of a Retention Pond (i.e., wet) pond (RP)
- Surcharge storage above the permanent pool of Wetland Basin (WB)
- Above or upstream of a Media Filters (MF)
- Above of upstream of a Rain Gardens (RG), sometimes called bio-retention cell.

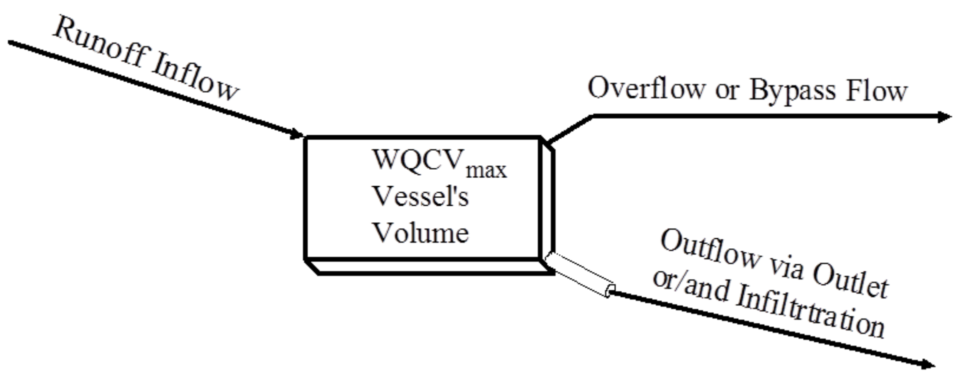
WQ-COSM is implemented as a single Excel spreadsheet utilizing VBA code. The ***Input Summary*** worksheet serves as an interface to collect information from the user, which is then processed by the VBA code to perform the necessary calculations. The code then prints all relevant results to separate summary output worksheets.

The WQ-COSM program performs the following basic tasks:

1. Imports precipitation data from an NCDC .csv file, processes the continuous precipitation data and identifies individual storms after excluding small, non-runoff producing, and user-defined large outlier storms. Reports statistical results for the entire data set and filtered precipitation data.

2. Processes the accepted continuous precipitation data to develop a continuous runoff record for each time increment in the filtered precipitation record. Reports statistical results of the resultant runoff data set. Optional output lists summary data for each individual storm.
3. Routes the continuous runoff data through a series of increasing basin (vessel) sizes (i.e., through a series of increasing WQCV basins) to develop data on runoff volumes and number of storms captured by each vessel size. Reports the percent and the total runoff volume, the percent of all runoff captured (i.e., volume-based approach) and the percent of individual storms captured in total (i.e., event-based approach) by various WQCV basin (vessel) sizes.
4. Finds the point of diminishing return in WQCV vessel size for the capture of total runoff volumes and for the capture of individual storms. Reports both.

The size (i.e., volume) of the WQCV vessel, or basin, is dependent on the runoff that results over time from the tributary catchment (step 2 above) and the time it takes to empty a brim-full WQCV vessel (i.e., the rate of discharge from the vessel) when there is no runoff entering it. The routing of runoff (step 3 above) through a WQCV basin (vessel) is illustrated in Figure 1.



Note: The discharge rate through the outlet is equal to [(WQCV$_{max}$)/(Drain Time)]

Figure 1. Routing Runoff through a WQCV Basin (Vessel).

For more information on the underlying methodology of the math model, the user is referred to the following sources: (Guo and Urbonas, 2002), (Urbonas, Guo, and Tucker 1990) and *Description of the WQ-COSM Computer Model to Generate a Capture Volume for Stormwater BMPS* (2011).

Installing WQ-COSM

WQ-COSM is distributed as freeware in the form of a Microsoft Excel Workbook. It is not necessary to install the Excel workbook onto your computer in anyway. Simply open the workbook in Microsoft Excel and enable macros when prompted. Next, read the Software Disclaimer and click Agree to start using the workbook.

WQ-COSM Input Requirements

After opening the WQ-COSM workbook you will be taken to the ***Intro*** worksheet which includes a brief overview of the model along with buttons which when clicked will redirect you to other worksheets within the workbook. To use WQ-COSM, go to the ***Input Summary*** worksheet and provide the necessary input parameters.

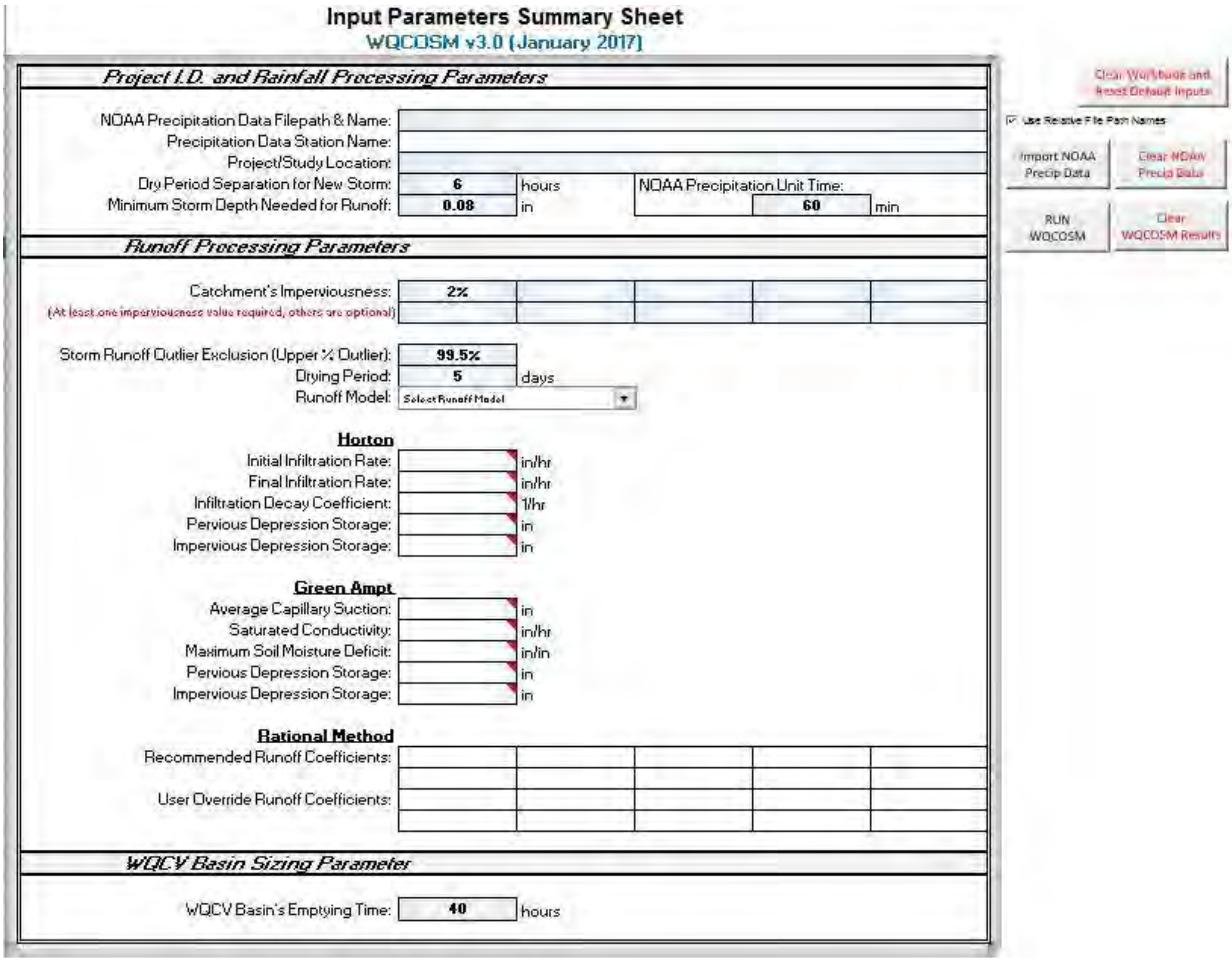


Figure 2. WQ-COSM Input Summary Worksheet.

Project I.D. and Rainfall Processing Parameters

The top section of inputs is titled "*Project I.D. and Rainfall Processing Parameters*". The first step is to import a precipitation data file. The continuous precipitation data file should be in the National Climatic Data Center (NCDC) comma separated values (*.csv) format. These data files can be obtained from NCDC operated by NOAA. In 2012 the NCDC changed the way the data are presented in these files, however WQ-COSM will recognize both the old format and the new format.

Note that when the file is imported, the file path location and name of the .csv file will be saved as the first input. If you only want this input to show the file path location relative to the open workbook you can click the checkbox to the right of the input cell. If this box is not checked, the entire file path will be shown (long file paths may exceed the width of the input cell).

To import the precipitation data file, simply click on the *Import NOAA Precip Data* button off to the right of the inputs. A Windows open/save dialog box will then open which will allow you to browse to the location of the precipitation data file. Once the appropriate .csv file has been located and selected, click "open" to import the file to the WQ-COSM workbook. The program will then automatically import the .csv file to the ***Raw Precip Data*** worksheet (last tab in the WQ-COSM workbook) and fill out the *Filepath & Name* and *Station Name* on the ***Input Summary*** worksheet. WQ-COSM will also assign a data processing *time-step* for performing continuous simulations of runoff that is the same as the one found in the downloaded NCDC precipitation file (i.e., 15- or 60- minute).

After importing the precipitation data file, continue filling out the other required Rainfall Processing Parameters including:

- **Project/Study Location (optional):** Enter the location of the project, study area, region or any other descriptor. This does not affect data processing and is used only for user information.

- **Dry Period Separation for New Storm:** Minimum time in hours between consecutive rainfall events (i.e., end of one storm and beginning of the next one) that marks the start of a new storm. Typically between 3 - 24 hours (default = 6 hours).

- **Minimum Storm Depth Needed for Runoff:** Minimum total storm depth (inches) for inclusion in the runoff and WQCV analysis. It is used to exclude non-runoff producing storms. State-of-practice for urban runoff suggests total minimum storm depths between 0.06 and 0.12 in. (default = 0.08 inches) is needed to produce runoff.

- **Excluded Dates:** Clicking on the ***Excluded Dates*** button launches the Tab 'Exclusions'. Using this Tab opens parameter fields that allow you to specify a season to exclude from all the years of record or specific dates to exclude from the analysis of the continuous precipitation record. For example, you may want to exclude precipitation data from a winter snow season which has completely different precipitation-runoff dynamic from rainfall. Or, you may want to exclude specific dates that may have questionable or bad data. If no dates are specified, WQ-COSM will use all of the precipitation data in the **NWS Climate** file.

<u>Runoff Processing Parameters</u>

The middle section of inputs is titled "*Runoff Processing Parameters*". The required inputs are outlined below.

- **Catchment Imperviousness:** The imperviousness of the catchment entered as a percentage (no default value recommended). A minimum of one imperviousness value is required to run the WQ-COSM program. Entering additional imperviousness values will result in the WQ-COSM program running in a batch mode where the model is run to completion for the first imperviousness value and then starts over with the next imperviousness value. Up to ten imperviousness values can be selected to evaluate the WQCV requirements for different levels of development in the catchment.

- **Storm Runoff Outlier Exclusion (Upper % Outlier):** The upper percentile of all individual storm runoff volumes to use in WQCV analysis. This excludes large outlier storms (program default = 99.5%). Storms above this percentile value are not used in finding the Maximized WQCV (i.e., the point of diminishing return capture volume).

- **Drying Time:** The time required for the catchment to recover its infiltration and depression storage capacity that may vary from 1 to 14 days (recommended default = 3 to 5 days). Suggested values for various soil types may be found in Appendix A.

- **Runoff Model:** Choose one of three runoff methods (select from pulldown list) to convert rainfall depths to runoff depths for each of the time increments in the filtered precipitation record. The three methods available are *Horton, Green-Ampt* and *Rational*. Depending on the method you choose, the required parameter input fields will be unlocked and the other methods will be blocked out.

- **Horton Infiltration Method**

  - **Initial Infiltration Rate:** The initial infiltration rate in inches per hour (no default recommended). Suggested values for various soil types may be found in Appendix A.

  - **Final Infiltration Rate:** The final infiltration rate in inches per hour (no default recommended). Suggested values for various soil types may be found in Appendix A.

  - **Infiltration Decay Coefficient:** The infiltration decay rate in 1.0/hr units (no default recommended). Suggested values for various soil types may be found in Appendix A.

  - **Pervious Depression Storage:** The maximum pervious depression storage for the basin in inches (recommended default = 0.3 in). Suggested values for various soil types may be found in Appendix A.

  - **Impervious Depression Storage:** The maximum impervious depression storage for the basin in inches (recommended default = 0.1 in). Suggested values for various soil types may be found in Appendix A.

- **Green-Ampt Infiltration Method**

  - **Average Capillary Suction:** The initial infiltration rate in inches per hour, depends on soil type (no default recommended). Suggested values for various soil types may be found in Appendix A.

  - **Saturated Conductivity:** The final infiltration rate in inches per hour, depends on soil type (no default recommended). Suggested values may be found in

Appendix A.

- **Maximum Soil Moisture Deficit:** A non-dimensional fraction difference between soil porosity and the actual moisture content (no default recommended). Suggested values by soil type may be found in Appendix A.
- **Pervious Depress Storage:** The maximum pervious depression storage for the basin in inches (recommended default = 0.3 in). Suggested values for various soil types may be found in Appendix A.
- **Impervious Depression Storage:** The maximum impervious depression storage for the basin in inches (recommended default = 0.1 in). Suggested values for various soil types may be found in Appendix A.

- **Rational Method**
    - **Recommended Runoff Coefficients:** The recommended Rational Method runoff coefficients are calculated automatically by the WQ-COSM program. The recommended values are based on the Catchment Imperviousness values entered above are calculated using an empirical equation.
    - **User Override Runoff Coefficients:** The recommended Rational Method runoff coefficients can be overridden by the user to better represent local criteria. Additionally, a table of suggested **Rational Runoff Coefficient 'C'** may be found in Appendix A.

WQCV Basin Sizing Parameter

The bottom section of inputs is titled "*WQCV Basin Sizing Parameter*". The only input required in this section is:

- **WQCV Basin Emptying Time:** Emptying time for the brim-full WQCV to be totally emptied out (in hours) when there is no inflow. This typically range between 12 and 96 hours and depends on the type of BMP being analyzed and meteorological region (default = 40 hours).

Running WQ-COSM

Once all of the required inputs have been entered, the WQ-COSM program can be run by clicking the button *Run WQ-COSM*. If any of the required inputs are missing, a message box will pop-up notifying the user what information is still required and the program will quit. Assuming all of the required inputs are entered, the program will run, calculate results, and print the results to various summary worksheets. While the program is running the status bar in the lower left corner of the Excel workbook displays a brief description of current step being performed by the software. Some routines in the program take longer than others, so keep an eye on the status bar to follow along with the progress. Should you encounter any problems, make a note of the status bar description when reporting the problem to assist UWRI in making improvements.

After all of the internal calculations have been completed, the results will be printed to several different summary worksheets. A complete set of results will be provided for each Imperviousness level provided on the Input Summary worksheet. The summary worksheets include:

- **Storm Data:** The ***Storm Data*** worksheet shows the processed continuous rainfall data and identifies the individual storm that each precipitation increment is associated with. The individual storms are determined by the user provided Dry Period separation time (hours). The individual storms exclude small non-runoff producing storms as defined by the user. The runoff volume (inches) and runoff rate (cfs) associated with each incremental precipitation depth is also shown on this worksheet.

- **All Storms Summary:** The ***All Storms Summary*** worksheet shows all runoff producing storms. Instead of showing all of the incremental depths like the ***Storm Data*** worksheet does, the ***All Storms Summary*** worksheet sums the incremental rainfall and runoff depths within each storm to provide the total rainfall and runoff for each storm. At the bottom of the worksheet, summary statistics for all the storms are provided including: total rainfall and runoff depths, mean rainfall and runoff depths, maximum rainfall and runoff depths, mean storm duration, maximum storm duration, mean storm separation time, and the number of storms less than the mean runoff depth.

- **Processed Storms Summary:** The ***Processed Storms Summary*** worksheet is the same as the ***All Storms Summary*** worksheet except that it does not include storms with runoff depths greater than the Upper Outlier Exclusion percentage set by the user. The same summary statistics are recalculated based on the smaller storm data set.

- **WQCV Table:** The ***WQCV Table*** worksheet provides a table of potential WQCV basin sizes ranging from a size of zero inches up to the basin size required to capture the maximum runoff depth in the processed storms. For each WQCV basin size the results include: Volume Captured (inches), Volume Captured (%), Normalized Volume Captured (%), Volume Normalized WQCV (inches), Storm Events Captured, Storm Events Captured (%), Normalized Storm Events Captured (%), Storm Event Normalized WQCV (in).

- **Output Summary:** The ***Output Summary*** worksheet provides a condensed summary of the results provided in the other worksheets described above. For each imperviousness level evaluated, the summary results include statistics for: All Runoff Producing Storms, Outlier Storms Excluded, Runoff Producing Storms Analyzed (excludes outlier storms), and Optimized WQCV values based on Runoff Volumes and Storm Events. Figure 3 below shows the Output Summary worksheet.

Output Results Summary Sheet
WQ-COSM v3.0 (January 2017)

NOAA Precipitation Data Start & End Date/Time:										
Catchment Imperviousness (%):	2%	20%	30%	40%	50%	60%	70%	80%	90%	100%
All Runoff Producing Storms										
Total Number of Runoff Producing Storms:										
Precipitation Depth of Largest Storm (in):										
Runoff Depth of Largest Storm (in):										
Total Precipitation Depth of All Storms (in):										
Total Runoff Depth of All Storms (in):										
Mean Precipitation Depth of All Storms (in):										
Mean Runoff Depth of All Storms (in):										
Number of Storms Below Mean Runoff Depth:										
Mean Duration of Runoff Producing Storms (hours):										
Mean Separation Time Between Storms (hours):										
Outlier Storms Excluded										
Number Outlier Storms Excluded:										
Runoff Depth of Outlier Exclusion Storm (in):										
Total Runoff Depth of All Storms Excluded (in):										
Runoff Producing Storms Analyzed										
Number of Storms Analyzed:										
Precipitation Depth of Largest Analyzed Storm (in):										
Runoff Depth of Largest Analyzed Storm (in):										
Total Precipitation Depth of Analzyed Storms (in):										
Total Runoff Depth of Analyzed Storms (in):										
Mean Precipitation Depth of Analyzed Storms (in):										
Mean Runoff Depth of Analyzed Storms (in):										
Number of Storms Below Mean Runoff Depth:										
Mean Duration of Analzyed Storms (hours):										
Mean Separation Time Between Storms (hours):										
Optimized WQCV Values										
WQCV Based on Runoff Volume										
Optimal WQCV (in):										
Volume Captured (in):										
Percent of Volume Captured (%):										
Number of Storms Captured:										
Percent of Storms Captured (%):										
WQCV Based on Storm Events										
Optimal WQCV (in):										
Volume Captured (in):										
Percent of Volume Captured (%):										
Number of Storms Captured:										
Percent of Storms Captured (%):										

Figure 3. WQ-COSM Output Summary Worksheet.

Please note that the model results will be overwritten each time the *Run WQ-COSM* button is clicked, unless the user saves the workbook with a new file name for the subsequent run. The remaining buttons with red text are all used to clear results. The top button *Clear Workbook and Reset Default Inputs* will clear all inputs and results and reset default input values. The middle button *Clear NOAA Precip Data* will clear the imported precipitation data and all results but will leave the remaining input parameters. The bottom button *Clear WQCOSM Results* will leave all user inputs and the imported precipitation data but will clear all results.

APPENDIX – A
Ranges in Rainfall Losses for Rational, Horton's and Green Ampt Methods

Rational Runoff Coefficient 'C'. This coefficient varies with soil type and degree of effective imperviousness of the catchment between 0.0 and 1.0. Based on EPS's Nationwide Urban Runoff Program Data from over 60 different sites in United States and the follow-up analysis performed by the Urban Drainage and Flood Control District (UDFCD) in the Denver Region, Table A1 offers suggested values when selecting values of C for use with WQ-COSM.

Table A1. Runoff Coefficient as a Function of Total Imperviousness

Percentage Imperviousness	Runoff Coefficient by NRCS Hydrologic Soil Groups		
	C & D	B	A
0%	0.04	0.02	0.00
10%	0.11	0.06	0.00
20%	0.17	0.12	0.06
30%	0.22	0.18	0.13
40%	0.28	0.23	0.19
50%	0.34	0.29	0.25
60%	0.41	0.37	0.33
70%	0.49	0.45	0.42
80%	0.60	0.57	0.54
90%	0.73	0.71	0.69
100%	0.89	0.89	0.89

Horton's Method Parameters. WQ-COSM uses the integrated form of Horton's equation to find rainfall losses on pervious surfaces during continuous simulation, namely:

$$= \ast + \frac{-}{} \ast (1 - {}^{-})$$

in which,

f = infiltration rate (in/hr),

f_o = final infiltration rate (in/hr),

f_i = initial infiltration rate (in/hr),

e = natural logarithm base,

a = decay coefficient (1/hour),

t = time (hours)

Horton's Initial Infiltration Rate varies with the types of soil. Typically used values range from 0.2 to 10.0 inches per hour (5 to 25 mm/h). Table A2 contains initial infiltration rates suggested for use with WQ-COSM and are based on ones originally suggested by Akan (1993), and others.

Table A2. Horton's Initial Infiltration by Soil Type

Soil Type	(in/hr)	(mm/hr)
Dry sandy soils with little or no vegetation	5.0	127
Dry loam soils with little or no vegetation	3.0	76.2
Dry clay soils with little or no vegetation	1.0	25.4
Dry sandy soils with dense vegetation	10.0	254
Dry loam soils with dense vegetation	6.0	152
Dry clay soils with dense vegetation	2.0	51
Moist sandy soils with little or no vegetation	1.7	43
Moist loam soils with little or no vegetation	1.0	25
Moist clay soils with little or no vegetation	0.3	7.6
Moist sandy soils with dense vegetation	3.3	84
Moist loam soils with dense vegetation	2.0	5.1
Moist clay soils with dense vegetation	0.7	18

Horton's Final Infiltration Rate also varies with the types of soil. Table A3 contains final infiltration rates suggested by Akan (1993), and others:

Table A3. Horton's Final Infiltration Rate by Soil Type

	Final Infiltration Rate	
Soil Type	(in/hr)	(mm/hr)
Clay loam, silty clay loam, sandy clay, silty clay, clay	0.01 - 0.08	0.25 - 2.0
Sandy clay loam	0.06 - 0.12	1.57 - 3.1
Silt loam, loam	0.15 - 0.30	3.8 – 7.6
Sandy loam	0.43 - 0.86	11 - 22
Loamy sand	1.2 - 2.4	30 - 60
Sand, ,	4.7 - 9.3	119 - 236

The final infiltration rate is the saturated hydraulic conductivity rate of the soil.

Horton's Infiltration Decay Rate can vary considerably. Values typically in use by modelers range from 2 to 6/hr (0.00056 to 0.00167/sec). Because there is little sensitivity in final results after the value of 3/hr is used, it is recommended a value of 3/hr be used with WQ-COSM for NRDC Soil Groups B, C and D and a value of 2/hr for Soil Group A.

Impervious Surface Depression Storage can also vary considerably depending on the type of the surface and its condition. Water stored in depressions on impervious areas is lost through evaporation.

Typical values in use by modelers range from 0.04 to 0.12 inches (1 to 3 mm). A value of 0.08 inches (2 mm) is recommended for use with WQ-COSM. See Table A4 for recommendations.

Pervious Depression Storage, in inches or millimeters, has to be filled up before runoff begins and is subject to both infiltration and evaporation. For grassed urban surfaces this ranges from 0.2 to 0.5 inches (6 to 13 mm) and a value 0.3 to 0.4 inches (8 to 10 mm) is recommended for use with WQ-COSM. See Table A4 for recommendations.

Table A4. Pervious and Impervious Surface Depression (Retention) Losses.

	Land Cover	Range	Recommended
Pervious Surfaces	Impervious:		
	Large paved areas	0.05 - 0.15	0.1
	Roofs-flat	0.1 - 0.3	0.1
	Roofs-sloped	0.05 - 0.1	0.05
Impervious Surfaces	Lawn grass	0.2 - 0.5	0.35
	Wooded areas and open fields	0.2 - 0.6	0.4

Drying Time used by modelers typically varies from 1 to 14 days, depending on local climate during the rainfall seasons. Table A5 lists drying times offered for your consideration.

Table A5. Drying times for use in continuous simulations with Horton's and Green-Ampt.

Climate/Region	Drying time in days (typically used)
Arid regions	1 to 2 (1)
Semi- Arid regions	2 to 4 (3)
Midwest, East and SE USA	3 to 8 (5)
Very Humid and prolonged precipitation regions	7 to 14 (10)

Green-Ampt Method Parameters. The Green-Ampt equation was suggested by Mein-Larson (1973) and operates in two-stages. First it predicts the volume of water that will infiltrate before the surface becomes saturated. After that infiltration capacity is predicted. The following algorithm describes these two stages:

Stage 1: When $F < F_s$; then $f = i$

if $i > K_s$; then $F_s = (S_u * IMD) / f$

Stage 2: Otherwise $f = F_p$

in which, $F_p = K_s * (1 + S_u * IMD / F)$

in which:

f = infiltration rate, ft/sec

F_p = infiltration capacity, ft/sec

i = rainfall intensity, ft/sec

F = cumulative infiltration volume, this event, ft

F_s = cumulative infiltration volume required to cause surface saturation, ft

*S_u = average capillary suction at the wetting front, ft water

* IMD = initial moisture deficit, ft/ft

*K_s = saturated hydraulic conductivity of soil, ft/sec

Note: * denotes parameters to be entered by the user.

Pervious Depress Storage: Same as for Horton's described above.

Impervious Surface Depression Storage: Same as for Horton's described above.

Drying Time: Same as Horton's described above.

Saturated Conductivity: Saturated hydraulic conductivity is similar to the **Horton's Final Infiltration Rate** described above. Table A6 lists values for your consideration.

Average Capillary Suction: The average capillary suction in inches (mm) of water. It may be the most difficult parameter to quantify accurately. It can be derived from soil moisture conductivity data. Table A6 lists values for your consideration.

Maximum Soil Moisture Deficit: This is the most sensitive parameter of all of the user inputs for the Green-Ampt method. It is non-dimensional fraction difference between soil porosity and the actual moisture content. Table A6 lists values offered for your consideration.

Table A6. Suggested values for Saturated Conductivity, Average Capillary Suction and Maximum Soil Moisture. (Ref. Maidment (1993) and Rawls, et. al. (1983).

	Average Capillary Suction		Saturated Hydraulic Conductivity		Maximum (Initial) Moisture Deficit	
	in	mm	in/hr	mm/hr	East Coast	West Coast
Sand	1.93	49.0	4.74 - 9.27	120 - 236	0.346	0.404
Loamy sand	2.4	61.0	1.18 - 2.35	30.0 - 59.7	0.312	0.382
Sandy loam	4.33	110	0.43 - 0.86	10.9 - 21.8	0.246	0.358
Loam	3.5	88.9	0.13 - 0.52	3.3 - 13.2	0.193	0.346
Silt loam	6.69	57.9	0.26 - 0.27	6.6 - 6.7	0.171	0.368
Sandy clay loam	8.66	220	0.06 - 0.12	1.57 - 3.1	0.143	0.25
Clay loam	8.27	104	0.04 - 0.08	1.0 - 2.0	0.146	0.267
Silty clay loam	10.6	269	0.04 - 0.08	1.0 - 2.0	0.105	0.263
Sandy clay	9.45	240	0.02 - 0.05	0.5 - 1.3	0.091	0.191
Silty clay	11.4	290	0.02 - 0.04	0.5 - 1.0	0.092	0.229
Clay	12.6	320	0.01 - 0.02	0.25 - 0.5	0.079	0.203

NOTE: Saturated hydraulic conductivity, or permeability, values differed between two sources used. Values from Rawls were about 50% of the values from Maidment. Both values are represented as a range.

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Attachment 2

Site-Specific and Regional Runoff Relationship Summaries

Hydrologic Soil Group C

Station: Sterling Ranch

Station ID	Station Name	City/Town	Start Date	End Date	Source
6011	Sterling Ranch	Sterling Ranch	4/1/2010	5/31/2018	Dominion/OneRain

- In total 8 of the 240 (2.5%) observed precipitation events (March – October) resulted in runoff simulated by WQ-COSM.
- Using the site-specific relationship 7 of 8 simulated runoff events fall below this relationship resulting in 99.2% (2.47 inches/2.49 inches) of the simulated runoff below the line.
- In total 239 of the 240 (99.6%) storm events are conservatively represented by the site-specific runoff relationship.
- Total administrative runoff volume (net impact to the river) from observed storm events is 7.3 times (18.26 inches/2.49 inches) greater than simulated runoff volume.

WQ-COSM Simulated Runoff Summary

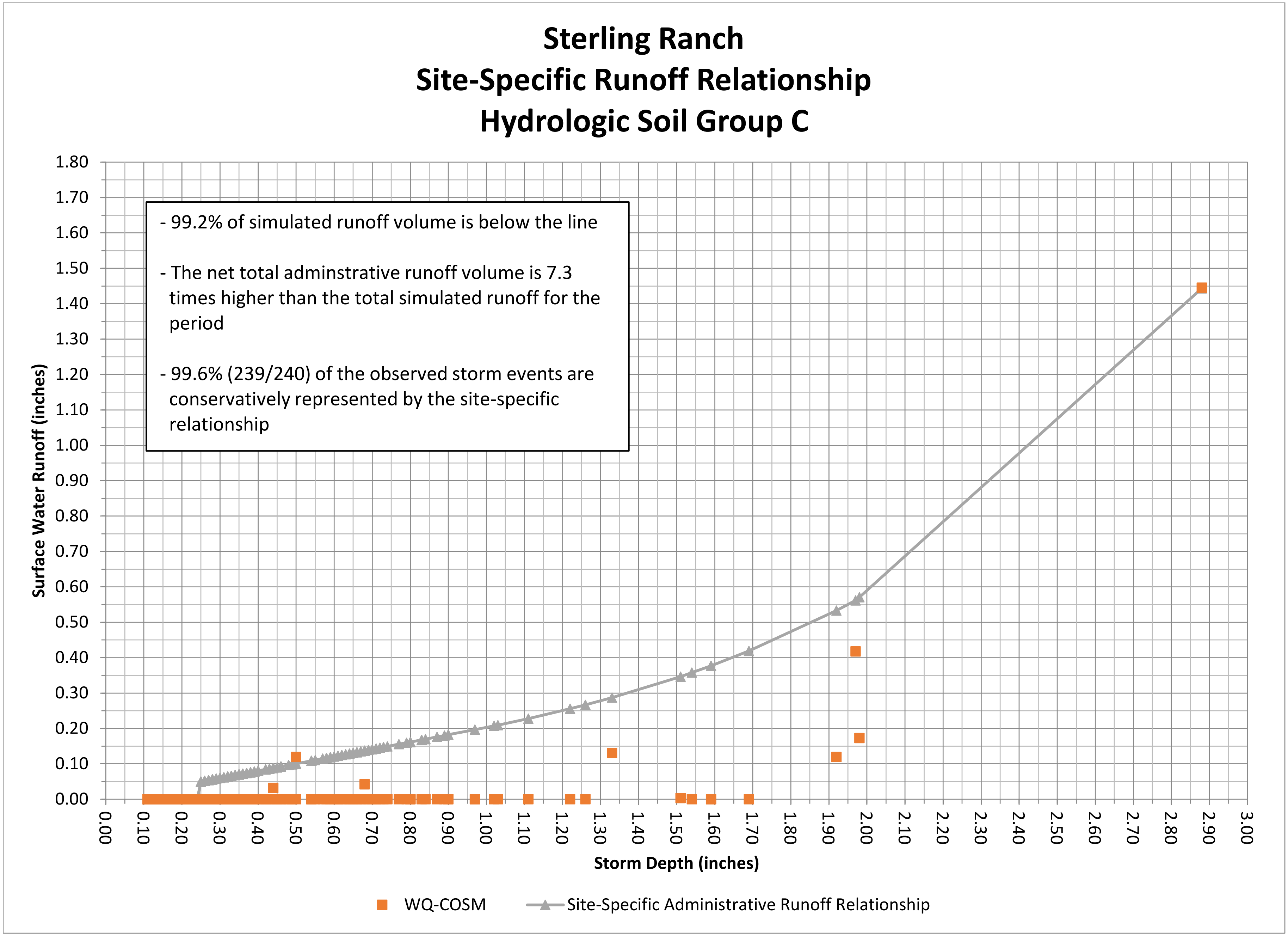
	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Runoff Volume Above the Line (inches)	0.00	0.02	0.00	0.02
Count of Runoff Events Above the Line	0	1	0	1
Percent of Runoff Above the Line (%)	0.0%	10.0%	0.0%	0.8%
Runoff Volume Below the Line (inches)	0.00	0.18	2.29	2.47
Count of Runoff Events Below the Line	0	2	5	7
Percent of Runoff Below the Line (%)	0.0%	89.6%	100.0%	99.2%
Total Runoff Volume (inches)	0.00	0.20	2.29	2.49
Total Count of Runoff Events	0	3	5	8

WQ-COSM Simulated Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Simulated Runoff Volume (inches)	0.00	0.20	2.29	2.49
Total Count of Runoff Events	0	3	5	8
Total Precipitation Volume (inches)	17.00	58.87	23.64	99.51
Total Count of Storm Events	102	123	15	240
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	0.3%	9.7%	2.5%
Percent of Storm Events Resulting in Runoff (%)	0.0%	2.4%	33.3%	3.3%

Administrative Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Administrative Runoff Volume (inches)	0.00	11.84	6.44	18.28
Total Count of Runoff Events	0	123	15	138
Total Precipitation Volume (inches)	17.00	58.87	23.64	99.51
Total Count of Storm Events	102	123	15	240
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	20.1%	27.2%	18.4%
Percent of Storm Events Resulting in Runoff (%)	0.0%	100.0%	100.0%	57.5%



Sterling Ranch
Site-Specific Runoff Relationship
Hydrologic Soil Group C
- 99.2% of simulated runoff volume is below the line
- The net total adminstrative runoff volume is 7.3 times higher than the total simulated runoff for the period
- 99.6% (239/240) of the observed storm events are conservatively represented by the site-specific relationship
Surface Water Runoff (inches)
Storm Depth (inches)
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20
2.30
2.40
2.50
2.60
2.70
2.80
2.90
3.00
WQ-COSM
Site-Specific Administrative Runoff Relationship

Station: Highlands Ranch WTP (UDFCD)

Station ID	Station Name	City	Start Date	End Date	Source
2710	Highlands Ranch WTP	Highlands Ranch	11/19/2009	6/19/2018	UDFCD/OneRain

- In total 9 of the 257 (3.5%) observed precipitation events (March – October) resulted in runoff simulated by WQ-COSM.
- Using the site-specific relationship 4 of 9 simulated runoff events fall below this relationship resulting in 78.6% (1.51 inches/1.92 inches) of the simulated runoff below the line.
- In total 252 of the 257 (98.1%) storm events are conservatively represented by the site-specific runoff relationship.
- Total administrative runoff volume (net impact to the river) from observed storm events is 5.9 times (11.26 inches/1.92 inches) greater than simulated runoff volume.

WQ-COSM Simulated Runoff Summary

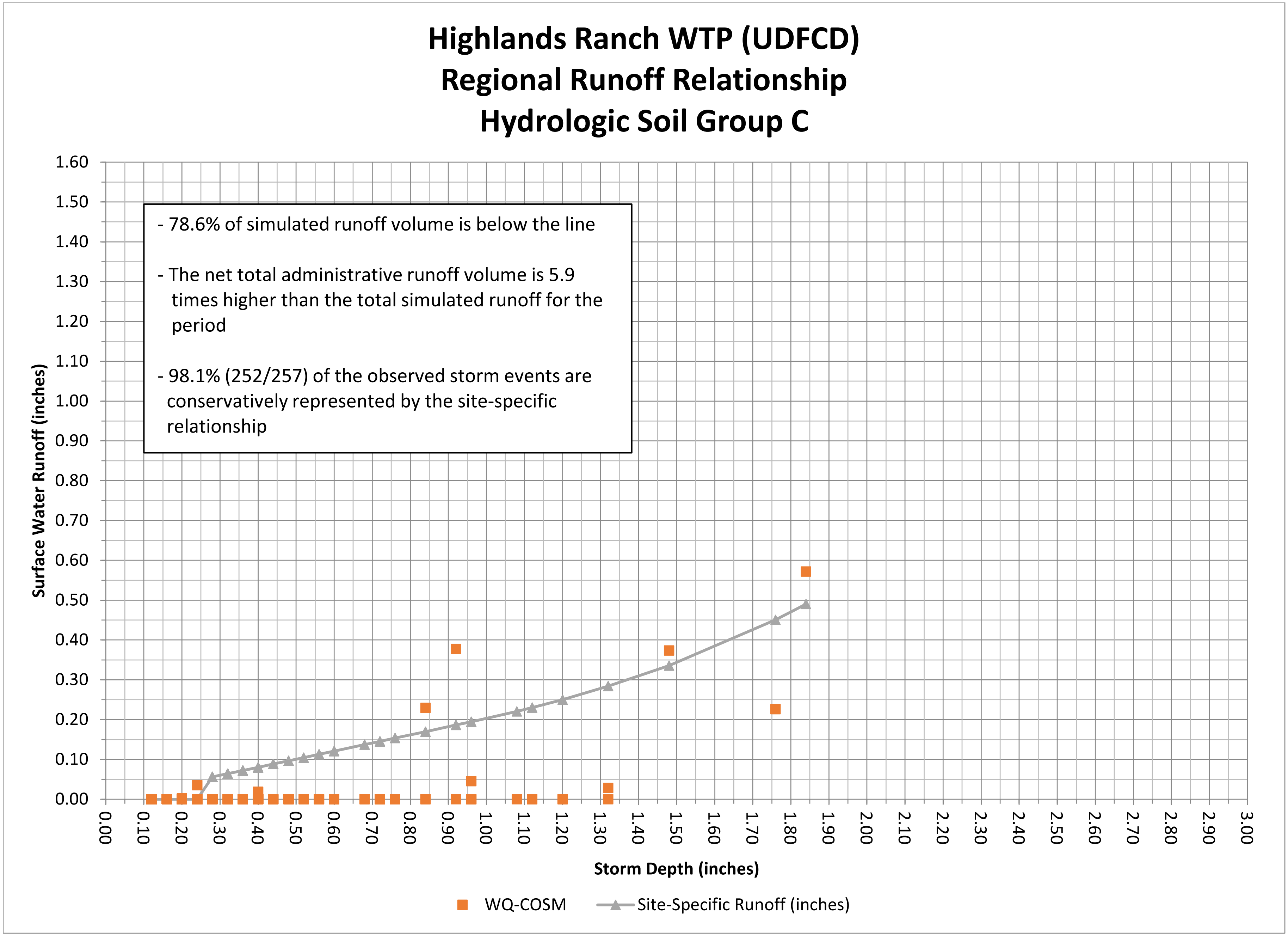
	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Runoff Volume Above the Line (inches)	0.04	0.25	0.12	0.41
Count of Runoff Events Above the Line	1	2	2	5
Percent of Runoff Above the Line (%)	100.0%	37.3%	10.0%	21.4%
Runoff Volume Below the Line (inches)	0.00	0.42	1.08	1.51
Count of Runoff Events Below the Line	0	2	2	4
Percent of Runoff Below the Line (%)	0.0%	63.3%	90.0%	78.6%
Total Runoff Volume (inches)	0.04	0.67	1.20	1.92
Total Count of Runoff Events	1	4	4	9

WQ-COSM Simulated Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Simulated Runoff Volume (inches)	0.04	0.67	1.20	1.92
Total Count of Runoff Events	1	4	4	9
Total Precipitation Volume (inches)	24.96	43.00	13.44	81.40
Total Count of Storm Events	154	93	10	257
Percent of Precipitation Volume Resulting in Runoff (%)	0.2%	1.6%	8.9%	2.4%
Percent of Storm Events Resulting in Runoff (%)	0.6%	4.3%	40.0%	3.5%

Administrative Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Administrative Runoff Volume (inches)	0.00	8.65	3.03	11.67
Total Count of Runoff Events	0	93	10	103
Total Precipitation Volume (inches)	24.96	43.00	13.44	81.40
Total Count of Storm Events	154	93	10	257
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	20.1%	22.5%	14.3%
Percent of Storm Events Resulting in Runoff (%)	0.0%	100.0%	100.0%	40.1%



Highlands Ranch WTP (UDFCD)
Regional Runoff Relationship
Hydrologic Soil Group C
- 78.6% of simulated runoff volume is below the line
- The net total administrative runoff volume is 5.9 times higher than the total simulated runoff for the period
- 98.1% (252/257) of the observed storm events are conservatively represented by the site-specific relationship
Surface Water Runoff (inches)
Storm Depth (inches)
WQ-COSM
Site-Specific Runoff (inches)

Station: Castle Rock (UDFCD)

Station ID	Station Name	City	Start Date	End Date	Source
2750	Castle Rock	Castle Rock	11/19/2009	6/19/2018	UDFCD/OneRain

- In total 12 of the 208 (5.8%) observed precipitation events (March – October) resulted in runoff simulated by WQ-COSM.
- Using the site-specific relationship 8 of 12 simulated runoff events fall below this relationship resulting in 75.6% (4.37 inches/5.78 inches) of the simulated runoff below the line.
- In total 204 of the 208 (98.1%) storm events are conservatively represented by the site-specific runoff relationship.
- Total administrative runoff volume (net impact to the river) from observed storm events is 2.20 times (11.53 inches/5.78 inches) greater than simulated runoff volume.

WQ-COSM Simulated Runoff Summary

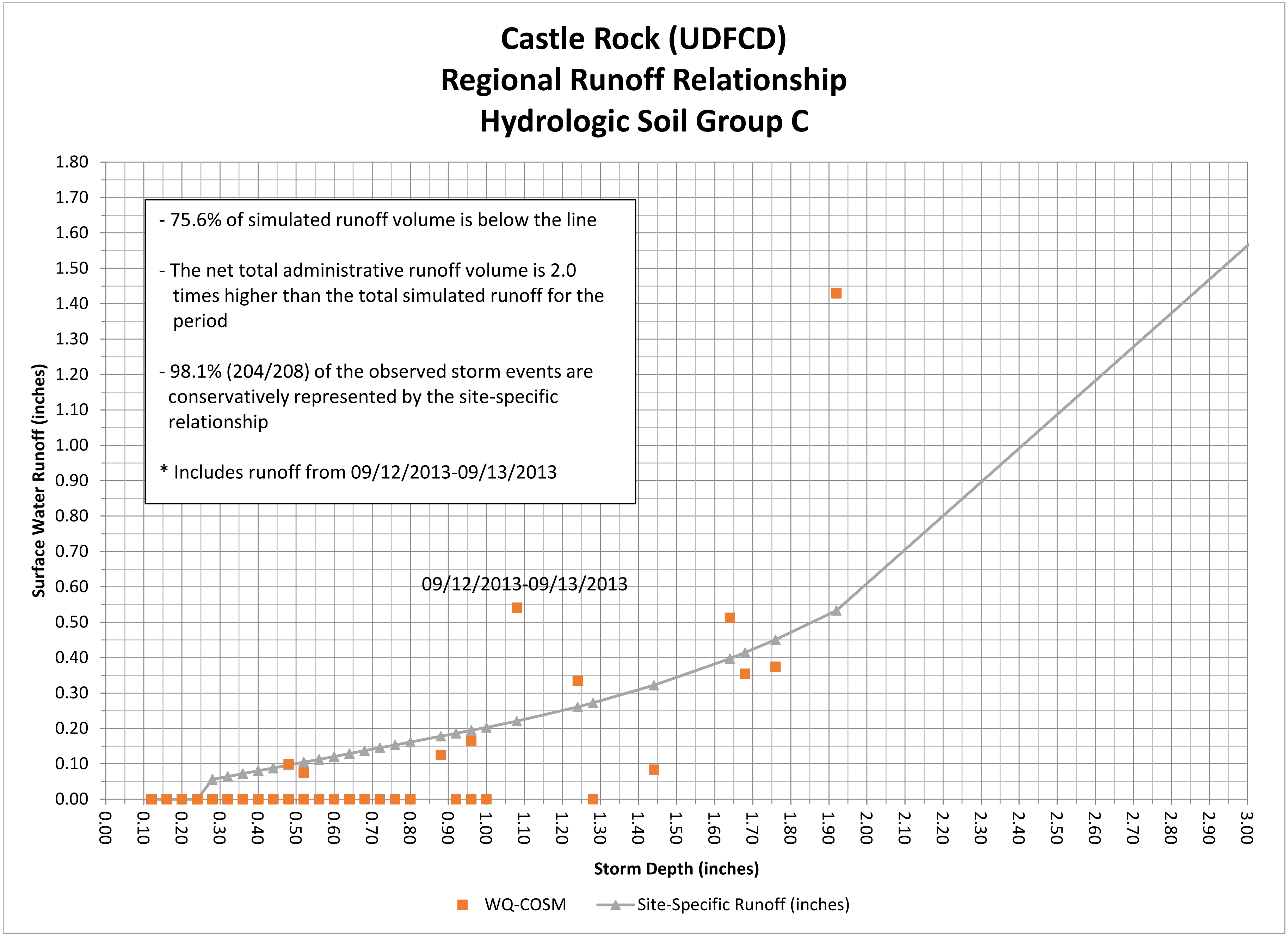
	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Runoff Volume Above the Line (inches)	0.00	0.00	1.41	1.41
Count of Runoff Events Above the Line	0	0	4	4
Percent of Runoff Above the Line (%)	0.0%	0.0%	26.6%	24.4%
Runoff Volume Below the Line (inches)	0.00	0.47	3.91	4.37
Count of Runoff Events Below the Line	0	4	4	8
Percent of Runoff Below the Line (%)	0.0%	99.0%	73.6%	75.6%
Total Runoff Volume (inches)	0.00	0.47	5.31	5.78
Total Count of Runoff Events	0	4	8	12

WQ-COSM Simulated Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Simulated Runoff Volume (inches)	0.00	0.47	5.31	5.78
Total Count of Runoff Events	0	4	8	12
Total Precipitation Volume (inches)	19.64	40.96	15.32	75.92
Total Count of Storm Events	115	84	9	208
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	1.1%	34.7%	7.6%
Percent of Storm Events Resulting in Runoff (%)	0.0%	4.8%	88.9%	5.8%

Administrative Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Administrative Runoff Volume (inches)	0.00	8.24	4.70	12.94
Total Count of Runoff Events	0	84	9	93
Total Precipitation Volume (inches)	19.64	40.96	15.32	75.92
Total Count of Storm Events	115	84	9	208
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	20.1%	30.7%	17.0%
Percent of Storm Events Resulting in Runoff (%)	0.0%	100.0%	100.0%	44.7%


Castle Rock (UDFCD)
Regional Runoff Relationship
Hydrologic Soil Group C
- 75.6% of simulated runoff volume is below the line
- The net total administrative runoff volume is 2.0 times higher than the total simulated runoff for the period
- 98.1% (204/208) of the observed storm events are conservatively represented by the site-specific relationship
* Includes runoff from 09/12/2013-09/13/2013
09/12/2013-09/13/2013
Surface Water Runoff (inches)
Storm Depth (inches)
WQ-COSM
Site-Specific Runoff (inches)
1.80
1.70
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20
2.30
2.40
2.50
2.60
2.70
2.80
2.90
3.00

Station: Diamond Hill, Denver (UDFCD)

Station ID	Station Name	City	Start Date	End Date	Source
10028	Diamond Hill	Denver	12/19/2008	12/8/2018	UDFCD/OneRain

- In total 11 of the 264 (4.2%) observed precipitation events (March – October) resulted in runoff simulated by WQ-COSM.
- Using the site-specific relationship 7 of 11 simulated runoff events fall below this relationship resulting in 83.2% (2.62 inches/3.15 inches) of the simulated runoff below the line.
- In total 260 of the 264 (98.5%) storm events are conservatively represented by the site-specific runoff relationship.
- Total administrative runoff volume (net impact to the river) from observed storm events is 4.8 times (15.22 inches/3.15 inches) greater than simulated runoff volume.

WQ-COSM Simulated Runoff Summary

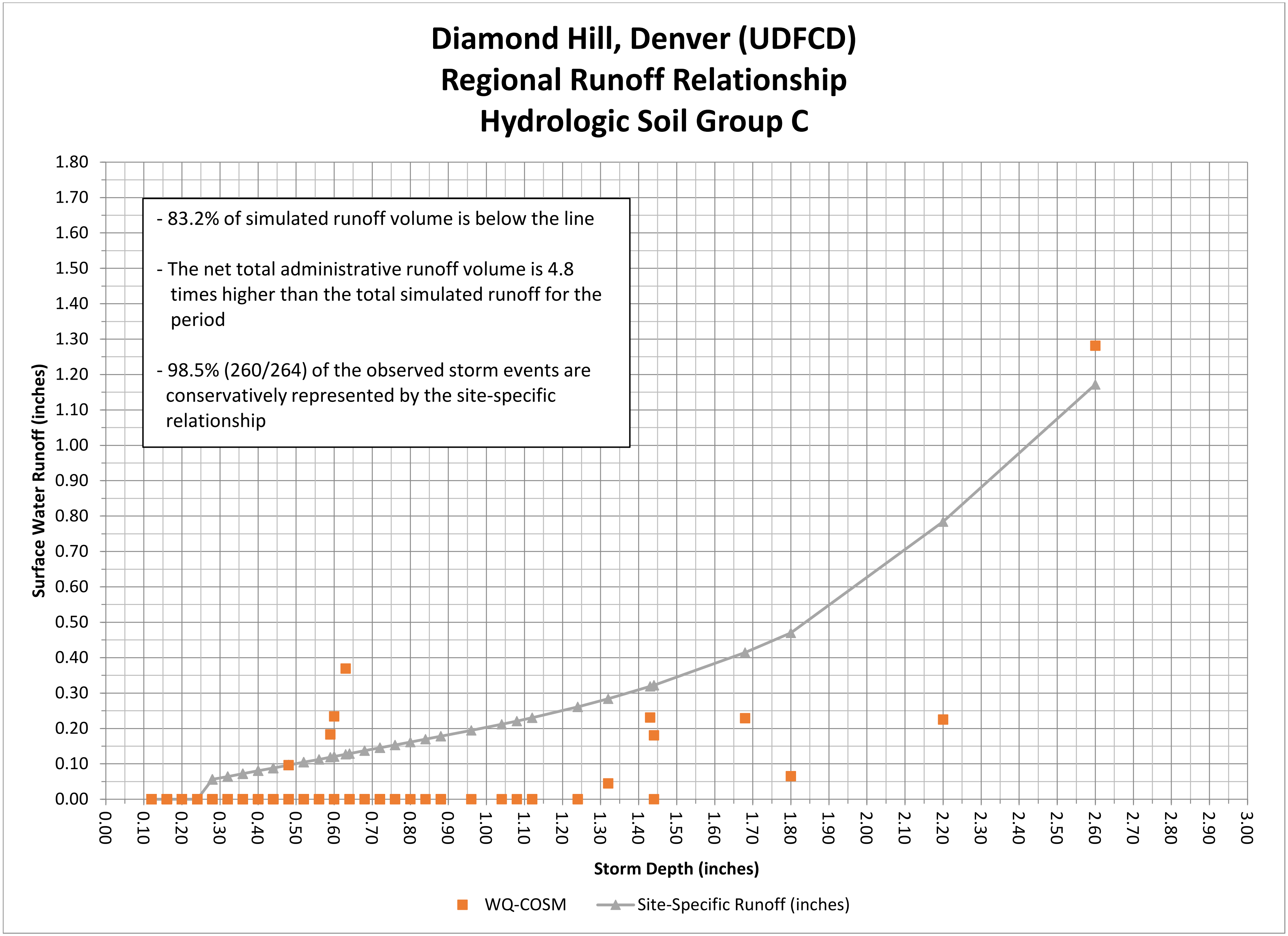
	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Runoff Volume Above the Line (inches)	0.00	0.42	0.11	0.53
Count of Runoff Events Above the Line	0	3	1	4
Percent of Runoff Above the Line (%)	0.0%	47.2%	4.9%	16.8%
Runoff Volume Below the Line (inches)	0.00	0.47	2.15	2.62
Count of Runoff Events Below the Line	0	1	6	7
Percent of Runoff Below the Line (%)	0.0%	52.4%	95.1%	83.2%
Total Runoff Volume (inches)	0.00	0.89	2.26	3.15
Total Count of Runoff Events	0	4	7	11

WQ-COSM Simulated Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Simulated Runoff Volume (inches)	0.00	0.89	2.26	3.15
Total Count of Runoff Events	0	4	7	11
Total Precipitation Volume (inches)	23.40	50.98	20.75	95.13
Total Count of Storm Events	139	111	14	264
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	1.7%	10.9%	3.3%
Percent of Storm Events Resulting in Runoff (%)	0.0%	3.6%	50.0%	4.2%

Administrative Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Administrative Runoff Volume (inches)	0.00	10.25	5.50	15.75
Total Count of Runoff Events	0	111	14	125
Total Precipitation Volume (inches)	23.40	50.98	20.75	95.13
Total Count of Storm Events	139	111	14	264
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	20.1%	26.5%	16.6%
Percent of Storm Events Resulting in Runoff (%)	0.0%	100.0%	100.0%	47.3%


Diamond Hill, Denver (UDFCD)
Regional Runoff Relationship
Hydrologic Soil Group C
- 83.2% of simulated runoff volume is below the line
- The net total administrative runoff volume is 4.8 times higher than the total simulated runoff for the period
- 98.5% (260/264) of the observed storm events are conservatively represented by the site-specific relationship
Surface Water Runoff (inches)
Storm Depth (inches)
WQ-COSM
Site-Specific Runoff (inches)

Station: Justice Center, Boulder (UDFCD)

Station ID	Station Name	City	Start Date	End Date	Source
4360	Justice Center	Boulder	1/20/2011	12/8/2018	UDFCD/OneRain

- In total 15 of the 259 (5.8%) observed precipitation events (March – October) resulted in runoff simulated by WQ-COSM.
- Using the site-specific relationship 8 of 15 simulated runoff events fall below this relationship resulting in 74.9% (5.13 inches/6.85 inches) of the simulated runoff below the line.
- In total 252 of the 259 (97.3%) storm events are conservatively represented by the site-specific runoff relationship.
- Total administrative runoff volume (net impact to the river) from observed storm events is 2.5 times (17.25 inches/6.85 inches) greater than simulated runoff volume.
- Excludes 09/11/2013 and 09/12/2013 Storm Events (Storm Depth > 5.0 inches, exceeds runoff relationship).

WQ-COSM Simulated Runoff Summary

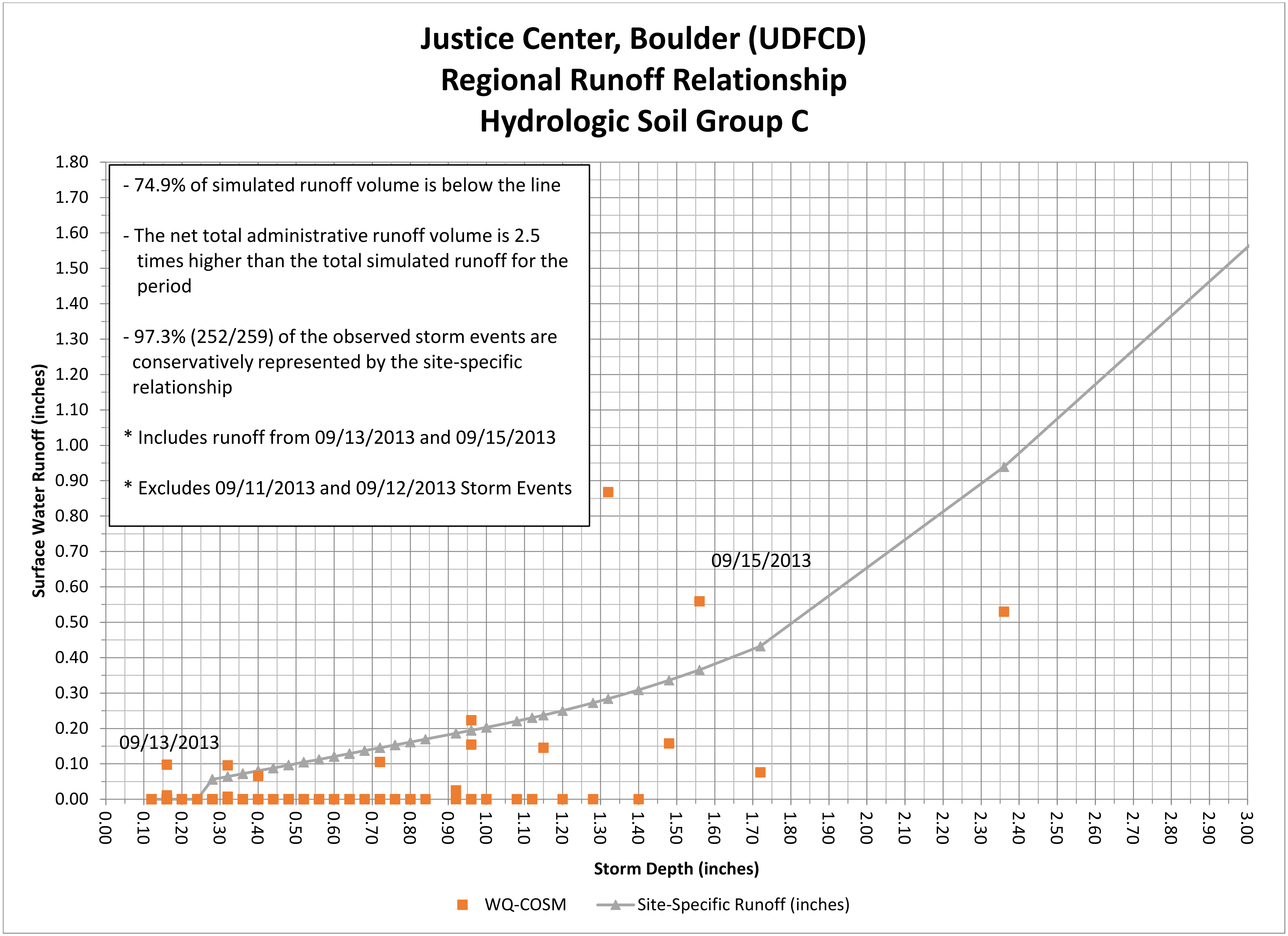
	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Runoff Volume Above the Line (inches)	0.11	0.06	1.55	1.72
Count of Runoff Events Above the Line	2	2	3	7
Percent of Runoff Above the Line (%)	100.0%	8.8%	25.6%	25.1%
Runoff Volume Below the Line (inches)	0.00	0.62	4.51	5.13
Count of Runoff Events Below the Line	0	4	4	8
Percent of Runoff Below the Line (%)	0.0%	91.2%	74.5%	74.9%
Total Runoff Volume (inches)	0.11	0.68	6.05	6.85
Total Count of Runoff Events	2	6	7	15

WQ-COSM Simulated Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Simulated Runoff Volume (inches)	0.11	0.68	6.05	6.85
Total Count of Runoff Events	2	6	7	15
Total Precipitation Volume (inches)	21.24	59.20	21.22	101.66
Total Count of Storm Events	128	118	13	259
Percent of Precipitation Volume Resulting in Runoff (%)	0.5%	1.1%	28.5%	6.7%
Percent of Storm Events Resulting in Runoff (%)	1.6%	5.1%	53.8%	5.8%

Administrative Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Administrative Runoff Volume (inches)	0.00	11.91	7.05	18.97
Total Count of Runoff Events	0	118	13	131
Total Precipitation Volume (inches)	21.24	59.20	21.22	101.66
Total Count of Storm Events	128	118	13	259
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	20.1%	33.2%	18.7%
Percent of Storm Events Resulting in Runoff (%)	0.0%	100.0%	100.0%	50.6%



Justice Center, Boulder (UDFCD)
Regional Runoff Relationship
Hydrologic Soil Group C
- 74.9% of simulated runoff volume is below the line
- The net total administrative runoff volume is 2.5 times higher than the total simulated runoff for the period
- 97.3% (252/259) of the observed storm events are conservatively represented by the site-specific relationship
* Includes runoff from 09/13/2013 and 09/15/2013
* Excludes 09/11/2013 and 09/12/2013 Storm Events
09/15/2013
09/13/2013
Surface Water Runoff (inches)
Storm Depth (inches)
WQ-COSM
Site-Specific Runoff (inches)

Station: Salisbury Park, Parker (UDFCD)

Station ID	Station Name	City	Start Date	End Date	Source
2730	Salisbury Park	Parker	12/19/2008	12/8/2018	UDFCD/OneRain

- In total 5 of the 226 (2.2%) observed precipitation events (March – October) resulted in runoff simulated by WQ-COSM.
- Using the site-specific relationship 3 of 5 simulated runoff events fall below this relationship resulting in 51.8% (0.85 inches/1.64 inches) of the simulated runoff below the line.
- In total 224 of the 226 (99.1%) storm events are conservatively represented by the site-specific runoff relationship.
- Total administrative runoff volume (net impact to the river) from observed storm events is 6.4 times (10.55 inches/1.64 inches) greater than simulated runoff volume.

WQ-COSM Simulated Runoff Summary

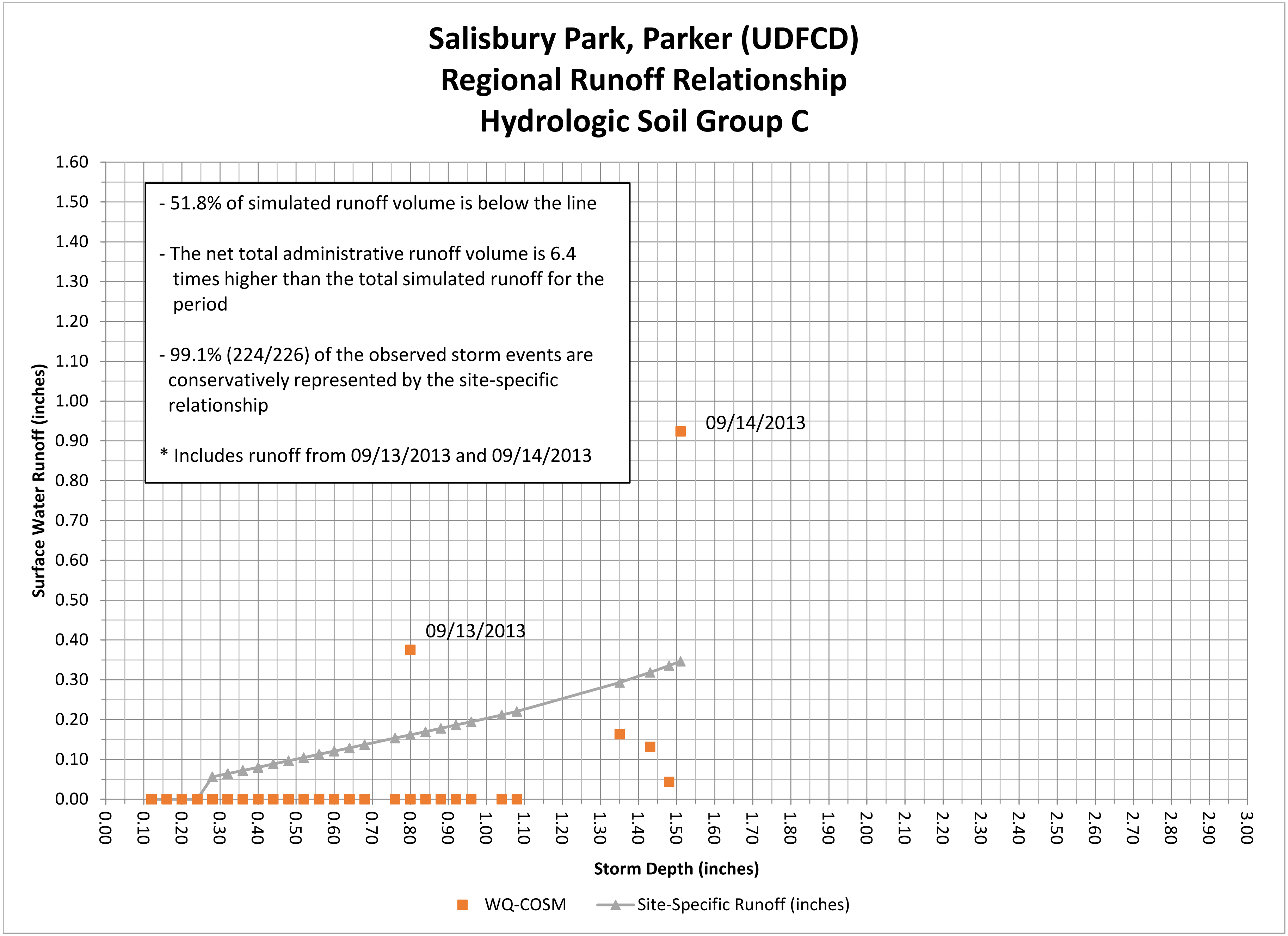
	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Runoff Volume Above the Line (inches)	0.00	0.21	0.58	0.79
Count of Runoff Events Above the Line	0	1	1	2
Percent of Runoff Above the Line (%)	0.0%	55.3%	46.0%	48.2%
Runoff Volume Below the Line (inches)	0.00	0.17	0.69	0.85
Count of Runoff Events Below the Line	0	0	3	3
Percent of Runoff Below the Line (%)	0.0%	43.5%	54.8%	51.8%
Total Runoff Volume (inches)	0.00	0.38	1.26	1.64
Total Count of Runoff Events	0	1	4	5

WQ-COSM Simulated Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Simulated Runoff Volume (inches)	0.00	0.38	1.26	1.64
Total Count of Runoff Events	0	1	4	5
Total Precipitation Volume (inches)	19.92	45.68	10.01	75.61
Total Count of Storm Events	120	98	8	226
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	0.8%	12.6%	2.2%
Percent of Storm Events Resulting in Runoff (%)	0.0%	1.0%	50.0%	2.2%

Administrative Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Administrative Runoff Volume (inches)	0.00	9.19	2.16	11.34
Total Count of Runoff Events	0	98	8	106
Total Precipitation Volume (inches)	19.92	45.68	10.01	75.61
Total Count of Storm Events	120	98	8	226
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	20.1%	21.6%	15.0%
Percent of Storm Events Resulting in Runoff (%)	0.0%	100.0%	100.0%	46.9%



Salisbury Park, Parker (UDFCD)
Regional Runoff Relationship
Hydrologic Soil Group C
- 51.8% of simulated runoff volume is below the line
- The net total administrative runoff volume is 6.4 times higher than the total simulated runoff for the period
- 99.1% (224/226) of the observed storm events are conservatively represented by the site-specific relationship
* Includes runoff from 09/13/2013 and 09/14/2013
09/14/2013
09/13/2013
Surface Water Runoff (inches)
1.60
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20
2.30
2.40
2.50
2.60
2.70
2.80
2.90
3.00
Storm Depth (inches)
WQ-COSM
Site-Specific Runoff (inches)

Station: Tollgate at 6th, Aurora (UDFCD)

Station ID	Station Name	City	Start Date	End Date	Source
700	Tollgate at 6th	Aurora	12/19/2008	12/8/2018	UDFCD/OneRain

- In total 11 of the 256 (4.3%) observed precipitation events (March – October) resulted in runoff simulated by WQ-COSM.
- Using the site-specific relationship 5 of 11 simulated runoff events fall below this relationship resulting in 71.0% (3.63 inches/5.11 inches) of the simulated runoff below the line.
- In total 250 of the 256 (97.7%) storm events are conservatively represented by the site-specific runoff relationship.
- Total administrative runoff volume (net impact to the river) from observed storm events is 2.7 times (14.00 inches/5.11 inches) greater than simulated runoff volume.
- Excludes 09/12/2013 Storm Events (Storm Depth > 5.0 inches, exceeds runoff relationship).

WQ-COSM Simulated Runoff Summary

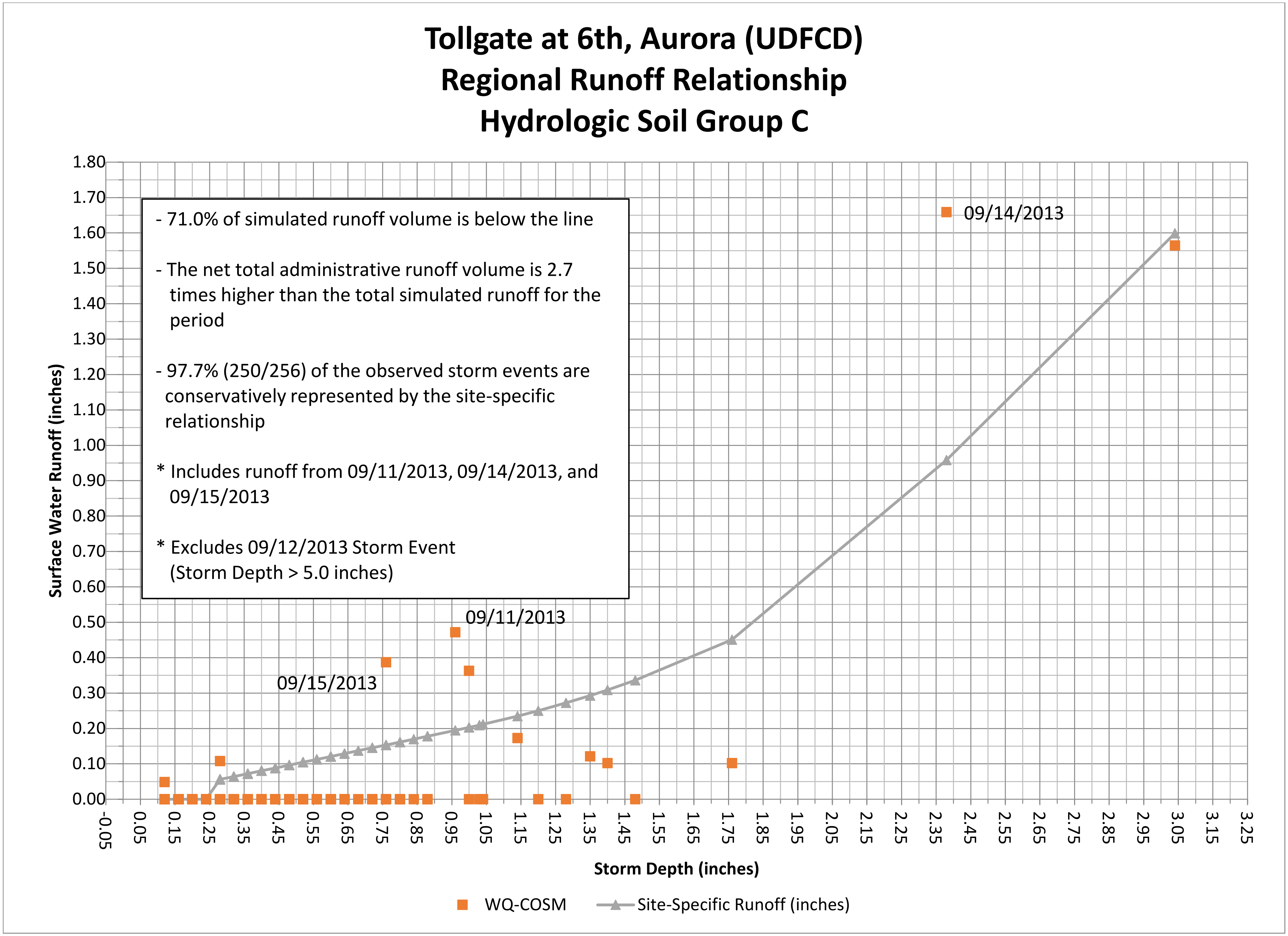
	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Runoff Volume Above the Line (inches)	0.05	0.72	0.70	1.47
Count of Runoff Events Above the Line	1	4	1	6
Percent of Runoff Above the Line (%)	100.0%	54.1%	18.8%	28.8%
Runoff Volume Below the Line (inches)	0.00	0.61	3.02	3.63
Count of Runoff Events Below the Line	0	0	5	5
Percent of Runoff Below the Line (%)	0.0%	45.9%	81.2%	71.0%
Total Runoff Volume (inches)	0.05	1.33	3.72	5.11
Total Count of Runoff Events	1	4	6	11

WQ-COSM Simulated Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Simulated Runoff Volume (inches)	0.05	1.33	3.72	5.11
Total Count of Runoff Events	1	4	6	11
Total Precipitation Volume (inches)	22.92	51.44	17.10	91.46
Total Count of Storm Events	138	107	11	256
Percent of Precipitation Volume Resulting in Runoff (%)	0.2%	2.6%	21.8%	5.6%
Percent of Storm Events Resulting in Runoff (%)	0.7%	3.7%	54.5%	4.3%

Administrative Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Administrative Runoff Volume (inches)	0.00	10.35	5.12	15.47
Total Count of Runoff Events	0	107	11	118
Total Precipitation Volume (inches)	22.92	51.44	17.10	91.46
Total Count of Storm Events	138	107	11	256
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	20.1%	29.9%	16.9%
Percent of Storm Events Resulting in Runoff (%)	0.0%	100.0%	100.0%	46.1%



Tollgate at 6th, Aurora (UDFCD)
Regional Runoff Relationship
Hydrologic Soil Group C
- 71.0% of simulated runoff volume is below the line
- The net total administrative runoff volume is 2.7 times higher than the total simulated runoff for the period
- 97.7% (250/256) of the observed storm events are conservatively represented by the site-specific relationship
* Includes runoff from 09/11/2013, 09/14/2013, and 09/15/2013
* Excludes 09/12/2013 Storm Event (Storm Depth > 5.0 inches)
09/14/2013
09/11/2013
09/15/2013
Surface Water Runoff (inches)
Storm Depth (inches)
WQ-COSM
Site-Specific Runoff (inches)

Station: South Academy Blvd, Colorado Springs (USGS)

Station ID	Station Name	City	Start Date	End Date	Source
384908104453301	South Academy Blvd	Colorado Springs	4/1/2011	12/19/2018	USGS (Colorado Springs Engineering)

- In total 27 of the 224 (12.1%) observed precipitation events (March – October) resulted in runoff simulated by WQ-COSM.
- Using the site-specific relationship 11 of 27 simulated runoff events fall below this relationship resulting in 85.8% (12.36 inches/14.41 inches) of the simulated runoff below the line.
- In total 208 of the 224 (92.9%) storm events are conservatively represented by the site-specific runoff relationship.
- Total administrative runoff volume (net impact to the river) from observed storm events is 1.6 times (22.40 inches/14.41 inches) greater than simulated runoff volume.

WQ-COSM Simulated Runoff Summary

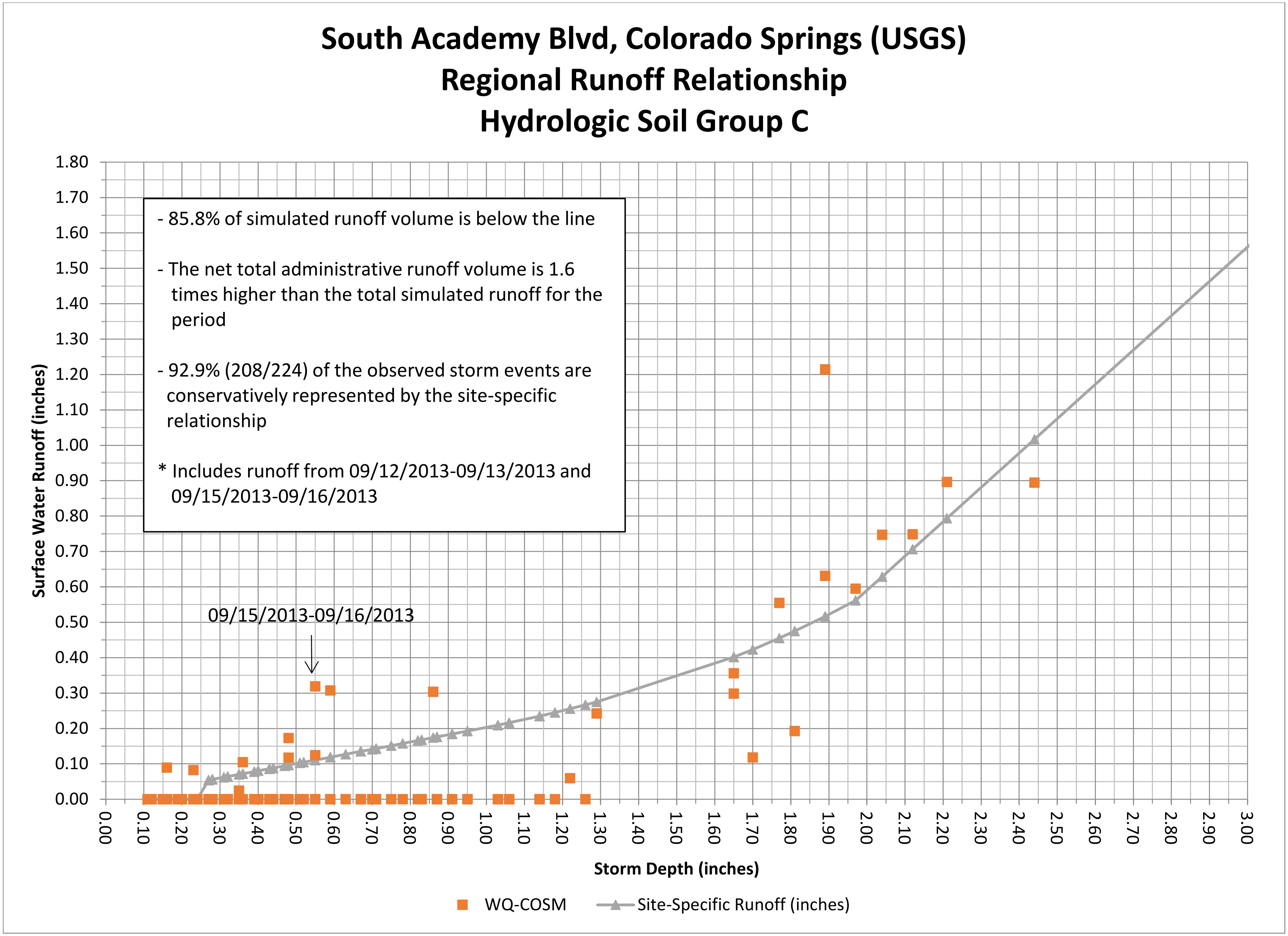
	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Runoff Volume Above the Line (inches)	0.17	0.67	1.21	2.05
Count of Runoff Events Above the Line	2	7	7	16
Percent of Runoff Above the Line (%)	100.0%	45.3%	9.5%	14.2%
Runoff Volume Below the Line (inches)	0.00	0.81	11.55	12.36
Count of Runoff Events Below the Line	0	1	10	11
Percent of Runoff Below the Line (%)	0.0%	54.5%	90.5%	85.8%
Total Runoff Volume (inches)	0.17	1.48	12.76	14.41
Total Count of Runoff Events	2	8	17	27

WQ-COSM Simulated Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Simulated Runoff Volume (inches)	0.17	1.48	12.76	14.41
Total Count of Runoff Events	2	8	17	27
Total Precipitation Volume (inches)	17.61	44.90	45.97	108.48
Total Count of Storm Events	110	88	26	224
Percent of Precipitation Volume Resulting in Runoff (%)	1.0%	3.3%	27.8%	13.3%
Percent of Storm Events Resulting in Runoff (%)	1.8%	9.1%	65.4%	12.1%

Administrative Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Administrative Runoff Volume (inches)	0.00	9.04	15.42	24.45
Total Count of Runoff Events	0	88	26	114
Total Precipitation Volume (inches)	17.61	44.90	45.97	108.48
Total Count of Storm Events	110	88	26	224
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	20.1%	33.5%	22.5%
Percent of Storm Events Resulting in Runoff (%)	0.0%	100.0%	100.0%	50.9%



South Academy Blvd, Colorado Springs (USGS)
Regional Runoff Relationship
Hydrologic Soil Group C
- 85.8% of simulated runoff volume is below the line
- The net total administrative runoff volume is 1.6 times higher than the total simulated runoff for the period
- 92.9% (208/224) of the observed storm events are conservatively represented by the site-specific relationship
* Includes runoff from 09/12/2013-09/13/2013 and 09/15/2013-09/16/2013
09/15/2013-09/16/2013
Surface Water Runoff (inches)
Storm Depth (inches)
WQ-COSM
Site-Specific Runoff (inches)

Station: Harvard Gulch at University Park, Denver (UDFCD/USGS)

Station ID	Station Name	City	Start Date	End Date	Source
394028104565501	Harvard Gulch at University Park	Denver	5/6/2009	12/19/2018	UDFCD/USGS

- In total 10 of the 203 (4.9%) observed precipitation events (March – October) resulted in runoff simulated by WQ-COSM.
- Using the site-specific relationship 5 of 10 simulated runoff events fall below this relationship resulting in 67.5% (2.16 inches/3.20 inches) of the simulated runoff below the line.
- In total 198 of the 203 (97.5%) storm events are conservatively represented by the site-specific runoff relationship.
- Total administrative runoff volume (net impact to the river) from observed storm events is 4.2 times (13.30 inches/3.20 inches) greater than simulated runoff volume.

WQ-COSM Simulated Runoff Summary

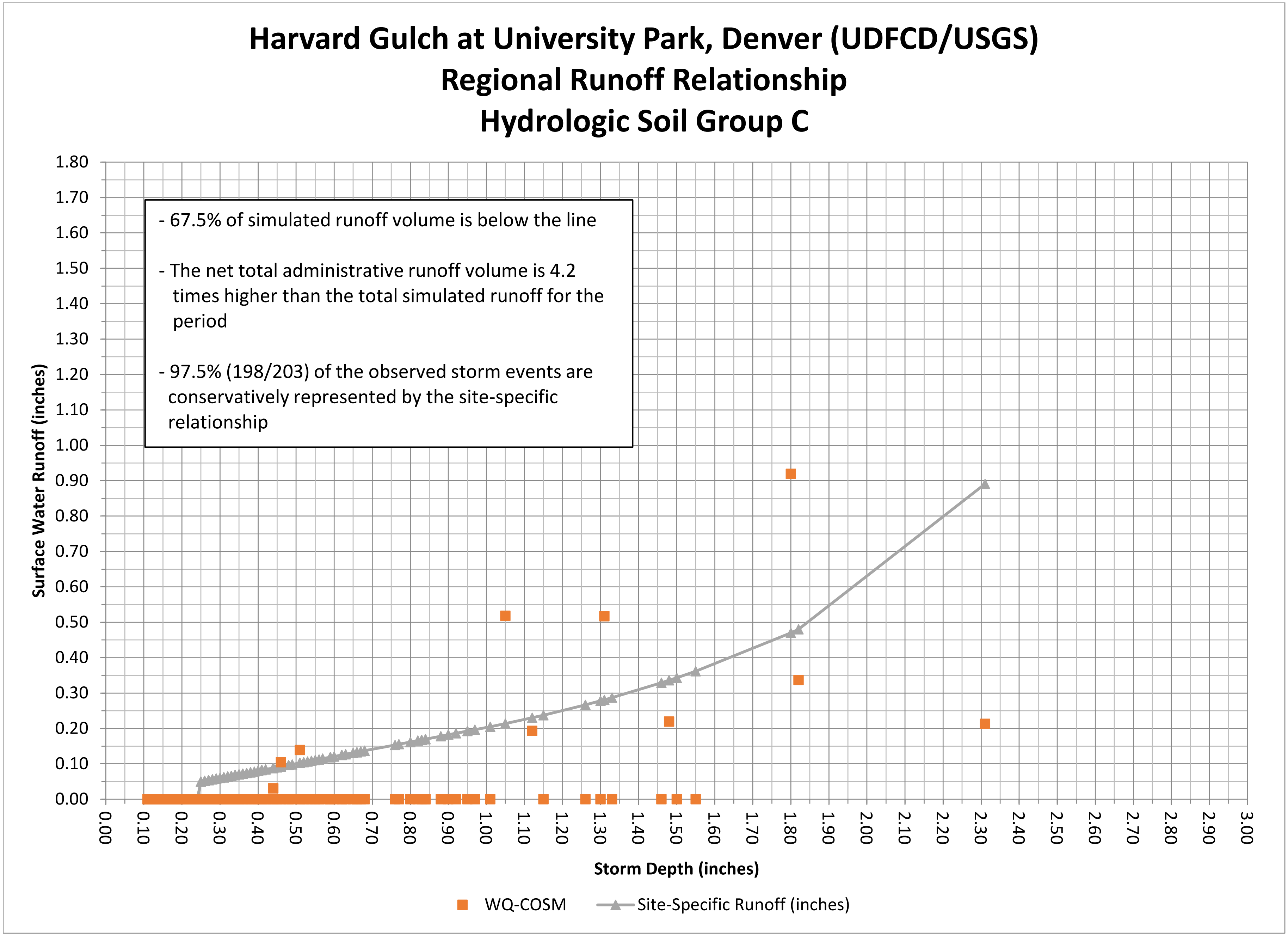
	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Runoff Volume Above the Line (inches)	0.00	0.05	0.99	1.04
Count of Runoff Events Above the Line	0	2	3	5
Percent of Runoff Above the Line (%)	0.0%	17.9%	33.9%	32.5%
Runoff Volume Below the Line (inches)	0.00	0.23	1.93	2.16
Count of Runoff Events Below the Line	0	1	4	5
Percent of Runoff Below the Line (%)	0.0%	81.9%	66.1%	67.5%
Total Runoff Volume (inches)	0.00	0.28	2.92	3.20
Total Count of Runoff Events	0	3	7	10

WQ-COSM Simulated Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Simulated Runoff Volume (inches)	0.00	0.28	2.92	3.20
Total Count of Runoff Events	0	3	7	10
Total Precipitation Volume (inches)	15.27	45.43	21.45	82.15
Total Count of Storm Events	91	97	15	203
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	0.6%	13.6%	3.9%
Percent of Storm Events Resulting in Runoff (%)	0.0%	3.1%	46.7%	4.9%

Administrative Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Administrative Runoff Volume (inches)	0.00	9.14	5.21	14.34
Total Count of Runoff Events	0	97	15	112
Total Precipitation Volume (inches)	15.27	45.43	21.45	82.15
Total Count of Storm Events	91	97	15	203
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	20.1%	24.3%	17.5%
Percent of Storm Events Resulting in Runoff (%)	0.0%	100.0%	100.0%	55.2%


Harvard Gulch at University Park, Denver (UDFCD/USGS)
Regional Runoff Relationship
Hydrologic Soil Group C
- 67.5% of simulated runoff volume is below the line
- The net total administrative runoff volume is 4.2 times higher than the total simulated runoff for the period
- 97.5% (198/203) of the observed storm events are conservatively represented by the site-specific relationship
Surface Water Runoff (inches)
Storm Depth (inches)
WQ-COSM
Site-Specific Runoff (inches)

Station: West Plum Creek, Sedalia (Town of Castle Rock/USGS)

Station ID	Station Name	City	Start Date	End Date	Source
6708690	West Plum Creek	Sedalia	4/2/2015	12/19/2018	Town of Castle Rock/USGS

- In total 5 of the 92 (5.4%) observed precipitation events (March – October) resulted in runoff simulated by WQ-COSM.
- Using the site-specific relationship 2 of 5 simulated runoff events fall below this relationship resulting in 73.4% (1.49 inches/2.03 inches) of the simulated runoff below the line.
- In total 89 of the 92 (96.7%) storm events are conservatively represented by the site-specific runoff relationship.
- Total administrative runoff volume (net impact to the river) from observed storm events is 2.2 times (4.37 inches/2.03 inches) greater than simulated runoff volume.

WQ-COSM Simulated Runoff Summary

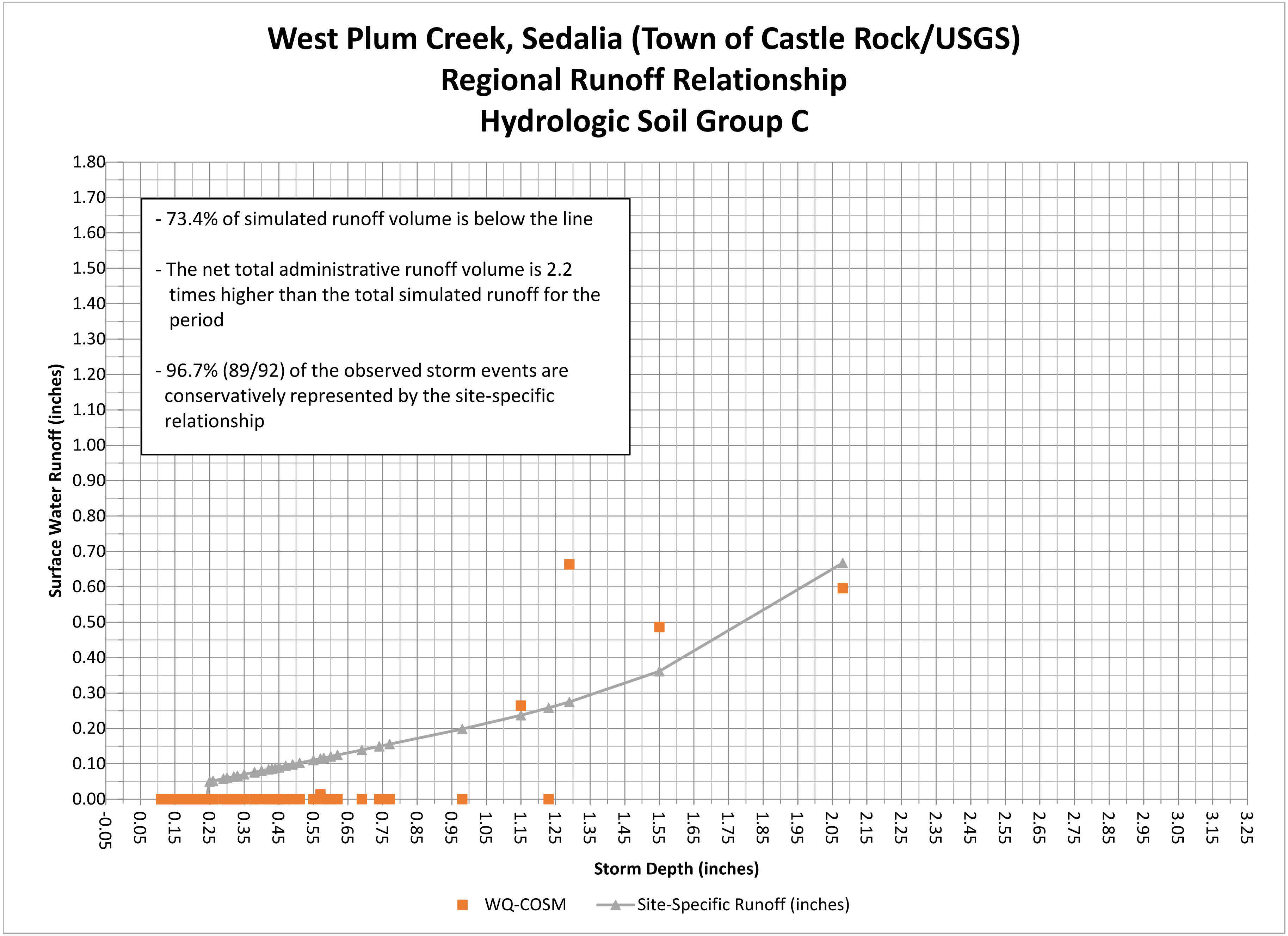
	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Runoff Volume Above the Line (inches)	0.00	0.00	0.54	0.54
Count of Runoff Events Above the Line	0	0	3	3
Percent of Runoff Above the Line (%)	0.0%	0.0%	26.9%	26.6%
Runoff Volume Below the Line (inches)	0.00	0.01	1.47	1.49
Count of Runoff Events Below the Line	0	1	1	2
Percent of Runoff Below the Line (%)	0.0%	147.8%	73.1%	73.4%
Total Runoff Volume (inches)	0.00	0.01	2.01	2.03
Total Count of Runoff Events	0	1	4	5

WQ-COSM Simulated Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Simulated Runoff Volume (inches)	0.00	0.01	2.01	2.03
Total Count of Runoff Events	0	1	4	5
Total Precipitation Volume (inches)	9.18	15.50	7.30	31.98
Total Count of Storm Events	52	35	5	92
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	0.1%	27.5%	6.3%
Percent of Storm Events Resulting in Runoff (%)	0.0%	2.9%	80.0%	5.4%

Administrative Event Summary

	<= 0.25 inch	>=0.25 & <= 1.0 inch	>1.0 inch	Total
Total Administrative Runoff Volume (inches)	0.00	3.11	1.80	4.91
Total Count of Runoff Events	0	35	5	40
Total Precipitation Volume (inches)	9.18	15.50	7.30	31.98
Total Count of Storm Events	52	35	5	92
Percent of Precipitation Volume Resulting in Runoff (%)	0.0%	20.1%	24.7%	15.4%
Percent of Storm Events Resulting in Runoff (%)	0.0%	100.0%	100.0%	43.5%



West Plum Creek, Sedalia (Town of Castle Rock/USGS)
Regional Runoff Relationship
Hydrologic Soil Group C
- 73.4% of simulated runoff volume is below the line
- The net total administrative runoff volume is 2.2 times higher than the total simulated runoff for the period
- 96.7% (89/92) of the observed storm events are conservatively represented by the site-specific relationship
Surface Water Runoff (inches)
Storm Depth (inches)
WQ-COSM
Site-Specific Runoff (inches)

DRAFT Memorandum

To: Tracy Kosloff, Colorado Division of Water Resources

From: Joel Barber P.E. , Leonard Rice Engineers, Inc.

Copy to: Sarah Stone, Dominion Water and Sanitation District

Reviewed by: Mark Mitisek and Greg Roush, Leonard Rice Engineers, Inc.

Date: December 28, 2018

Project: Colorado Water Plan Grant – Regional Factor Development for Precipitation Harvesting

Subject: Task 4C – Site-Specific and Regional Deep Percolation

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Purpose

The purpose of this memorandum is to outline the methods, assumptions, and results of calculating the site specific deep percolation flows and deep percolation factor and provide a recommended regional groundwater deep percolation factor. Deep percolation can be applied as a groundwater return flow by lagging the deep percolation to the stream. For the purpose of this analysis we assumed the following definitions for deep percolation and groundwater return flows.

Deep percolation factors are the annual percentage of the total precipitation that passes the root zone, recharges the aquifer, and will accrue to the stream system as a groundwater return flow.

Groundwater return flows are deep percolation returns flows that are time lagged to the stream.

The simulated site specific groundwater deep percolation presented in this memorandum are calculated as daily deep percolation for the period of observations in Sterling Gulch. We provide a recommended site specific deep percolation factor as a percent of annual precipitation. We provide a recommended regional groundwater deep percolation factor based on the site specific modeling and published regional studies and references applicable to the Colorado Front Range and plains climate and geology.

The analysis presented was developed to conservatively simulate deep percolation under pre-development conditions and the recommended factors were selected to be protective of the stream.

Steps for Developing Deep Percolation Factors

The steps for developing site specific and regional factors are summarized in **Figure 1**. We developed a calibrated Hydrus 1-D model and a simplified soil moisture reservoir (SMR) accounting model to simulate deep percolation in the Sterling Gulch as a basis for the recommendation of site specific and regional groundwater return flow factors. The results were compared to published regional studies and references applicable to Colorado to provide a recommendation of regional deep percolation factors.

Deep Percolation

Deep percolation is defined as precipitation that infiltrates through the vadose zone and recharges groundwater. Precipitation which infiltrates beyond the rooting zone and is not accessible by the shallow rooting grasses and bushes which dominate the vegetation in the basin and for the purpose of this analysis is considered groundwater recharge and deep percolation.

Observed Deep Percolation

Deep percolation is measured in the field using the on-site lysimeter as described in detail in Section *Task 3A – Site Characterization*. **Figure 2** is a plot of observed deep percolation at the lysimeter from April, 2014 through July, 2018. Significant deep percolation was only observed in 2015 and 2016 with 2.16 and 0.53 inches respectively.

Simulated Deep Percolation

We simulated deep percolation in the Sterling Ranch drainage basin with two models. We developed a numerical model of the soil moisture reservoir in one-dimension (1-D) using Hydrus 1-D which simulated the water balance of soil column in 5 minute or less time steps. We also developed a standard daily numerical soil moisture accounting model using the Soil-Water-Balance Method (Dingman, 2008).

Numerical Model of Soil Moisture Reservoir Accounting (Hydrus-1D)

The four water balance components evaporation, transpiration, runoff, and deep percolation which accounts for inflow and outflow from the vadose zone were simulated in Hydrus 1-D, a finite difference model used for calculating one-dimensional (1-D) movement of water in variably saturated media. Hydrus 1-D is a commonly used and industry accepted model for simulating the soil water balance in natural conditions; including variably saturated flow through porous media, vapor flow, root water uptake, and atmospheric/surface interactions (Simunek et al, 2008). This section provides a summary of the model set-up and results, with a focus on the calculated deep percolation component of the water balance. A detailed description of the model is included in *Task 4A – Site-Specific Water Balance Model Memorandum.*

The numerical model simulates the following conceptual model:

Under the drainage basins natural conditions, precipitation enters storage in the soil pore space in the vadose zone unless the rate of precipitation is greater than the infiltration capacity of the soil, in which case the precipitation runs-off. Water which enters soil moisture storage is removed by either evaporation and transpiration (as a combination referred to as the ET component of the water balance) or deep percolation. Deep percolation occurs if infiltration is greater than the available storage. Deep percolation recharges the alluvial groundwater system. Over long periods of time (i.e. years) the change in storage in the vadose zone is nearly zero and all precipitation evaporates, transpires, runs-off, or recharges groundwater.

Variably saturated water flow is simulated using the Richard's equation. Evapotranspiration and water uptake by plants is simulated using an atmospheric boundary and potential evapotranspiration (PET) is defined using the Penman-Monteith equation. Deep percolation is calculated by simulating free drainage at the bottom of the model, defined at the base of the root zone.

We calibrated the model to the on-site lysimeter (see *Task 3A – Site-Specific Data Compilation* memo for a detailed description of the lysimeter). The model is 3.75 feet deep, mirroring the depth of the lysimeter. A atmospheric top boundary allowing for ponding and surface runoff simulates evaporation and transpiration fluxes out of the soil column. Daily average wind speed, maximum temperature, minimum temperature, and radiation are assigned using the on-site climate station. Precipitation data from the on-site weighing bucket was input in 5 minute time steps.

The calibration run simulated a 2618 day period representative of lysimeter observations from April, 2010 to June, 2017. The model was calibrated to; (1) observed soil moisture in the lysimeter at depths of 10 inches and 20 inches, (2) total observed changes in water volume in the lysimeter, and (3) measured seepage from the bottom of the lysimeter. **Figure 3** depicts the simulated versus observed changes in total soil moisture for selected period of high quality lysimeter data (Spring 2017). The selected calibration period is suitable for evaluating the model because the lysimeter scale had just been calibrated and there is a minimal amount of identified error in the readings (see *Task 3A – Site-Specific Data Compilation*).

Figure 4 is the simulated versus observed soil moisture at depths of 10 inches and 20 inches in the lysimeter. The simulated water content is greater than the soil moisture probe readings, but closely simulates the timing of wetting and drying cycles. The discrepancy in the modeled and observed moisture content is potentially due to the soil moisture probes not being calibrated to the in-situ soils. Additionally, higher simulated moisture contents indicate a higher magnitude of downward flux and more deep percolation.

The simulated and observed deep percolation is presented in **Table 1**. The model accurately simulates the infrequency of deep percolation events. During a wet year (2015) the model closely simulates the magnitude of observed deep percolation. In 2016 the model underestimates deep percolation. The error in simulated versus observed deep percolation is 0.3% of the total mass balance which is deemed an acceptable calibration.

Table 1: Modeled versus observed deep percolation.

Year	Modeled Deep Percolation (in)	Observed Deep Percolation (in)
2010	0.00	-
2011	0.00	-
2012	0.00	-
2013	0.00	-
2014	0.00	0.00
2015	2.26	2.16
2016	0.01	0.53
2017	0.00	0.04
2018	0.00	0.00
Total	**2.27**	**2.73**
Note: No lysimeter observations available prior to 2014.		

The basin wide simulation models a period of 2982 days representative of April, 2010 through May, 2018. All inputs in the forward run are based on the model calibration except for the following;

1. the hydraulic conductivity of the soil which was selected to be 0.99 ft/day based on 8 double ring infiltrometer tests conducted in the basin (See *Task 3A – Site Characterization*).
2. The allowable ponding was reduced to 0.05 inches from 1.0 inches. For more details on the allowable ponding please see *Task 4A - Site Specific Water Balance Model*.

The simulated soil moisture accounting is presented in **Table 2**. The simulated deep percolation was 1.4% of precipitation or 42 acre-feet over the 2982 day modeling period. The observed deep percolation, extrapolated from the lysimeter to the entire 223.2 acre area, is 50.5 acre-ft or 2% of precipitation.

Table 2: Modeled Sterling Gulch soil moisture water balance for a modeling period from April 2010 through May 2018.

Water Balance Component	Modeled Value (Acre-Ft)	Factor of Precipitation (%)
Precipitation	2527	100%
Runoff	65	3%
Evaporation	1257	50%
Transpiration	1164	46%
Deep Percolation	42	2%

Standard Soil Moisture Reservoir Accounting

Soil moisture reservoir accounting is a standard method used to calculate the amount of infiltration that deep percolates into the groundwater system. A daily soil moisture reservoir (SMR) water budget accounting model was developed following the soil-water-balance methods outlined in Dingman (2008). A max rooting depth of 24 inches was used based on the vegetation and lysimeter depth at Sterling Ranch.

Deep percolation events will be quantified using continuous daily soil moisture accounting. Deep percolation events will occur only when the soil moisture reservoir is exceeded. The continuous soil moisture accounting is calculated using the following equation:

$$Deep\ Percolation = P - ET - Q_{sw} + \Delta S$$

Where P is precipitation, ET is Evapotranspiration, Q_{sw} is runoff, and ΔS is change in storage, where there is a maximum amount of storage in the soil column. The accounting was conducted on a daily basis. ET was assigned the PET calculated in Hydrus model. The Hydrus model calculated PET following the Penman-Monteith method (Simunek et al, 2008). We calculated three different deep percolation values assuming Q_{sw} equals (1) the calculated runoff from the WQ-COSM Model, (2) the Hydrus 1-D model, and (3) observed runoff (for more information on runoff values see *Task 4B Site-Specific Surface Water Return Flows* and *Task 3A – Site-Specific Data Compilation* memos for more information). The accounting model assumes that all excess precipitation goes to storage up to the point where the available storage in the soil column is reached, at which point ΔS goes to zero and excess precipitation becomes deep percolation. The maximum available storage is calculated as the product of the soils available water content and the depth to the base of the rooting zone. The soils available water content is assumed to be 3.6 inches with an available water content of 15% for a sandy clay loam and a rooting depth of 24 inches (NRCS, 2018).

A continuous soil moisture reservoir accounting was constructed for Sterling Ranch from July 2010 to June 2018. A daily time step is used in the accounting. **Table 3** summarizes the count and volume of deep percolation events occurring in each year. Using this approach the average annual deep percolation over the period for Hydrologic Soil Group C is 2.7 to 3.1 inches or approximately 2.2% of precipitation.

Table 3: SMR Model Calculated Deep Percolation Events Counts.

Year	Using Observed Runoff as Input		Using Hydrus 1-D Calculated Runoff as Input		Using WQ-COSM Calculated Runoff as Input	
	Number of Deep Percolation Events	Total Deep Percolation (inches)	Number of Deep Percolation Events	Total Deep Percolation (inches)	Number of Deep Percolation Events	Total Deep Percolation (inches)
2010	-	-	0	0.0	0	0.0
2011	-	-	0	0.0	0	0.0
2012	-	-	0	0.0	0	0.0
2013	-	-	0	0.0	0	0.0
2014	0	0.0	0	0.0	0	0.0
2015	8	2.6	8	2.4	8	2.5
2016	0	0.0	0	0.0	0	0.0
2017	3	0.5	3	0.4	3	0.5
2018	0	0.0	0	0.0	0	0.0
TOTAL	11	3.1	11	2.7	11	3.0
% Precip	**N/A**	**2.2%**	**N/A**	**2.0%**	**N/A**	**2.2%**
Note: Observations are not available before 2014.						

Discussion of Deep Percolation Events

Deep percolation events occur as a result of the available storage in the soil reservoir being exceeded. Deep percolation was observed in 2015 not only because it is the wettest year in the study period, but also that the timing of events resulted in exceeding the capacity of the soil reservoir without sufficient periods between events to remove the water from storage. Because deep percolation is sensitive to the magnitude and timing of individual events, there is not a direct correlation between total annual precipitation and deep percolation. **Figure 3** is the cumulative 1-D (inches) simulated change in storage from the Hydrus 1-D model. As shown, typically the positive changes in storage (i.e flow into the soil column) is followed by periods of negative change in storage (i.e flow out of the column) such that the soil moisture is ballance and deep percolation does not occur. In 2015 subsequent storms backed up together with infrequent period of ET resulted in a change in storage of 6 inches in the soil column, which exceeds the available storage and results in deep percolation.

Published Studies

LRE reviewed estimates of deep percolation from hydrology studies along the Front Range and Colorado plains and compared these to the Sterling Ranch site-specific estimates.

South Platte Decision Support System Groundwater Flow Model

The South Platte Decision Support System (SPDSS) groundwater flow model is a regional scale model of the South Platte River alluvial aquifer along the Front Range. Sterling Gulch is part of the South Platte drainage basin and therefore estimates of recharge from the SPDSS groundwater flow model are a good reference for regional deep percolation estimates. Deep percolation estimates are 3% of precipitation, regardless of precipitation magnitude, timing, or surficial soil type (CDM Smith, 2013; Brown and Caldwell, 2017). This estimate is 1.0% of precipitation greater than simulated in Hydrus 1-D for Sterling Gulch and 0.8% greater than the accounting model.

Rio Grande Decision Support System

Under the Rio Grande Decision Support System estimates of groundwater recharge vary by land use, but do not very based on precipitation magnitude, timing, or surficial soil type. In the RGDSS recharge is estimated to be 3% of precipitation for all native soils (RGDSS, Wilson, et Al., 2000). This estimate is 1.0% of precipitation greater than simulated in Hydrus 1-D for Sterling Gulch and 0.8% greater than the accounting model.

Republican River Basin

Groundwater recharge curves were developed as part of the Republican River Basin groundwater flow model (Republican River Compact, 2003). The published recharge curves (Republican River Compact, 2003) indicate that deep percolation is sensitive to both the annual precipitation and soil type, with recharge increasing as precipitation increases. For fine grained natural soils deep percolation is less than 3% for years with less than approximately 25 inches of rain and less than 1% for years with less than approximately 19 inches of rain. Deep percolation is less than 2% for medium grained natural soils and an annual precipitation less than approximately 17 inches. Between 2011 and 2017 the average precipitation recorded at the Sterling Ranch precipitation station is 17.4 inches with a maximum of 22.6 inches in 2015. Additionally, the native soils are predominantly fine grained fine to medium grained. The calculated deep percolation at sterling ranch, using the Republican River basin recharge curves, is less than 0% to 2%. The calculated recharge rates using the recharge curves are in agreement with the Hydrus 1-D simulated deep percolation and greater than the analytical soil reservoir accounting model.

Comparison Simulated to Observed Deep Percolation

Figure 5 shows a comparison of modeled deep perc and published literature values of deep percolation. For an average annual precipitation (17.5 inches) and the maximum recorded precipitation (22.5 inches) recorded at the sterling ranch rain gauge, the Hydrus model and accounting model simulated more deep percolation than is used in the Republican River Groundwater Model. Both the Hydrus model and accounting model simulate average deep percolation that is approximately 1% less than assumed in the SPDSS and RGDSS models. In general, all the models evaluated indicate that the long-term average deep percolation in the Sterling Ranch Basin is expected to be less than or equal to 3% of annual precipitation.

On an annual basis, the assumptions used in the SPDSS, RGDSS, and Republican River Basin models would estimate more annual deep percolation than the Sterling Ranch models for all years outside of 2015. They would underestimate the Sterling Ranch observed deep percolation in 2015 and 2016. Despite this, the published models overestimate the average annual deep percolation from the entire observed and modeled period (2011 to 2018).

Conclusions and Recommendations

We developed a numerical finite element model using Hydrus 1-D and an analytical SMR accounting model to simulate deep percolation in the Sterling Ranch drainage. The Hydrus 1-D simulated deep percolation in the basin is approximately 2.0% of precipitation. The SMR model simulated deep percolation is approximately 2.2% of precipitation. The Hydrus 1-D and SMR accounting simulated deep percolation are within 2% of published literature deep percolation values.

We recommend assigning a constant 3% of precipitation be accounted as deep percolation for a site specific factor at Sterling Ranch for hydrologic soil group C. The 2% of deep percolation is consistent with the observed deep percolation, Hydrus simulated deep percolation, and SMR modeled deep percolation. A 3% deep percolation factor would assume significantly more groundwater recharge for the years simulated and observed outside of 2015. 2015 was the wettest year observed at the Sterling Ranch climate station with a total of 22.6 inches of observed prescription, as a result we observed and modeled approximately 9% to 9.5% deep percolation. Deep percolation occured in 2015 and not other years because 2015 was the wettest year on record and the magnitude and relative timing of individual events in 2015 resulted in filling the soil reservoir beyond capacity. During other wet periods there was available storage in the soil reservoir to hold the magnitude of precipitation and periods of ET between events to remove water from the reservoir. Therefore a 3% factor may under account deep percolation during very wet years, but averaged over the entire observation record (2010 to 2018) the 3% factor over-estimates deep percolation by approximately 1% to 1.5%.

We recommend assigning a constant 3% of precipitation to be accounted as deep percolation as a regional factor for hydrologic soil group C. Sterling Ranch is predominantly hydrologic soil group C and the findings of this analysis are limited to basins of similar hydrologic characteristics. 3% of precipitation to deep percolation is greater than the average modeled and observed values and in line with the published values in the SDSS, RGDSS, and Republican River groundwater model, as shown on **Figure 5**. Increasing the deep percolation factor regionally accounts for some spatial variability in climate and soil. The recommended regional factor of 3% is protective of the stream because it is greater than simulated deep percolation and is in line with published values.

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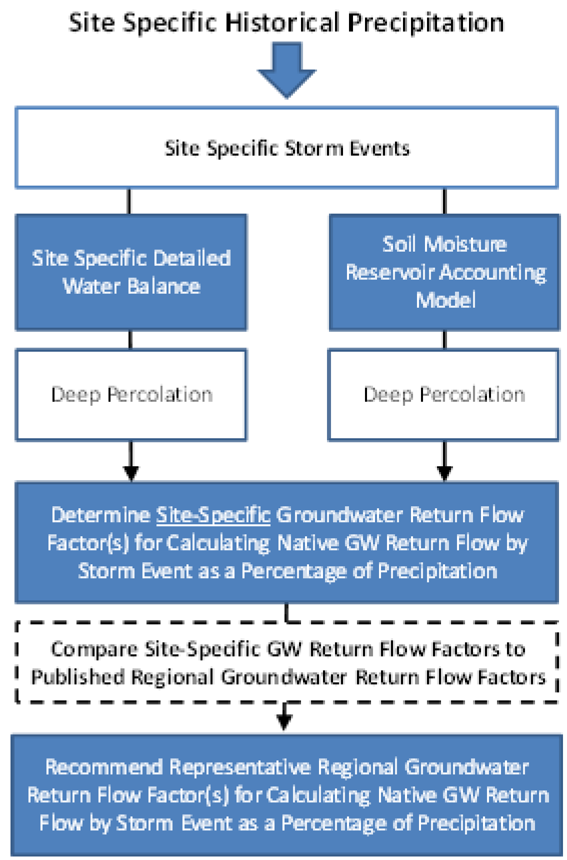

Figure 1
Steps for Developing Site Specific and Regional Groundwater Return Factors

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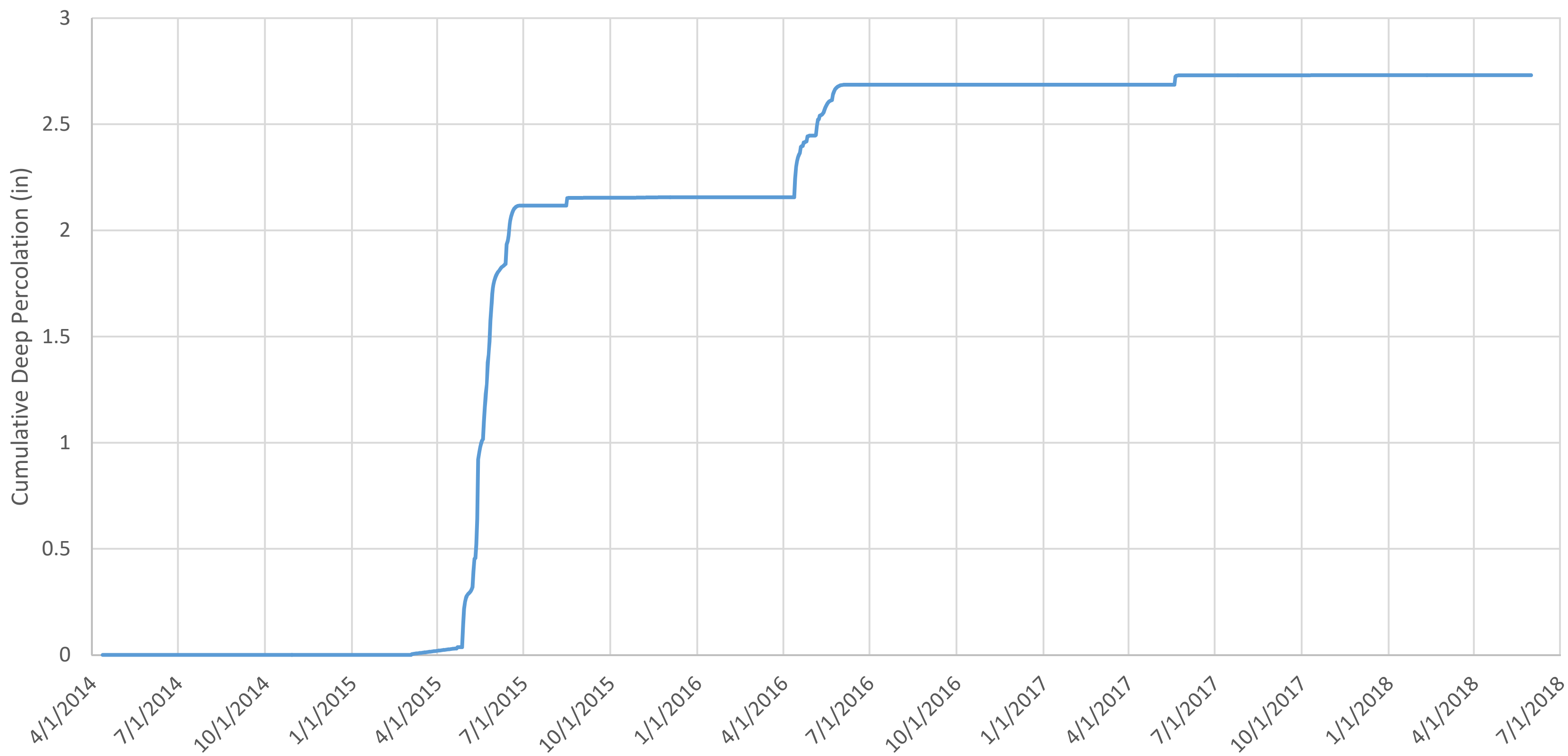

Figure 2
Observed Lysimeter Deep Percolation

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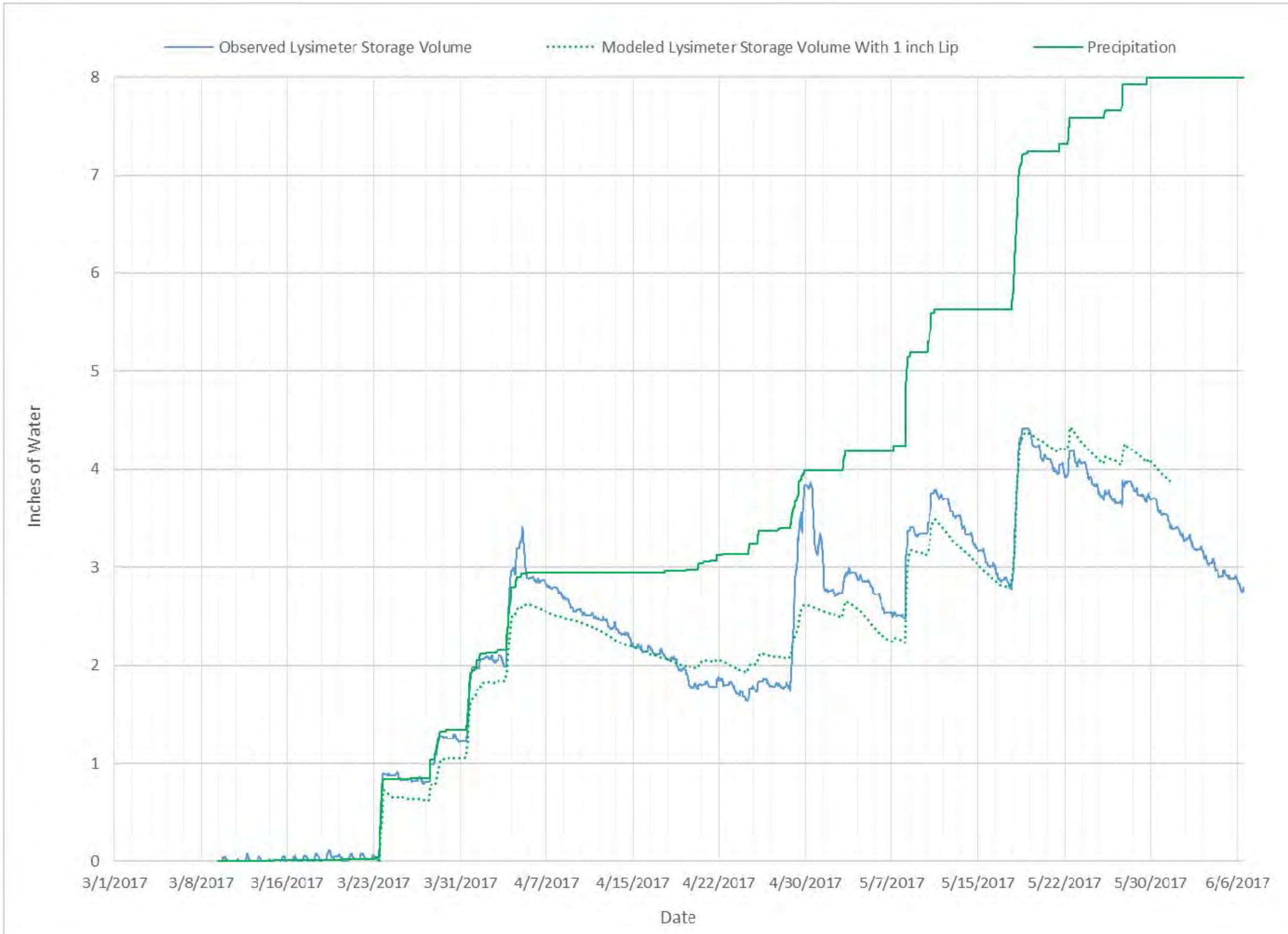

Figure 3
Observed Versus Simulated
Storage in the Lysimeter

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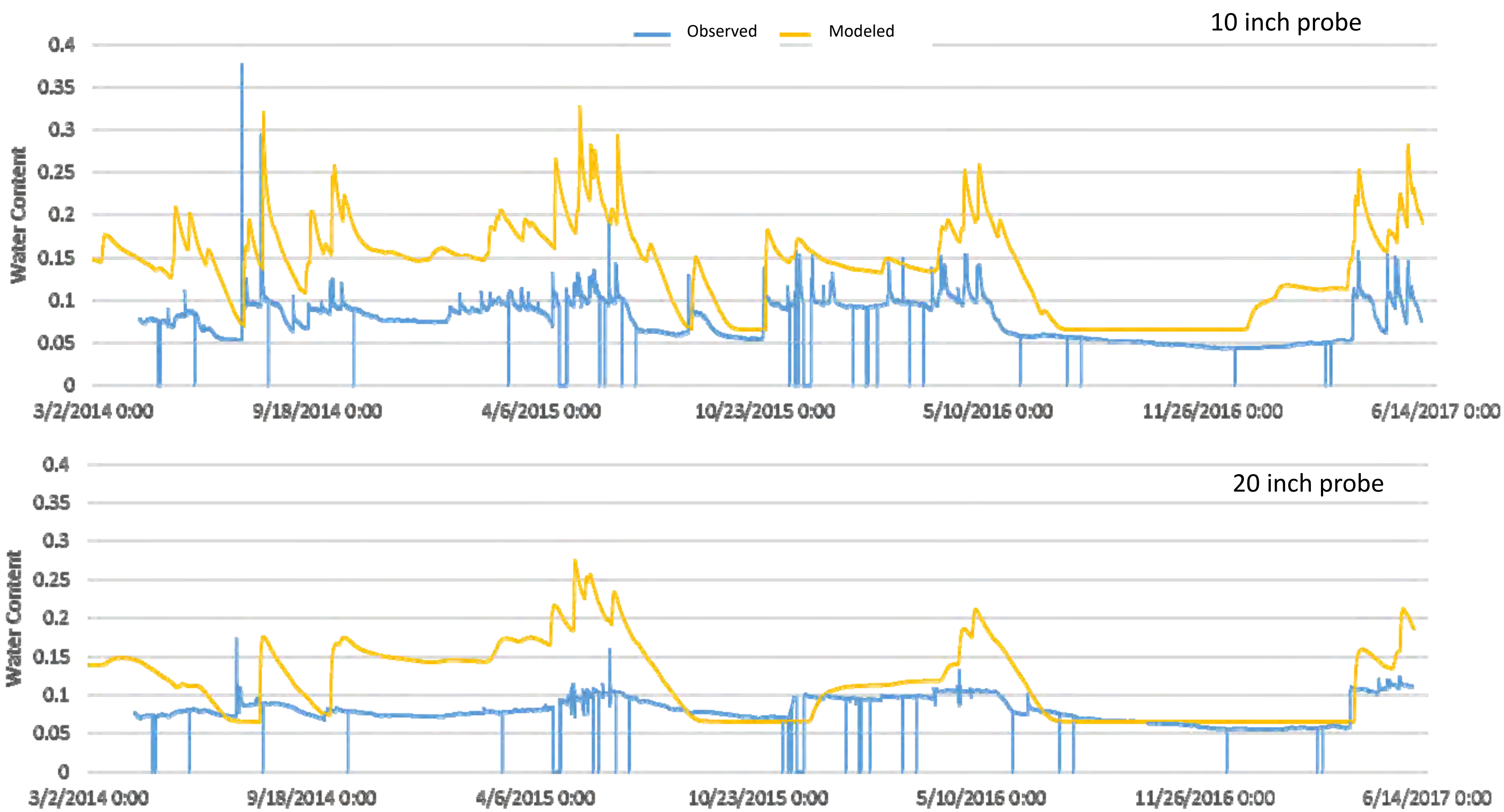

Figure 4
Observed Versus Simulated
Storage in the Lysimeter

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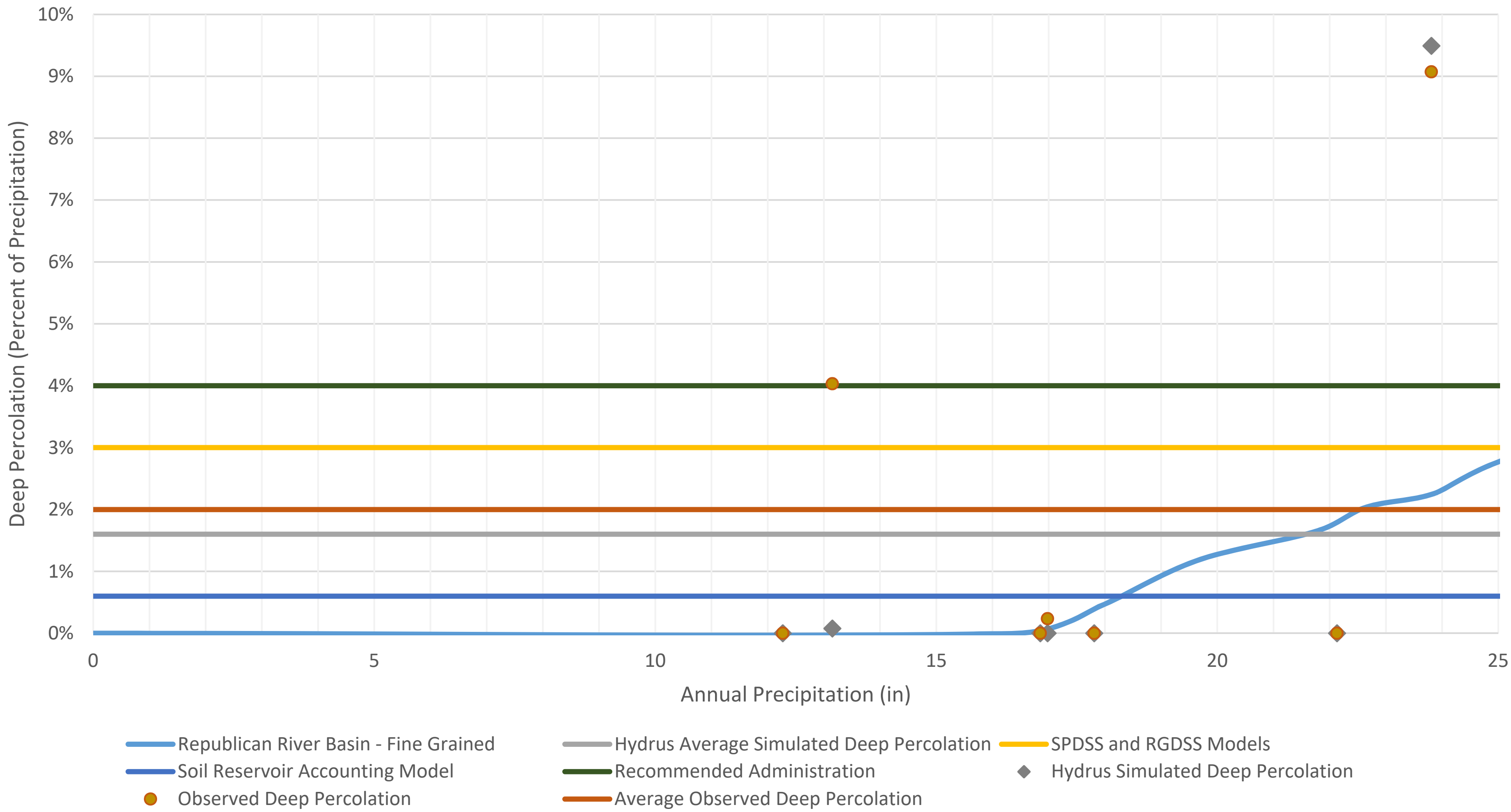

Figure 5
Deep Percolation Factors Summary

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DRAFT - Memorandum

To:	Tracy Kosloff, Colorado Division of Water Resources
From:	Jacob Bauer P.G., Leonard Rice Engineers, Inc.
Copy to:	Sarah Stone, Dominion Water and Sanitation District
Reviewed by:	Mark Mitisek and Greg Roush, Leonard Rice Engineers, Inc.
Date:	May 17, 2019
Project:	Colorado Water Plan Grant – Regional Factor Development for Precipitation Harvesting
Subject:	Task 4D – Delayed Groundwater Return Flows

Introduction

This memorandum summarizes the results of our stream accretion timing analysis for groundwater returns from precipitation recharge in the Sterling Gulch watershed. This memorandum also summarizes our initial investigation to determine the aquifer conditions for which groundwater return flows from precipitation can be assumed to occur on a relatively constant basis in contrast to a watershed where the variability of return flows requires the use of a site-specific unit response function (URF).

The purpose of our analysis was to answer the following questions:

- Do groundwater accretions from precipitation in Sterling Gulch occur to Plum Creek at a relatively constant rate OR is a site-specific URF required to replicate monthly delayed precipitation groundwater accretion pattern to Plum Creek?

When precipitation is captured,

- Under what aquifer conditions are site-specific URF's needed to replace lagged groundwater precipitation return flows?
- Under what aquifer conditions is it appropriate to assume replacement of owed precipitation groundwater return flows can be made at a constant monthly rate during the following 12 months of capture rather than relying on a site-specific URF?

Delayed Groundwater Return Flows

Many locations throughout the South Platte River region have little or no local groundwater table connected to the nearby stream alluvium. However, to make this approach applicable regionally and to be conservative to the stream system, quantified natural deep percolation of precipitation is assumed to reach the groundwater table and flow into stream(s) and is assumed to be available to downstream water users.

Two methods will be evaluated for maintaining the historical pattern of delayed groundwater recharge: The first method will establish a site-specific Unit Response Function (URF) for delayed return flows based on aquifer properties to determine the timing and amount of delayed groundwater return flows. The second method should be implemented when delayed groundwater return flows occur at a constant or nearly constant rate. Due to the slow rate of groundwater flow and associated groundwater return flow rates, the second method may be applicable more often on a regional scale compared to the first method. These methods are described in more detail below:

Method # 1: Site-Specific Unit Response Function

Accounting for the change in groundwater return flow patterns to the stream when land use transitions from natural to developed conditions requires an estimate of the lag time for the deep percolation of precipitation to travel through the local aquifer and reach the stream. The lag time is often presented as a URF that expresses the groundwater return flows each day or month as a percentage of the initial month of deep percolation. For a given location, the URF is a function of several site-specific factors including the subsurface geology and hydrogeology, the distance to the stream or other accretion points, and the distance to the aquifer boundary. The Glover (1954) method has been used extensively in Colorado for well-depletion lagging, groundwater return flow lagging, and other purposes. For precipitation harvesting projects monthly URFs computed using the Glover Method provide a reasonable basis for estimating the return flow timing of captured deep percolation water in a rainwater harvesting facility. This method would apply to locations where development occurs near the stream and where aquifer conditions result in quick response time of groundwater returns.

Method # 2: Continuous Return Flows

When the results of Method 1 show slow response times that smooth the variability of groundwater return flows accreting to the stream over time, then the observed precipitation record from Method 1 is likely to result in continuous delayed groundwater return flows accreting to the stream. To determine that constant return flows are a reasonable assumption, a sensitivity analysis was conducted evaluating sensitivity to distance from development to the stream and other aquifer parameters.

Glover Analysis

Accounting for the change in groundwater return flows to the stream from natural to developed conditions requires an estimate of the lag time for the deep percolation of precipitation to travel through the local aquifer and reach the stream (i.e. a URF). For a given location, the URF is a function of several site-specific factors including the subsurface geology and hydrogeology, the distance to the stream or other accretion points, and the distance to the aquifer boundary. For precipitation harvesting projects daily URFs computed using the Glover Method provide a reasonable basis for evaluating groundwater return flow timing. The Glover method is an analytical expression that calculates a ratio of the stream depletion rate from the well (q) to the pumping rate of the well (Q) as follows:

$$\frac{q}{Q} = erfc\left(\sqrt{\frac{x^2S}{4tT}}\right) = erfc\left(\sqrt{\frac{SDF}{4t}}\right)$$

Where: x is the distance to the stream, S is the storage coefficient of the aquifer, t is the time being evaluated, and T is the aquifer transmissivity. A lumped parameter known as a Stream Depletion Factor (SDF) is equal to X^2S/T or X^2/D, where D = hydraulic diffusivity = T/S, which simplifies the Glover Equation. When calculated in days, the stream depletion factor is equal to the time at which streamflow depletion is equal to 28 percent of the volume pumped for a given location. The greater the SDF, the longer the lag time to the stream and the more attenuated any temporal variation in accretion amount. The inherent assumptions and other specific details of the Glover Method are not discussed here due to the widespread knowledge of these details in the water resources industry in Colorado.

Sterling Gulch Groundwater Accretion Analysis

A standard Glover approach was used to determine if groundwater accretions at Sterling Gulch occur at a constant rate. Below is a description of the data sources, approach, and the result of this analysis.

1. The Sterling Gulch watershed was delineated from 2013 LiDAR available from the Denver Regional Council of Governments (DRCOG). The total watershed area is calculated as 223.2 acres. **Figure 1** presents a depiction of the watershed. In contrast to many watersheds, the Sterling Gulch watershed does not contain any perennially flowing streams where groundwater accretes to. For this reason, the “Assumed Recharge Outlet” point shown on **Figure 1** was used as the accretion point. This method assumes all recharge at the outlet is instantaneously available to Plum Creek for downstream water users. A more common distance measurement for a Glover analysis is to the closest location of a continuously flowing stream. However, for this analysis, selecting a shorter distance is conservative.
2. A representative point for evaluating groundwater return flow timing for the watershed was chosen. In this case, the watershed centroid was used to determine parameters for the Glover analysis. The analysis was conducted with a computer code using the Python computer language. The centroid of the watershed was selected as the location of all recharge in the watershed for the timing analysis. The distance from the representative point (centroid) to the outlet from the watershed (X) is 2,535 ft.
3. The distance from the nearest no-flow boundary, through the centroid, to the recharge outflow point for the watershed (W) is 3,542 ft. This distance was chosen to approximate the average effect of the aquifer boundary in the watershed.
4. The Alluvial Aquifer option was used in this analysis.
5. The specific yield was set to 0.18.
6. A transmissivity value of 3,740 GPD/ft (500 ft^2/day) was used in the simulation to accelerate the timing of stream response, account for uncertainty in the transmissivity estimate, and to ensure that the system reached steady state within the simulation period. The maximum actual aquifer transmissivity was estimated at 37.4 gallons per day per foot (GPD/ft) (5 feet squared per day; ft^2/day). This T value was derived from a hydraulic conductivity of 1 ft/day estimated during infiltration testing at the site, and an assumed maximum saturated thickness of 5 ft. The maximum saturated thickness was assumed to

be 5 ft because of the lack of of saturated thickness observed during monitoring well drilling at the site. The maximum T value of 5 ft^2/day would result in similarly steady accretions at steady-state when compared to the T value of 500 ft^2/day used in our analysis.

7. Precipitation records from Sterling Ranch climate station were used for the pattern of groundwater recharge within the watershed for the April 2010 through June 2018 time period. Three percent of monthly precipitation was estimated as deep percolation (the estimated portion of precipitation that becomes groundwater recharge) and was used as the recharge input amount for the simulation.
8. The recharge record was repeated several times to ensure that steady-state conditions were reached.
9. The simulation was run in daily time steps.
10. Stream accretions steadily increase until an approximate steady state condition is reached. Thereafter the month-to-month and annual accretions show little variation. In other words, the groundwater return flows are stable and continuous at steady state.
11. The Glover method assumes that the stream is infinite, however, violation of this assumption is unlikely to alter the significant finding of our analysis, which is that groundwater return flows are reasonably steady on a month to month and annual basis.

Figure 2 shows the precipitation recharge record in blue and shows the approximate steady-state accretion at the outflow point from the Sterling Gulch watershed. Precipitation recharge was computed by multiplying the daily precipitation rate by the area of the watershed and then multiplying this value by the 3 % of precipitation that becomes recharge. The steady-state accretions total of 0.027 AF/day is noted on **Figure 2**. As shown in **Figure 2**, the accretions reach a steady state where there is no discernable variation with time. Our results were generated using the centroid of the watershed as a representative point for all recharge within the watershed. A small percentage of the watershed may generate recharge outflow that shows more variability (i.e. recharge to locations near the outflow boundary). However, based on the size of the watershed, and the long lag times that are generated using various distance and transmissivity inputs to our analysis, adding additional recharge points to the analysis will not change the significant finding of this analysis, which is that groundwater outflow from the Sterling Gulch Watershed are stable from month-to-month. This analysis shows that it is not necessary to lag groundwater return flows from individual storms for the Sterling Gulch Watershed because groundwater outflow from the watershed to the stream system is stable although there is variability in precipitation. Therefore, it is reasonable to calculate the groundwater return flows for the Sterling Gulch watershed by multiplying the average annual precipitation by the percentage of precipitation that becomes recharge and assume that it returns to the stream at a constant rate.

Constant Groundwater Return Flow Sensitivity Analysis

A sensitivity analysis was conducted to determine what pilot project location and aquifer conditions would require using a site-specific URF, versus assuming a constant rate of return flow.

According to the Glover Equation, recharge timing is proportional to the SDF, which is a function of distance to the stream (X) squared as well as the aquifer parameters S and T. Thus, return flow delays are more impacted by a change in distance to the stream than the aquifer parameters. Also, the same SDF can occur with different combinations of X, S, and T. We tested this relationship by varying T, S, and x distance values (aquifer parameters) using the Glover Equation applied to an infinite aquifer and confirmed that the URF produced for any equivalent SDF yields the same stream accretion timing. Similarly, this relationship was tested using the Glover Equation in a bounded aquifer where the distance from the stream to the river (x) was also the distance from the representative recharge point to the aquifer boundary. We confirmed that for equivalent SDF values the same accretion timing will be produced as long as the distance to the stream is assumed to be the same as the distance to the aquifer boundary. The aquifer boundary was incorporated numerically using the method of Miller (2007).

Several SDF values ranging from 0.1 to 10,000 were tested using the same daily precipitation pattern for the Sterling Ranch watershed (considered a representative precipitation record for the South Platte region of Colorado) to determine the range of SDF values that would result in steady accretions at the stream from variable daily precipitation. The results of this analysis are shown in **Figure 3**, which shows the recharge, and recharge accretion pattern at steady state for the tested SDF values. Note that on Figure 3, the volume of recharge has been computed using the daily recharge (set to 3% of precipitation) applied to a theoretical, large 640-acre (section sized) parcel with a centroid a distance X to the stream. Recharge volumes can be scaled based on actual development sizes to determine recharge volumes for a development. Based on this geometry, the distance x was held constant at 2,640 ft (1/2 mile) or 264 ft (1/10 mile), Sy was held constant at 0.2, and T distances were varied to adjust the SDF value. **Figure 3** shows two sets of T, W, and X values for each SDF value indicating that there are multiple parameter sets that yield the same SDF values. **Figure 3** also shows the maximum difference between the highest accretion rate per day and steady-state accretion each day. This value represents the error of assuming steady state accretions rather than variable, URF-based groundwater accretions for a particular URF. Additionally, we note that this analysis assumes the Sterling Ranch watershed precipitation record is representative regionally, and that the bounded aquifer formulation with W set to twice the X value is generally applicable.

For the purpose of Regional Factors, the CWCB may want to establish a threshold value to determine when a particular pilot project should not assume a constant groundwater return flow and lagging is necessary. One possible metric is to require lagging return flows when the maximum difference between the accretions calculated using the actual URF, and the steady-state accretion rate exceeds a flow rate that could be impactful to senior water rights on the stream. In the analysis provided here, we have provided results using a conservative example threshold value of 0.1 cfs (**Figure 4**). The 0.1 cfs value was selected as a potential threshold because this value represents a value near the accuracy of many water accounting and measurement protocols. If this threshold is used, an SDF value of approximately 25.81, yields a difference of 0.1 cfs between the values calculated using the actual URF, and the average groundwater accretion rate.

For each analysis, two important points for generating URFs for a precipitation harvesting project include:

- In contrast to implementing Glover method for point depletion source such as a well, the more distributed nature of a precipitation harvesting project may require subdividing the area of the precipitation harvesting project into several smaller representative areas. The URFs from each representative area can then be averaged together to calculate a representative URF for the entire area. This was not done in our example analysis but could be investigated in future analyses.
- Based on prior experience in implementing the Glover Method, it is frequently necessary to include the distance to the aquifer boundary when implementing the Glover Method rather than relying on the infinite aquifer assumption. This is especially applicable in regions where groundwater return flows occur through an alluvial layer that is only present within the drainage basin where the development is located (i.e. the alluvium is disconnected from adjacent drainages).

Based on the analysis described above, for large developments (in this example 640 acres) and SDF values of less than 25.81, it may be appropriate to lag the return flows. A threshold of 0.1 cfs was used to define the maximum allowable difference between the lagged daily groundwater accretions and the accretions generated using the average daily groundwater accretions. **Figure 5** shows the range of S/T values (1/D, the inverse of hydraulic diffusivity) vs. “x” values that yield an SDF of 25.81.

Conclusions

Based on the above described analysis, we have reached the following conclusions:

- For the Sterling Gulch Watershed, it is <u>not</u> necessary to use a URF, because groundwater outflow from the watershed is relatively stable showing little variation from month-to-month or annually. Therefore, groundwater return flows owed from the Sterling Gulch watershed can be calculated for each month by multiplying the total precipitation for the month by the percentage of precipitation that becomes recharge, times the number of acres made impervious within the catchment area. With the total monthly volume owed to the stream distributed equally over the next 12 months.
- For other watersheds, it <u>may be</u> necessary to lag groundwater return flows utilizing traditional Glover or more complex methods. The SDF can provide some insight into whether groundwater return flows can be made at a constant rate. In a section-sized (640 acres or 1 mile on each side) parcel located within an alluvial aquifer, when SDF values are less than 25.81, the maximum difference between the average steady-state accretions, and calculated lagged accretions was less than 0.1 cfs.

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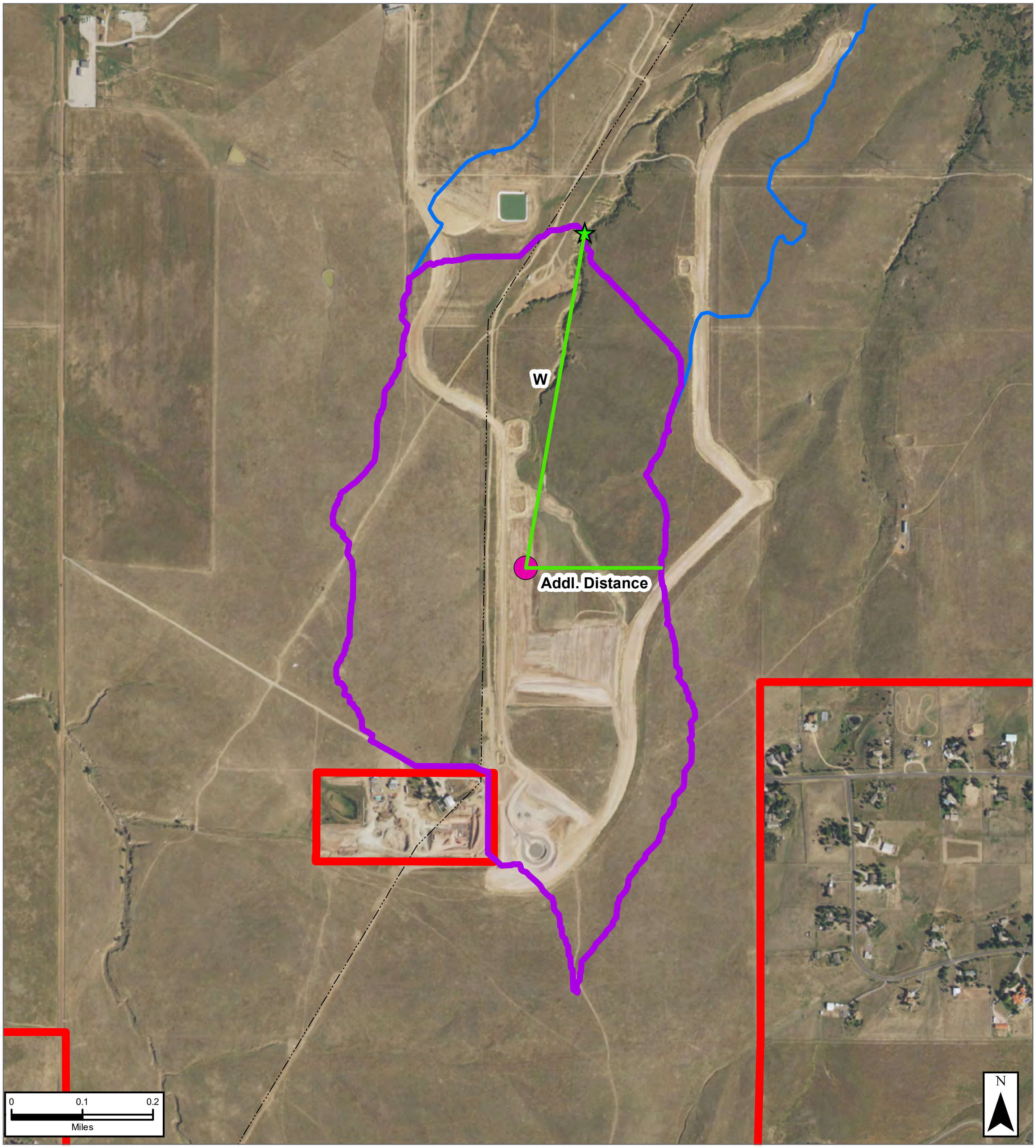

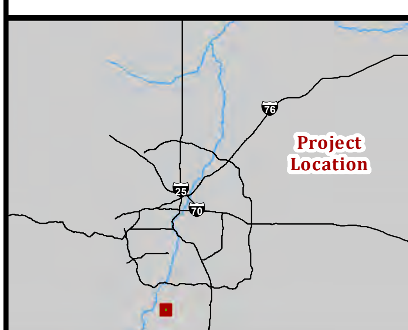

- Measurement Line Used in Glover Analysis
- Watershed Centroid
- Assumed Recharge Outflow Point
- Watershed Boundary
- Watershed Boundary downstream of Outflow Pt.
- Sterling Ranch Boundary

FIGURE 1
GROUNDWATER RETURN FLOW ANALYSIS MAP

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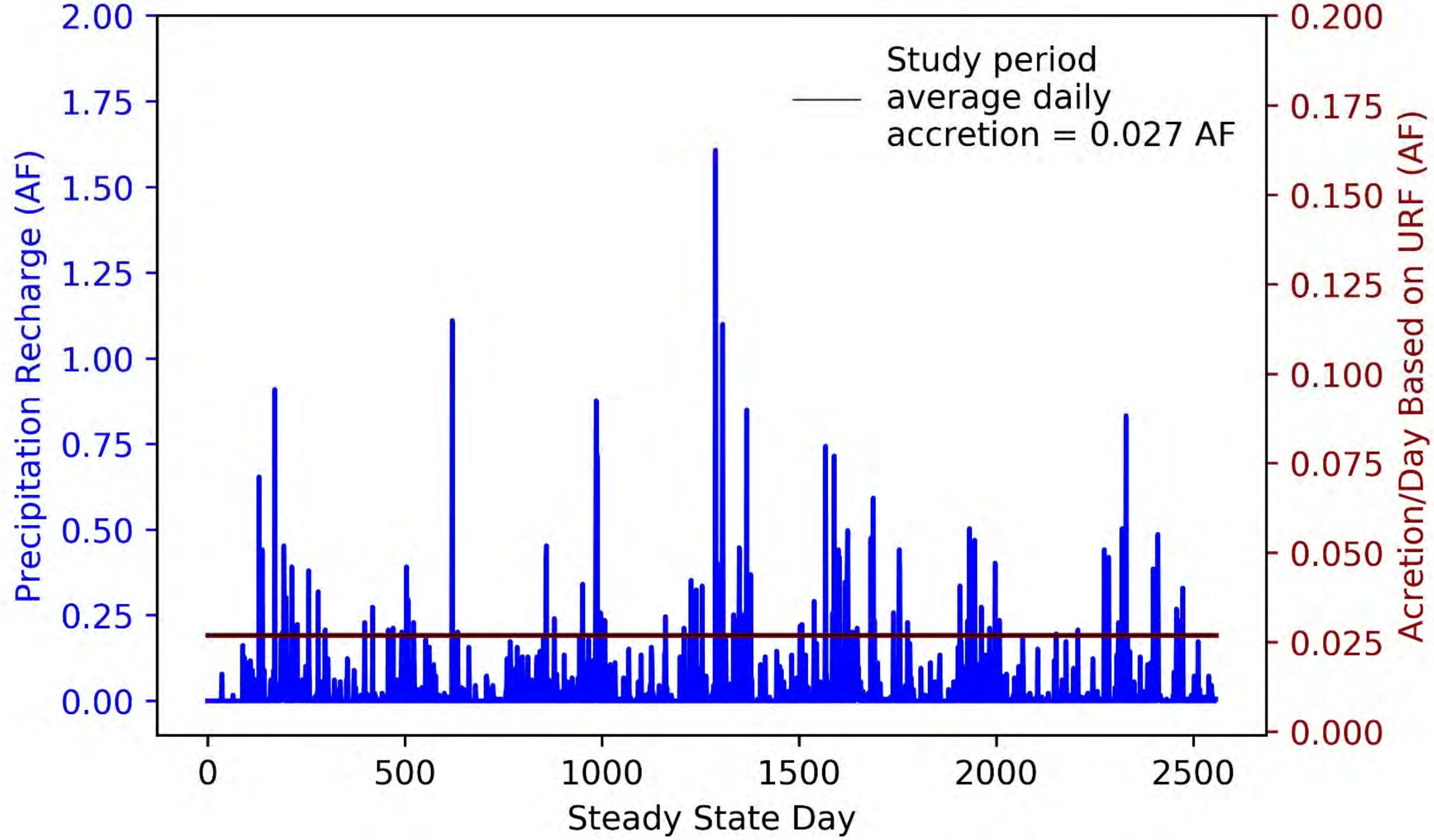

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Figure 2:
Steady State Groundwater Accretions
in the Sterling Gulch Watershed

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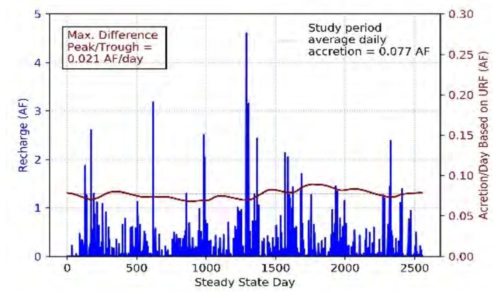
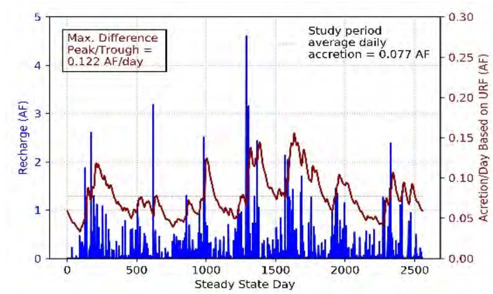
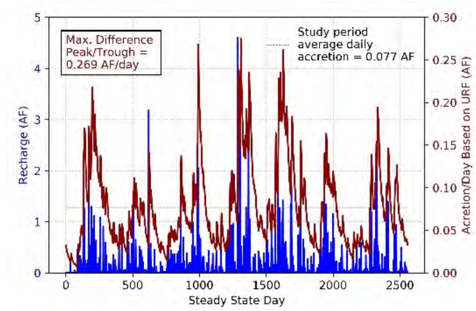
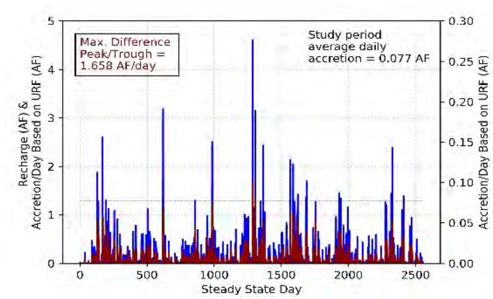
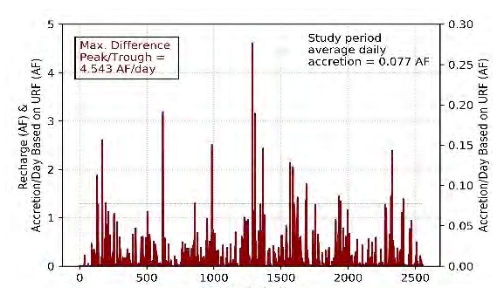
Figure 3: Recharge and Accretion Timing for Several SDF Values

SDF	Aquifer Type	T, $ft^2\ day^{-1}$	Boundary Lengths	S	Plot
1,000	Wide, medium transmissivity aquifer	1,394	X = 2,640 ft W = 5,280 ft	0.2	
	Narrow, low transmissivity aquifer	13.94	X = 264 ft W = 528 ft	0.2	
100	Wide, medium transmissivity aquifer	13,939	X = 2,640 ft W = 5,280 ft	0.2	
	Narrow, low transmissivity aquifer	139.4	X = 264 ft W = 528 ft	0.2	
25.81	Wide, medium transmissivity aquifer	54,007	X = 2,640 ft W = 5,280 ft	0.2	
	Narrow, low transmissivity aquifer	540.1	X = 264 ft W = 528 ft	0.2	
1	Wide, high transmissivity aquifer[1]	1,393,920	X = 2,640 ft W = 5,280 ft	0.2	
	Narrow, low transmissivity aquifer	13,939	X = 264 ft W = 528 ft	0.2	
0.01	Wide, high transmissivity aquifer[1]	139,392,000	X = 2,640 ft W = 5,280 ft	0.2	
	Narrow, high transmissivity aquifer	1,393,920	X = 264 ft W = 528 ft	0.2	

Note: [1]Transmissivity outside reasonable hydrogeologic ranges

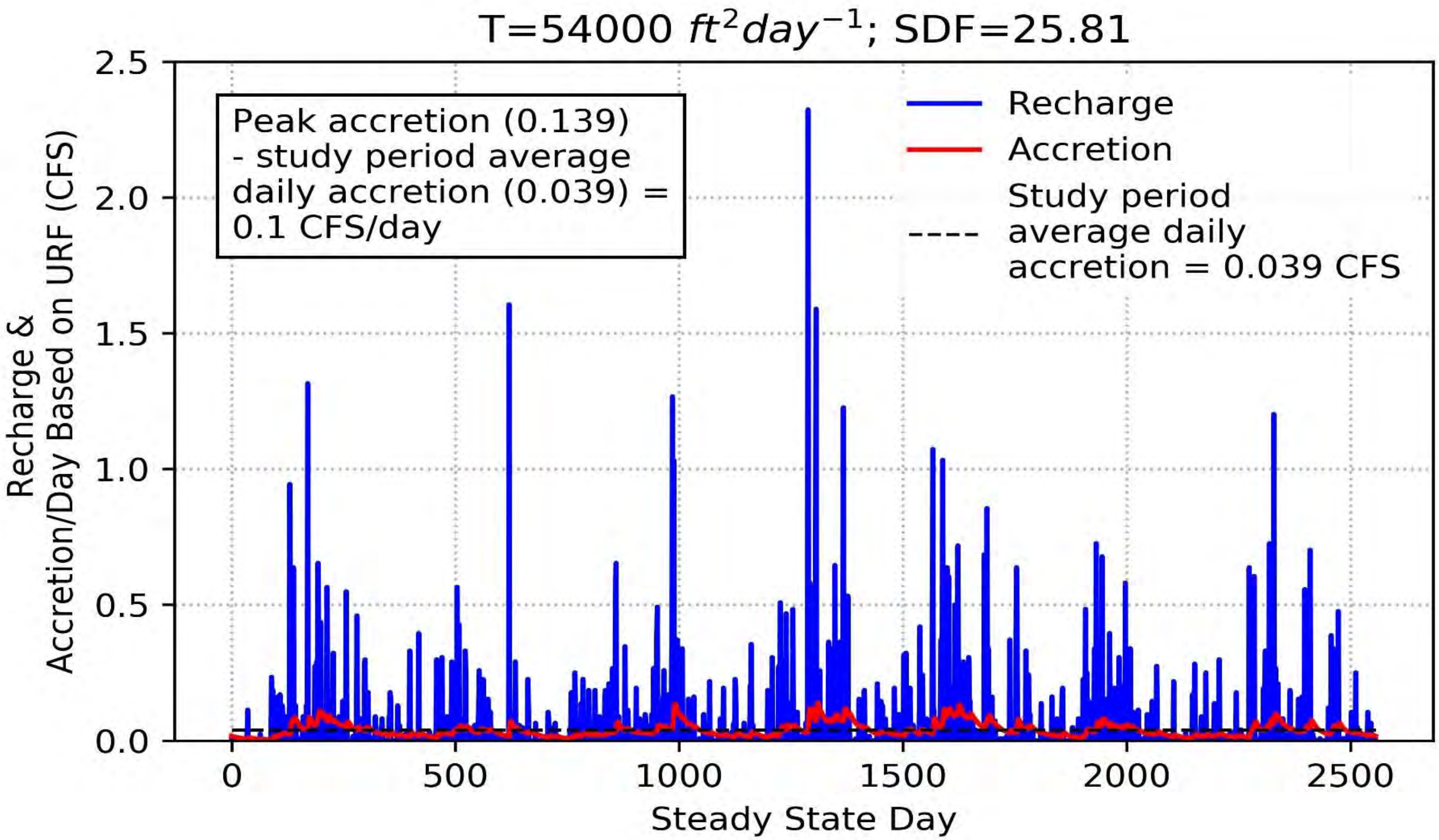


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Figure 4:
Steady State Groundwater Accretions
SDF=25.81

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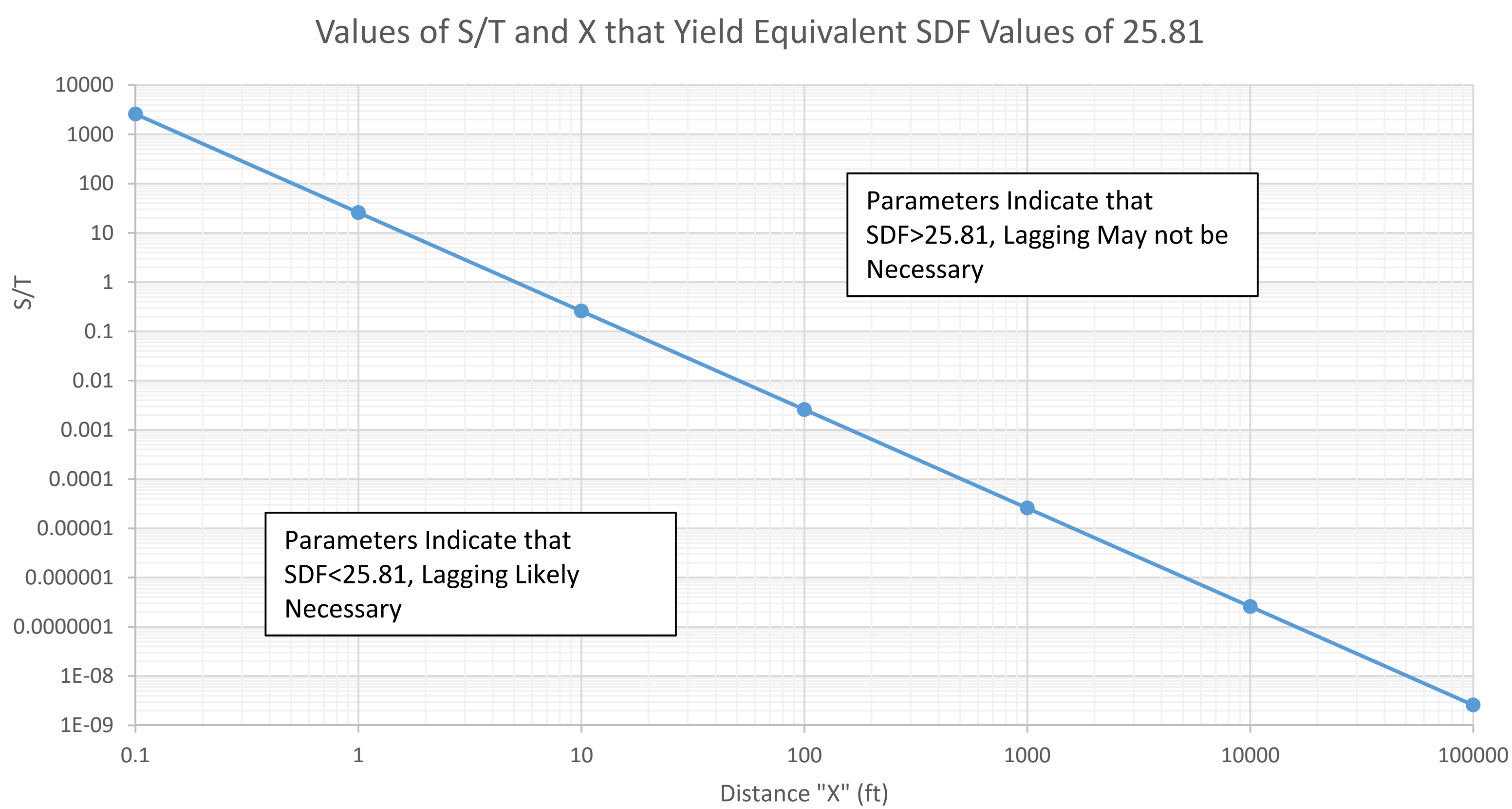

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Figure 5:
Values of S and T that Yield Equivalent SDF Values of 25.81

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