Long-term Hydrologic Assessment of Effect of Full Spectrum Detention on Water Balance and Water Rights

Prepared for:
Urban Drainage and Flood Control District

Prepared by:
Wright Water Engineers, Inc.

WWE

Wright Water Engineers, Inc.

April 2016

151-028.000

TABLE OF CONTENTS

Page

APPENDICES

Tables:

Figures:

Presentation:

Long-term Hydrologic Assessment of Effect of Full Spectrum Detention on Water Balance and Water Rights

1.0 EXECUTIVE SUMMARY

This report presents the results of a hydrologic evaluation of the effects of Full Spectrum Detention (FSD) on water rights for the Front Range of Colorado. Analysis included modeling using the EPA Stormwater Management Model (SWMM) to quantify hydrologic changes resulting from varying levels of development for a hypothetical one-square mile watershed, with soils and precipitation typical of areas within Urban Drainage and Flood Control District (UDFCD). The SWMM analysis was used to compare yield for undeveloped versus developed scenarios and for developed scenarios with and without Full Spectrum Detention (FSD). The SWMM model yielded results that confirmed expected hydrologic trends associated with development and FSD:

1. Increasing impervious area significantly increases the amount of surface water yielded by a watershed. This is largely due to the effect of reduced evapotranspiration due to impervious cover and corresponding increases in runoff. These changes are most significant at higher imperviousness levels, with a site with imperviousness of 65% yielding more than 200 acre-feet of runoff per year more than an undeveloped site on average over a 64-year simulation period.
2. FSD has little effect on the overall quantity of water from a developed site. This is because water is stored in FSD facilities for no more than 72 hours (and often for even shorter periods). Over this timespan following a significant precipitation event, the amount of depression storage (0.35 inches for pervious areas) available for evapotranspiration would be similar to that evaporated from a ponded surface.
3. FSD does affect the timing of runoff and provides important public health, safety, and welfare benefits by temporarily storing water and releasing at a controlled rate. This is not only beneficial from the standpoint of flood protection but also benefits stream stability and erosion for downstream water rights infrastructure.
4. The scenarios with FSD effectively demonstrate peak attenuation benefits. Detention for peak attenuation is required by many local ordinances for purposes of water quality and flood protection, and although the scenarios with FSD have lower release rates immediately following the event, the extended supply of “new” water as the FSD facility releases is a net benefit to downstream users relative to undeveloped conditions.

The SWMM model provided daily outflows for all scenarios with and without FSD, and this information was used as input for a water rights model of Big Dry Creek. Big Dry Creek was chosen for this case study because it is mostly within UDFCDs boundary, the watershed has significant development potential which will require FSD, and WWE was able to obtain diversion and return flow records necessary to construct a water rights model. Water rights simulations were performed to determine the water availability on Big Dry Creek as a result of various development scenarios with FSD and without. Re-timed flows as a result of FSD were modeled with and without river call scenarios to determine potential impacts to water rights holders. Simulations were performed to determine the water availability on Big Dry Creek as a result of various development scenarios with FSD. Because Big Dry Creek has not been subject to a sub-basin specific river call, historical calls on the South Platte River were analyzed relative to Big Dry Creek diversions.

Theoretically, the scenarios without FSD *could* provide greater flow rates to the system during and immediately following runoff and less flow on following days. However, from a practical standpoint, such uncontrolled releases of runoff would have the potential to cause significant erosion and damage in downstream waterways, causing flooding and affecting water delivery infrastructure. Many of the erosion problems on Big Dry Creek, including washed out head gates and collapsing banks, are due to hydromodification (BDCWA 2005), which can be mitigated through implementation of FSD.

This modeling effort, while general in nature, provides a method that can be applied to assess interactions between development, stormwater management, and water rights along the Front Range of Colorado. The clear (and anticipated) results of the analysis are that replacement of vegetated pervious areas with impervious areas increases runoff available to water users that would largely be lost to evapotranspiration under undeveloped conditions, and that FSD plays an important role in regulating the delivery of this water and protecting the stability of the streams that deliver water to users.

2.0 INTRODUCTION

Wright Water Engineers, Inc. (WWE) and the Urban Drainage and Flood Control District (UDFCD) have prepared this report to present the results of a long-term hydrologic modeling study on the effects of full spectrum detention (FSD) on downstream water rights users. FSD is intended to reduce the flooding and stream degradation impacts associated with urban development by controlling peak flows in the stream for a range of events.

FSD addresses limitations of traditional minor and major storm detention by controlling peak discharges over the full spectrum of runoff events from small, frequent storms up to the 100-year flood. FSD facilities produce outflow hydrographs that, other than a small release rate of the excess urban runoff volume (EURV), mimic the shape of pre-development hydrographs. FSD modeling has been shown to reduce urban runoff peaks to levels similar to pre-development conditions over an entire watershed, even with multiple independent detention facilities. Because FSD capture and slowly release runoff, water rights users in the State of Colorado have raised questions related to evaporative losses of stored water and the timing and magnitude of releases.

Senate Bill 15-212 was signed into law by Governor Hickenlooper in May 2015 and became effective on August 5, 2015 as Colorado Revised Statute (CRS) §37-92-602 (8). This statute provides legal protection for any regional or individual site stormwater detention and infiltration facility in Colorado, provided the facility meets the following criteria:

1. It is owned or operated by a governmental entity or is subject to oversight by a governmental entity (e.g., required under an MS4 permit)
2. It continuously releases or infiltrates at least 97% of all of the runoff from a rainfall event that is less than or equal to a 5-year storm within 72 hours after the end of the event
3. It continuously releases or infiltrates as quickly as practicable, but in all cases releases or infiltrates at least 99% of the runoff within 120 hours after the end of events greater than a 5-year storm
4. It operates passively and does not subject the stormwater runoff to any active treatment process (e.g., coagulation, flocculation, disinfection, etc.)
5. If it is in the Fountain Creek (tributary to the Arkansas River) watershed it must be required by or operated in compliance with an MS4 permit

The statute specifies that runoff treated in stormwater detention and infiltration facilities shall not be used for any other purpose by the owner/operator/overseer (or that entity's assignees), shall not be released for subsequent diversion or storage by the owner/operator/overseer (or that entity's assignees), and shall not be the basis for a water right or credit.

This study was initiated as the legislation was making its way through committees to ultimate approval in May 2015. UDFCD opted to continue with this study even after the legislation was approved to provide a detailed technical assessment of water balance and water rights implications of FSD.

The objective of this investigation was to perform continuous simulation hydrologic modeling to evaluate changes in hydrology due to development with varying levels of imperviousness with and without FSD and how these changes affect downstream water rights users. Stormwater

Management Model (SWMM) simulations were conducted for undeveloped, 20%, 35%, 50%, 65%, and 80% imperviousness scenarios, with and without FSD. The results of these SWMM model scenarios were used to evaluate the site water balance and to develop time series flow data for input into a water rights model to determine how downstream users would potentially be affected by the various scenarios.

3.0 CONCEPTUAL APPROACH

The conceptual approach for this investigation involved application of SWMM for site-level rainfall, runoff, infiltration, evapotranspiration, detention, and other calculations. The output from SWMM was used as input for a water rights accounting spreadsheet, which evaluates calls and diversions by water rights users downstream on the basis of prior appropriation. To evaluate the effects of FSD under “typical” development scenarios, WWE analyzed a one (1) square mile watershed using SWMM. Representative watershed parameters were selected from the Big Dry Creek (ADCO) Phase A Report (WWE 2006). This area was selected based on WWE’s familiarity with master planning of the area, the presence of downstream water rights users, the increasing growth/development in this area, and the fact that the area is within UDFCD’s jurisdiction. WWE then used the results of these SWMM simulations as input to the water rights model set up for Big Dry Creek. Figure 1 illustrates the conceptual watershed and stream scenarios modeled.

The SWMM models are intended to generically represent the hydrologic effects of development on the Front Range at the scale where regional FSD would be used for control of runoff quality and quantity. The water rights model is specific to Big Dry Creek and was created based on review of diversion and return flow records, municipal water rights data, interviews with the Water Commissioner, and past knowledge of the Big Dry Creek watershed. The SWMM models developed as a part of this study can be applied in other locations by adjusting model input for sub-basin parameters, precipitation data, local groundwater conditions, and climate inputs. These results could then be used with a water rights model for a specific stream to which the area of interest drains.

3.1 SWMM Model Scenarios

Multiple SWMM scenarios were evaluated to assess the effects of development, with and without FSD, on runoff that is delivered to receiving waters. The SWMM scenarios were intended to simulate long-term hydrology including wet and dry weather processes including rainfall, runoff, infiltration, evaporation (surface water), evapotranspiration (soil moisture), snowpack/snowmelt, tributary groundwater recharge and other hydrologic processes. The following scenarios were evaluated:

- Baseline – Undeveloped
- 20% Impervious Area (IA) – with and without FSD
- 35% Impervious Area (IA) – with and without FSD
- 50% Impervious Area (IA) – with and without FSD
- 65% Impervious Area (IA) – with and without FSD
- 80% Impervious Area (IA) – with and without FSD

These simulations were created to span the likely range of imperviousness that would be encountered in regional detention situations. Imperviousness less than 20% was not evaluated (except for baseline undeveloped condition) because low density developments typically will use on-site water quality/detention or low impact development (LID) to meet requirements. Imperviousness greater than 80% was not evaluated because most municipalities have landscaping and/or open space requirements that make imperviousness greater than 80% infeasible in most situations. Additional SWMM input and output information is provided below.

These SWMM model scenarios were performed to develop time series of outflow from the overall system, and results were compiled for comparisons between undeveloped, developed, and developed with FSD scenarios. The time series output from SWMM (system outflow versus time) were used as input for the water rights model to evaluate gains and losses to downstream water users relative to undeveloped, developed, and developed with FSD scenarios.

3.2 Water Rights Model Scenarios

Water rights within the South Platte River basin and Big Dry Creek sub-basin are complex in nature. Administrative calls are frequently placed on the South Platte River during the irrigation season and junior water rights holders are subsequently limited or curtailed in diversions. In order to simulate water rights call scenarios within the Big Dry Creek sub-basin, an excel-based point flow model was developed for the system.

Streamflow records are available in the Big Dry Creek Basin at Westminster and just upstream of the confluence between Big Dry Creek and South Platte River. Although streamflow records are not available or complete in all years within the period, streamflow records from 1985 through 2013 do indicate Big Dry Creek basin is a gaining reach due to non-native inflows. Non-native inflow contribution is mostly due to Standley Lake releases, transbasin diversions and municipal waste water treatment effluents.

Simulations were performed to determine the water availability on Big Dry Creek as a result of various development scenarios with FSD. Because Big Dry Creek has not been subject to a sub-basin specific river call, historical calls on the South Platte River were analyzed relative to Big Dry Creek diversions. Re-timed flows as a result of FSD were modeled with and without river call scenarios to determine potential impacts to water rights holders.

4.0 HYDROLOGIC MODELING USING STORMWATER MANAGEMENT MODEL (SWMM)

This assignment involved application of SWMM for continuous simulation of rainfall, runoff, evaporation, evapotranspiration[1], snowpack/snowmelt, and groundwater recharge (assumed to be tributary groundwater). WWE obtained hourly rainfall data and daily data for temperatures, wind speed, and other climate parameters from the National Climatic Data Center (NCDC). WWE used data from the Stapleton Gauge from the start of 1949 to the end of 2013 because this provided the longest period of record with parameters needed for model input[2]. This period of record includes both wet periods and droughts that are reflected in the continuous simulation of hydrology.

In other locations along the Front Range of Colorado daily, monthly, and annual precipitation data would vary from the Stapleton gauge, with lower variability as the time scale of comparison

[1] In this report, we refer both evaporation (from surface water) and evapotranspiration (from soil moisture) because SWMM models these processes separately.

[2] Data obtained from NCDC Climate Data Online (CDO) Global Historical Climate Network Daily Records for Denver Stapleton CO US: GHCND: USW00023062. Hourly precipitation data were obtained from the same station through NCDC/CDO.

increases. Because this continuous simulation modeling has been conducted over a 65-year period, spatial differences in short-term precipitation and climate inputs average out over time, and the model provides good representation of watersheds within UDFCD's jurisdiction and many others across the Front Range.

4.1 Baseline Model Scenario

The general/baseline model scenario for this assessment was developed to be representative of the scale and levels of imperviousness associated with development along the Front Range of Colorado. To develop a baseline scenario, WWE used information from the Big Dry Creek Northern Tributaries Outfall Systems Plan (UDFCD 2006) to select representative model parameters representative of Hydrologic Soil Group (HSG) C conditions, which are common in the region.

A scale of a one (1) square mile watershed was selected for evaluation because a watershed of this size would fall within UDFCD's classification of the "regional" drainage system and because it is the upper limit of where an "on-line" water quality facility would be considered. Modeling on a unit basis (per square mile) also enables easy extrapolation of results to larger or smaller areas depending on the size of a specific development.

To be consistent with typical watershed analysis conducted in the region, the one-square mile watershed was divided into four sub-watersheds of 160 acres each. The sub-watersheds have identical parameters for losses, impervious/pervious areas, and other input parameters; however, by modeling at a typical sub-watershed scale, the overland flow and internal sub-basin routing parameters produce a more realistic rainfall-runoff response.

Table 1 summarizes sub-watershed parameters for model simulations. Sub-watershed parameters were selected from typical values recommended in the Urban Storm Drainage Criteria Manual and the SWMM User's Manual. Horton infiltration loss parameters were adjusted within the bounds of UDFCD and SWMM User Manual guidance for "calibration" of the undeveloped scenario..

Although not included in this analysis, SWMM has capabilities that could be used to simulate irrigation and return flows and/or scenarios of historical agricultural use.

4.1.1 Climate Data

Time series inputs for SWMM were developed based on NCDC data. Data were obtained from January 1, 1949 through November 30, 2013, roughly a 64-year period of record. Data availability is good over this period of record for precipitation, temperature, and other climatic data. Hourly precipitation data were used for input for all simulations. Daily data for model input included minimum and maximum daily temperatures.

For potential evaporation/evapotranspiration, daily data were unavailable, so average monthly values for potential evaporation/evapotranspiration were used from SPDSS Task Memo 53.3 for Water District 1-Lower (LRE 2006), and actual evaporation/evapotranspiration rates were calculated by the model based on availability of water to satisfy the demand.

4.1.2 Aquifer Parameters

To model evapotranspiration between runoff events, a simple groundwater aquifer was added to the SWMM models to allow for infiltration to the groundwater table and evapotranspiration of soil moisture. Because explicitly modeling groundwater flow was not needed as a part of this assessment, the aquifer was modeled as a shallow, alluvial aquifer, rising and falling in response to infiltration and evapotranspiration. Although aquifer outflow is not explicitly modeled, the difference in aquifer storage from the start of the simulation to the end of the simulation can be considered as a gain or loss in tributary groundwater. Table 2 summarizes aquifer parameters.

4.1.3 Snowpack

Daily minimum and maximum temperature data were used to differentiate between rain and snow in the SWMM model, and model input data were provided for melt coefficients and snow removal parameters from impervious areas using guidance from the SWMM Manual. A temperature of 36ºF was used as the dividing temperature between snow and rain – this value was selected several degrees above the freezing point due to the fact that there are often wide variations between daily minimum and maximum temperatures on the Front Range of Colorado, and even on days with snow, average temperatures may be above the freezing point. The snowpack model includes adjustments for elevation and latitude.

Snowmelt was included in the SWMM model (as opposed to modeling all precipitation as rainfall) to provide a more realistic simulation and to better represent the different precipitation/infiltration/runoff response in winter months. The SWMM model has not been rigorously calibrated for snow depths and instead is intended to represent the processes over the long-term. More detailed analysis could be conducted to "fine tune" the snowmelt parameters; however, in the context of this assignment, which is focused on effects of FSD on downstream water rights, results are insensitive to snowmelt assumptions.

4.2 Undeveloped Model

The undeveloped model was created to estimate the long-term hydrologic budget and outflow time series for typical undeveloped land along the Front Range. "Natural" imperviousness of 2% was assumed for this scenario. This model was "calibrated" by adjusting infiltration parameters and aquifer parameters to achieve a state where long-term evaporation and evapotranspiration roughly balance with average annual precipitation. Native grasses are adapted to efficiently use the limited available precipitation in this part of Colorado, and over the long-term, evapotranspiration from native grasses should roughly balance with available moisture. Based on studies along the Front Range, long-term, average annual runoff from undeveloped land is on the order of 0.5 inches per year (Gebert et al., 1987). For the "calibrated" model, the long-term average annual runoff was 0.4 inches. To further verify these results, the EPA National Stormwater Calculator (NSWC) was applied using typical parameters from the Big Dry Creek watershed. NSWC results agreed well with the "calibrated" SWMM results.

4.3 Developed Models

Developed models were created by modifying the imperviousness and percent routed parameters for sub-watersheds in SWMM (parameters in Table 1). All other model parameters remained the same.

Irrigation and changes in potential evapotranspiration (higher demands due to landscaping) were not evaluated for developed scenarios. It is assumed that increased water demands for bluegrass, landscaping, etc. would be satisfied with imported water. Return flows from irrigation water would increase overall system outflow, and this is not accounted for in the model. These assumptions tend to underestimate the delivery of water to the downstream system, and therefore are conservative assumptions for purposes of evaluating impacts to downstream water rights from FSD.

4.4 Developed Models with FSD

To add FSD to developed models, UDFCD's Full Spectrum Detention Sizing Spreadsheet (UD-FSD v1.10) was applied to generate stage-area and stage-discharge relationships for the range of imperviousness evaluated. FSD scenarios were modeled using a storage unit and outlet in each of the developed SWMM models. Storage unit input parameters were set to allow for full evaporation. Seepage from FSD facilities was assumed to be negligible and was not modeled[3].

To model FSD, a short time step was required in SWMM to maintain continuity. Ultimately a 1-minute time step was used for runoff, and a 30-second time step was used for routing. A reporting time step of 1 hour was used for generating statistical results used for water balance summaries. Figure 2 illustrates hydrograph routing from SWMM that shows that the FSD input and time steps used are appropriately representing attenuation of flow.

4.5 Results

Tables 3 and 4 present summaries of results from SWMM modeling, and Figure 3 provides a graphical representation of the water balances. Table 3 provides average annual water balance results, and Table 4 provides event statistics. The following observations follow from the data in these tables and figure:

- Precipitation is the same all simulations. Note that results for precipitation are summarized based on daily totals and not 6-hour separated storms. Daily totals were used for comparability with other statistics calculated on a daily time step.
- Increased imperviousness shifts the hydrologic balance of undeveloped land from a quasi-equilibrium of precipitation and evaporation/evapotranspiration with native vegetation to a condition where runoff is more frequent and infiltration, evaporation, and evapotranspiration decrease.

[3] Some degree of seepage would be expected to occur in FSD facilities due to permeability of underlying soils and the head created by water stored in the facility. For purposes of water rights modeling, whether water flows out of the system via seepage or surface outflow is immaterial since both sources would be considered tributary to stream flows in the model.

- System outflows follow expected patterns. The frequency of outflow from the system increases dramatically from an undeveloped condition to developed scenarios.
- The magnitudes of mean and peak outflows increase as imperviousness increases, and the effects of FSD are demonstrated by lower mean and peak values for FSD scenarios. Comparisons of mean and peak runoff and outflow from SWMM show the attenuation effects of FSD, while the effects of extending the runoff hydrograph are shown in the increase in the numbers of days with outflow between FSD and non-FSD scenarios.
- Mean and peak daily evaporation/evapotranspiration rates are relatively consistent for all simulations as would be expected. However, the annual evaporation and evapotranspiration are influenced heavily by the amount of impervious area. Impervious area has lower depression storage, which decreases the volume of precipitation available for evaporation on these surfaces, and as impervious areas increase, pervious areas, which typically have higher evaporation/evapotranspiration, decrease.
- Annual runoff increases substantially as imperviousness increases. A 50% imperviousness scenario yields approximately 160 acre-feet more runoff than an undeveloped scenario. FSD has virtually no effect on the annual runoff yield, and for all but the 20% imperviousness scenario, average annual outflow was the same with or without FSD. While it might be expected that water storage associated with FSD would increase evaporation losses, the difference is negligible because FSD facilities drain within 72 hours and the potential evapotranspiration over 72-hours is of the same order of magnitude as pervious depression storage[4].

4.5.1 Output for Water Rights Model

While the hydrologic balance results presented above provide a macro-level understanding of the effects of development and FSD on runoff, evaporation/evapotranspiration, storage, and other parameters, to assess the effects on downstream water users, output data from SWMM were analyzed using a water rights model. Time series of daily system outflow (e.g. water reaching the stream) were generated using SWMM for the undeveloped, developed, and developed with FSD scenarios.

5.0 WATER RIGHTS MODELING

Water rights accounting within the point flow model summarizes changes in Big Dry Creek's physical water supply available to water rights holders as a result of development with temporary storage in FSD. Table 5 provides a list of senior water rights in the Big Dry Creek basin. Figure

[4] Whether the water is being evaporated from a FSD facility, from depression storage, or from upper zone soil moisture, the evaporation/evapotranspiration losses are essentially the same over a 72-hour time period following rainfall.

4 provides summary of municipal waste water treatment plant effluent to Big Dry Creek. Figure 5 provides a summary of historical diversions on Big Dry Creek. The following observations follow from this analysis, data, and conversations relative to the Big Dry Creek watershed and its historical water use:

- More than 97 percent of Big Dry Creek's 14 inches of annual rainfall is lost to evapotranspiration on an undeveloped one square mile watershed. Because of the losses associated with evapotranspiration, water rights holders have not received groundwater returns or runoff historically as a result of precipitation. Therefore, as various densities of development occur within the watershed, evapotranspiration losses will decrease and runoff available for water rights holders will increase. Figure 6 shows the relationship between various densities of development and the increase in runoff on a one square mile watershed in the Big Dry Creek sub-basin.
- Streamflow records were procured on a daily basis and are incomplete throughout the period. Missing data were filled based on ordinary least squares regression analysis with nearby stream gages.
- There have been no historical calls on Big Dry Creek sub-basin due the stream's non-native imports for delivery to downstream water users on the South Platte River. Call analysis relative to the water rights model was performed on the South Platte River. Table 6 provides a summary of historical river calls relative to outflow from FSD.
- Municipal water accounting within the sub-basin is provided to Colorado's Division of Water Resources and was used for quantifying inflows to Big Dry Creek. Multiple municipal waste water treatment facilities release effluent to Big Dry Creek that may be available for downstream use. Additionally, transbasin diversion accounts deliver flows to meet downstream augmentation obligations. Following conversations with the Colorado Division of Water Resources and their Coordinator of River Operations on the South Platte River, the cities of Broomfield, Northglenn, Thornton and Westminster were considered for this analysis.
- Diversions are recorded during the irrigation season for main diversion structures on Big Dry Creek.
- Re-timed flows provide additional flow in Big Dry Creek that was otherwise lost to evapotranspiration on an undeveloped one square mile watershed. Additional water as a result of development may be available as supply for water rights holders within the sub-basin of Big Dry Creek and for downstream water users along the South Platte.

6.0 CONCLUSIONS

Based on the long term analysis of varying imperviousness scenarios, it is clear that development in Colorado creates a substantial amount of "new" water for downstream users--this is not a surprising conclusion and has been known for decades. Increases in physical streamflow along the

Front Range are coveted and impactful for water rights users on Big Dry Creek and the South Platte River. The following conclusions have been drawn from the analysis:

1. Relative to undeveloped scenarios in which precipitation largely balances with evapotranspiration, developed scenarios decrease evaporation and evapotranspiration losses and increase runoff. The new "yield" of water is significant when compared to undeveloped conditions.
2. As density of development increases, surface water yield increases and evapotranspiration losses decrease. Full spectrum detention attenuates peak discharges and extends the release hydrographs, primarily affecting the timing of runoff as a result of development.
3. Analysis indicated little to no change in evapotranspiration losses between scenarios with and without FSD. This is due to the fact that over the relatively short period that water is stored in a FSD facility (anywhere from a few hours to 72 hours), the amount of evaporation that would occur from the stored water surface is not very different from the amount of water that would be evapotranspired from pervious areas on the site, which have depression storage of up to 0.35 inches.
4. The SWMM analysis clearly demonstrates the benefits of FSD for attenuating peak flows over a wide range of storm events, and as expected, the scenarios with FSD have lower outflow rates and longer duration releases relative to comparable scenarios with no FSD.
5. The SWMM results followed expected trends with increased runoff (magnitude and frequency) as imperviousness increased. These changes are most significant at higher imperviousness levels, with a site with imperviousness of 65% yielding more than 200 acre-feet of runoff per year more than an undeveloped site on average over a 64-year simulation period.
6. The primary effect that FSD has on the delivery of this "new" water to the system is related to timing. By providing temporary storage, FSD facilities provide extended and controlled release of runoff that is a net benefit to downstream water users.
7. In most Front Range municipalities providing detention to attenuate peak flows from development is required by ordinance, and in MS4 areas there are regulatory requirements for stormwater quality facilities. FSD facilities provide important public safety benefits in terms of flood control. From these perspectives and from a public works perspective, the drainage and stormwater infrastructure, including FSD facilities, is an integral part of an overall development and not optional.
8. Theoretically, the scenarios without FSD *could* provide greater flow rates to the system during and immediately following runoff and less flow on following days. However, from a practical standpoint, such uncontrolled releases of runoff would have the potential to cause significant erosion and damage in downstream waterways, causing flooding and affecting water delivery infrastructure. Many of the erosion problems on Big Dry Creek, including washed out head gates and collapsing banks, are due to hydromodification (BDCWA 2005), which can be mitigated through implementation of FSD.

This modeling effort, while general in nature, provides a method that can be applied to assess interactions between development, stormwater management, and water rights along the Front Range of Colorado. The clear (and anticipated) results of the analysis are that replacement of vegetated pervious areas with impervious areas increases runoff available to water users that would largely be lost to evapotranspiration under undeveloped conditions, and that FSD plays an important role in regulating the delivery of this water and protecting the stability of the streams that deliver water to users.

7.0 REFERENCES

Allen, Rick, et al, 1998. Utah State University. *Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements – FAO Irrigation and Drainage Paper 56.*

Big Dry Creek Watershed Association 2005. *Lower Big Dry Creek Hydrologic Study*. Report prepared by Wright Water Engineers, Inc., Denver, CO.

Colorado Division of Water Resources (DWR) 2015. *Division Filing – Accounting & Spreadsheets.* http://dwrweblink.state.co.us/dwrweblink/search.aspx?dbid=0

EPA 2014. *National Stormwater Calculator, Version 1.1.* http://www.epa.gov/water-research/national-stormwater-calculator.

EPA 2015. *Stormwater Management Model Reference Manual – Volume 1- Hydrology*. EPA Office of Research and Development, Water Supply and Water Resources Division, EPA/600/R-15/162.

EPA 2015. *Stormwater Management Model (SWMM), Version 5.0.1.010*. EPA Office of Research and Development, Water Supply and Water Resources Division.

Gebert, W.A., Graczyk, D.J., and Krug, W.R., 1987. *Average annual runoff in the United States, 1951-80.* U.S. Geological Survey, Hydrologic Investigations Atlas HA-710, scale 1:7,500,000.

Hydrobase August 24, 2015. Colorado's Decision Support System (CDSS). http://cdss.state.co.us/Pages/CDSSHome.aspx

Leonard Rice Engineers (LRE) 2006. *SPDSS Memorandum Final.* Memorandum to Ray Alvarado and Ray Bennett from LRE, Re: Task 53.3 – Assign Key Climate Information to Irrigated Acreage and Reservoirs, Revised February 1, 2006.

National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) 2015. *NCDC Climate Data Online (CDO) Global Historical Climate Network Daily Records for Denver Stapleton CO US*: GHCND: USW00023062, including hourly precipitation. Downloaded September 2015.

UDFCD 2006. *Big Dry Creek (ADCO) Northern Tributaries Outfall System Plan, Phase A Report*. Prepared by WWE for UDFCD, Adams County, City of Thornton, City & County of Broomfield, and City of Westminster.

UDFCD 2015. Memorandum from Ken MacKenzie, Re: New Colorado Revised Statute §37-92-602 (8) "*Concerning a Determination that Water Detention Facilities Designed to Mitigate the Adverse*

Effects of Storm Water Runoff Do Not Materially Injure Water Rights." Updated October 15, 2015 (Original July 7, 2015).

UDFCD 2015. *Urban Storm Drainage Criteria Manual, Volumes 1 & 2*. UDFCD, Denver, CO.

Z:\Project Files\15\151-028\151-028.000\Engineering\Report\Final UDFCD Water Rights Report.docx

Attachments

Tables

Table 1. Sub-watershed Input Parameters for SWMM Simulations

Parameters	Model Scenario						Source/Comments
	Undeveloped	20%	35%	50%	65%	80%	
Sub-watershed Area (acres)	160	160	160	160	160	160	One-square mile watershed
Number of Sub-watersheds	4	4	4	4	4	4	
Width (ft)	1890	1890	1890	1890	1890	1890	~ 2:1 L:W ratio
Slope (%)	1%	1%	1%	1%	1%	1%	Overland flow slope, typical value
Imperviousness (%)	2%	20%	35%	50%	65%	80%	
Manning's n for Overland Flow Impervious Area	0.013	0.013	0.013	0.013	0.013	0.013	SWMM User Manual (concrete)
Manning's n for Overland Flow Pervious Area	0.15	0.15	0.15	0.15	0.15	0.15	SWMM User Manual (short prairie)
Depression Storage Impervious Area (in)	0.10	0.10	0.10	0.10	0.10	0.10	UDFCD Runoff Chapter
Depression Storage Pervious Area (in)	0.35	0.35	0.35	0.35	0.35	0.35	UDFCD Runoff Chapter
Infiltration Rate (in/hr)	2.5	2.5	2.5	2.5	2.5	2.5	SWMM User Manual for clay loam, infiltration rate was used as calibration parameter for undeveloped scenario ~ 0.5 in/yr runoff on average
Final Infiltration Rate (in/hr)	0.04	0.04	0.04	0.04	0.04	0.04	
Infiltration Decay Constant (1/day)	4	4	4	4	4	4	UDFCD Runoff Chapter & SWMM User Manual
Drying Time (days)	7	7	7	7	7	7	SWMM User Manual

Table 2. Aquifer Parameters for SWMM Simulations

Characteristic	Definition	Units	Default	Typical Range	Value Used	Notes	Source
Porosity	Volume of voids / total soil volume.	% (volumetric fraction)	0.5	0.3-0.6	0.4	Coarse-textured soils tent to be less porous than fine-texture soils [(Volume of Air in soil + Volume of water in soil) / (Volume Total)]	Text - Fundamentals of Soil Physics (Hillel); PDF (SoilPorosity_modeling_approach_appendix_a)
Wilting Point	Soil moisture content at which plants cannot survive.	% (volumetric fraction)	0.15	0.05-0.30	0.2	Fine grained soils (e.g., clay, made of "platy" minerals) have a high porosity (many small pores) leading to a high field capacity and high wilting point.	PDF - Soil Characteristics_Soil Society of America - saxton2006 (pg 9)
Field Capacity	Soil moisture content after all free water has drained off.	% (volumetric fraction)	0.3	0.1-0.42	0.35	The maximum amount of water that a soil can hold after gravitational drainage	PDF - Soil Characteristics_Soil Society of America - saxton2006 (pg 9)
Conductivity	Soil's saturated hydraulic conductivity.	in/hr	5	0.14-1.42	0.06	For Soil Group C: Sandy Clay Loam	PDF - Soil Characteristics_Soil Society of America - saxton2006 (pg 9)
Conductivity Slope	Average slope of log(conductivity) versus soil moisture deficit (i.e., porosity minus moisture content) curve	curve (unitless)	10	5-14.5	5	For Clay Loam.	SWMM Knowledge Database
Tension Slope	Average slope of soil tension versus soil moisture content curve.	inches	15	0	0	According to source, tension slope was made for SWMM 4. In SWMM 5, should be set to zero to keep GW model consistent.	SWMM Knowledge Database
Upper Evaporation Fraction	Fraction of total evaporation available for evapotranspiration in the upper unsaturated zone.	% (fraction)	0.35	0.3-0.7	0.3	Value can range; use as calibration parameter	SWMM Knowledge Database
Lower Evaporation Depth	Maximum depth below the surface at which evapotranspiration from the lower saturated zone can still occur.	feet	14	2-27	8	For Sandy Clay Loam	SWMM Knowledge Database
Lower GW Loss Rate	Rate of percolation from saturated zone to deep groundwater.	in/hr	0.002	0.001-0.02	0	Assumed to be 0. Groundwater assumed to be shallow, tributary groundwater.	
Bottom Elevation	Elevation of the bottom of the aquifer.	feet	0		4970	20 feet below junction connected to subcatchment; 40 feet below groudn surface.	
Water Table Elevation	Elevation of the water table in the aquifer at the start of the simulation.	feet	10		4970	Assumed at bottom of aquifer for January start date (seasonally low groundwater)	
Unsaturated Zone Moisture	Moisture content of the unsaturated upper zone of the aquifer at the start of the simulation (cannot exceed soil porosity).	% (volumetric fraction)	0.3	0.29-0.59	0.2	Set unsat moisture below porosity	

Table 3. Long-term Water Balance Summary

Undeveloped					
Avg Annual Precipitation =	14.2	in	758	ac-ft	100%
Avg Annual ET + Evaporation =	13.8	in	734	ac-ft	96.9%
Avg Annual Runoff =	0.4	in	22	ac-ft	2.9%
Avg Annual Triburaty Groundwater =	0.04	in	2.0	ac-ft	0.3%

20%											
20% IA						**20% IA + FSD**					
Avg Annual Precipitation =	14.2	in	758	ac-ft	100%	Avg Annual Precipitation =	14.2	in	758	ac-ft	100%
Avg Annual ET + Evaporation =	12.9	in	686	ac-ft	90.5%	Avg Annual ET + Evaporation =	12.9	in	690	ac-ft	91.1%
Avg Annual Runoff =	1.3	in	70	ac-ft	9.2%	Avg Annual Runoff =	1.2	in	66	ac-ft	8.6%
Avg Annual Triburaty Groundwater =	0.03	in	1.8	ac-ft	0.2%	Avg Annual Triburaty Groundwater =	0.04	in	2.3	ac-ft	0.3%
35%											
35% IA						**35% IA + FSD**					
Avg Annual Precipitation =	14.2	in	758	ac-ft	100%	Avg Annual Precipitation =	14.2	in	758	ac-ft	100%
Avg Annual ET + Evaporation =	11.9	in	635	ac-ft	83.7%	Avg Annual ET + Evaporation =	11.9	in	635	ac-ft	83.7%
Avg Annual Runoff =	2.3	in	122	ac-ft	16.1%	Avg Annual Runoff =	2.3	in	122	ac-ft	16.1%
Avg Annual Triburaty Groundwater =	0.03	in	1.5	ac-ft	0.2%	Avg Annual Triburaty Groundwater =	0.03	in	1.5	ac-ft	0.2%
50%											
50% IA						**50% IA + FSD**					
Avg Annual Precipitation =	14.2	in	758	ac-ft	100%	Avg Annual Precipitation =	14.2	in	758	ac-ft	100%
Avg Annual ET + Evaporation =	10.8	in	575	ac-ft	75.8%	Avg Annual ET + Evaporation =	10.8	in	575	ac-ft	75.8%
Avg Annual Runoff =	3.4	in	182	ac-ft	24.0%	Avg Annual Runoff =	3.4	in	182	ac-ft	24.0%
Avg Annual Triburaty Groundwater =	0.02	in	1.23	ac-ft	0.2%	Avg Annual Triburaty Groundwater =	0.02	in	1.23	ac-ft	0.2%
65%											
65% IA						**65% IA + FSD**					
Avg Annual Precipitation =	14.2	in	758	ac-ft	100%	Avg Annual Precipitation =	14.2	in	758	ac-ft	100%
Avg Annual ET + Evaporation =	9.2	in	489	ac-ft	64.4%	Avg Annual ET + Evaporation =	9.2	in	489	ac-ft	64.4%
Avg Annual Runoff =	4.7	in	250	ac-ft	33.0%	Avg Annual Runoff =	4.7	in	250	ac-ft	33.0%
Avg Annual Triburaty Groundwater =	0.4	in	19.8	ac-ft	2.6%	Avg Annual Triburaty Groundwater =	0.4	in	19.8	ac-ft	2.6%
80%											
80% IA						**80% IA + FSD**					
Avg Annual Precipitation =	14.2	in	758	ac-ft	100%	Avg Annual Precipitation =	14.2	in	758	ac-ft	100%
Avg Annual ET + Evaporation =	7.9	in	423	ac-ft	55.9%	Avg Annual ET + Evaporation =	7.9	in	423	ac-ft	55.9%
Avg Annual Runoff =	5.7	in	303	ac-ft	40.0%	Avg Annual Runoff =	5.7	in	303	ac-ft	40.0%
Avg Annual Triburaty Groundwater =	0.6	in	31.4	ac-ft	4.1%	Avg Annual Triburaty Groundwater =	0.6	in	31.4	ac-ft	4.1%

Table 4. Comparison of Model Statistics for Varying Levels of Imperviousness

Variables	Undeveloped	20% IA	20% IA + FSD	35% IA	35% IA + FSD	50% IA	50% IA + FSD	65% IA	65% IA + FSD	80% IA	80% IA + FSD
Precipitation											
Number of Events	4931	4931	4931	4931	4931	4931	4931	4931	4931	4931	4931
Mean Daily Precip (in)	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Max Daily Precip (in)	3.39	3.39	3.39	3.39	3.39	3.39	3.39	3.39	3.39	3.39	3.39
System Outflow											
Number of Events	163	5545	5871	5652	6372	5738	6852	5838	7361	5927	7812
Mean Daily Outflow (cfs)	12.2	1.3	0.6	2.1	0.9	3.0	1.2	3.9	1.4	4.4	1.7
Peak Daily Outflow (cfs)	196	264	228	365	352	523	433	697	511	851	516
Mean Daily Outflow (ac-ft)	8.9	0.9	0.7	1.5	1.2	2.2	1.7	2.9	2.2	3.5	2.6
Max Daily Outflow (ac-ft)	77	94	72	113	96	129	102	144	125	158	133
Evaporation											
Number of Events	20689	22032	22833	22443	22443	23529	23529	23707	23707	23707	23707
Daily Mean Evap (in)	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Peak Daily Evap (in)	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Storage											
Number of Events	0	0	6080	0	6569	0	7044	0	7858	0	7972
Daily Mean Storage (ac-ft)	0	0	0.2	0	0.6	0	1.1	0	1.4	0	1.9
Daily Peak Storage (ac-ft)	0	0	12	0	23	0	35	0	47	0	59

Table 5. Water Rights on Big Dry Creek

Structure ID	Water Right Name	Approp. Date	Admin. No.	Case No.	Decreed Use	Diversion Rate (cfs)		
						Absolute	Conditional	Alt Pt
872	German Ditch	1885-11-30	13118.00000	CA8568	Irrigation	0.99		
871	Bull Canal (Whipple Ditch)	1885-12-31	13149.00000	CA8568	Irrigation	0.99		
871	Bull Canal (Whipple Ditch)	1884-09-01	15895.12663	CA54658	Irrigation	5		
872	German Ditch	1885-11-25	15895.13113	01CW0273	Irrigation	40		
873	Big Dry Creek Ditch	1889-12-15	15895.14594	CA54658	Irrigation	36.66		
874	Yoxall Ditch	1896-07-27	17010.00000	CA40750	Irrigation	16.8		
880	Thornton Golf Course Pipeline	1987-12-10	50382.00000	96CW0244	Irrigation, Recreation, Other Beneficial Uses	5		140
880	Thornton Golf Course Pipeline	1996-12-31	53691.00000	96CW1116	Municipal			130
871	Bull Canal (Whipple Ditch)	2004-11-15	56567.00000	04CW0310	Municipal		31	
871	Bull Canal (Whipple Ditch)	2004-12-20	56602.00000	04CW0310	Municipal			21

Table 6. Historical River Calls on the South Platte River Relative to Outflows from Full Spectrum Detention

	Admin #	Call Structure	Days	Percent	Undeveloped	20% - IA	20% - IA+FSD	35% - IA	35% - IA+FSD	50% - IA	50% - IA+FSD	65% - IA	65% - IA+FSD	80% - IA	80% - IA+FSD
	No Call		13,883	60%	0.052	0.184	0.171	0.325	0.330	0.487	0.504	0.672	0.693	0.814	0.900
German Ditch - 1st Priority; Bull Canal - 1st Priority	5803.00000	FARMERS INDEPENDENT DITCH	50	0.2%	0.0	0.053	0.026	0.104	0.046	0.161	0.066	0.224	0.088	0.259	0.111
	5965.00000	MEADOW ISLAND 1 DITCH	190	0.8%	0.094	0.240	0.207	0.399	0.350	0.565	0.469	0.746	0.653	0.894	0.849
	5967.00000	MEADOW ISLAND DITCH	143	0.6%	0.165	0.439	0.363	0.722	0.649	1.028	0.895	1.360	1.163	1.637	1.470
	5969.00000	HEWES COOK DITCH	146	0.6%	0.0	0.082	0.062	0.165	0.117	0.266	0.177	0.384	0.236	0.459	0.302
	7671.00000	PLATTEVILLE DITCH	10	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	7739.00000	LUPTON BOTTOM DITCH	1	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	7892.00000	HEWES COOK DITCH	126	0.5%	0.041	0.183	0.101	0.339	0.148	0.496	0.188	0.659	0.345	0.790	0.532
	7948.00000	EVANS NO 2 DITCH	1,476	6.3%	0.098	0.233	0.180	0.374	0.302	0.530	0.403	0.704	0.539	0.837	0.703
	7975.00000	BRIGHTON DITCH	375	1.6%	0.0	0.098	0.075	0.194	0.144	0.311	0.230	0.446	0.340	0.547	0.468
	8127.00000	FARMERS HIGHLINE CNL	53	0.2%	0.0	0.226	0.189	0.476	0.387	0.783	0.613	1.134	0.853	1.419	1.104
	8218.00000	BRANTNER DITCH	32	0.1%	0.0	0.059	0.052	0.117	0.088	0.185	0.222	0.263	0.309	0.311	0.343
	8659.00000	LUPTON BOTTOM DITCH	136	0.6%	0.477	0.819	0.641	1.186	0.942	1.570	1.108	1.984	1.403	2.331	1.739
	8689.00000	PLATTEVILLE DITCH	109	0.5%	0.500	0.799	0.608	1.108	0.863	1.437	1.014	1.789	1.323	2.077	1.658
	9075.00000	UNION DITCH	196	0.8%	0.063	0.245	0.181	0.447	0.330	0.655	0.474	0.880	0.692	1.065	0.949
	9597.00000	MEADOW ISLAND DITCH	3	0%	0.0	0.038	0.033	0.071	0.063	0.108	0.097	0.147	0.134	0.169	0.173
	9686.00000	FULTON DITCH	501	2.2%	0.024	0.195	0.136	0.377	0.240	0.583	0.352	0.811	0.541	0.993	0.771
	9821.00000	FARMERS INDEPENDENT DITCH	271	1.2%	0.0	0.125	0.104	0.248	0.224	0.396	0.368	0.568	0.488	0.696	0.632
	10180.00000	LOWER LATHAM DITCH	243	1.0%	0.199	0.579	0.377	0.980	0.647	1.419	0.871	1.894	1.188	2.296	1.525
	10184.00000	CHURCH DITCH	1	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	10215.00000	MEADOW ISLAND DITCH	26	0.1%	0.0	0.079	0.058	0.155	0.117	0.242	0.189	0.340	0.272	0.399	0.364
	10480.00000	DENVER CONDUIT NO 20	2	0.0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	10546.00000	CHURCH DITCH	1	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	10610.00000	HIGHLINE CNL	93	0.4%	0.933	1.433	1.312	2.007	1.970	2.547	2.295	3.114	3.018	3.571	3.523
	10901.00000	FULTON DITCH	15	0.1%	0.019	0.465	0.165	0.987	0.227	1.597	0.303	2.266	0.627	2.896	1.132
	11139.00000	DENVER CONDUIT NO 20	5	0%	0.0	0.114	0.096	0.218	0.191	0.336	0.298	0.468	0.342	0.544	0.372
	11338.00000	BRANTNER DITCH	68	0.3%	0.0	0.047	0.042	0.094	0.106	0.150	0.204	0.214	0.278	0.256	0.337
	11620.00000	LOWER LATHAM DITCH	156	0.7%	0.015	0.206	0.174	0.406	0.367	0.636	0.592	0.897	0.838	1.106	1.096
	11629.00000	UNION DITCH	2	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	11807.00000	MEADOW ISLAND 1 DITCH	15	0.1%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	13108.00000	BURLINGTON D RIVER HEADGATE	2,164	9.3%	0.029	0.189	0.167	0.355	0.323	0.549	0.491	0.769	0.663	0.938	0.878
Bull Canal Pr2	14423.00000	CHEESMAN RES	106	0.5%	0.0	0.118	0.089	0.238	0.161	0.382	0.244	0.552	0.351	0.677	0.503
	15585.00000	DENVER CONDUIT NO 20	6	0.0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
BDC Ditch	15973.00000	CHEESMAN RES	23	0.1%	3.264	3.927	3.243	4.701	4.630	5.369	5.275	6.020	5.942	6.578	6.782
Thorncreek Pipeline; Bull Canal	18018.00000	DENVER CONDUIT NO 20	26	0.1%	0.0	0.0	0.000	0.000	0.001	0.000	0.002	0.001	0.006	0.002	0.011
	19055.00000	CROKE CANAL	18	0.1%	0.0	0.0	0.0	0.0	0.000	0.0	0.029	0.0	0.089	0.0	0.157
	21150.00000	BURLINGTON D RIVER HEADGATE	21	0.1%	0.0	0.042	0.035	0.075	0.063	0.110	0.096	0.149	0.135	0.169	0.193
	21252.00000	BURLINGTON D RIVER HEADGATE	102	0.4%	0.0	0.124	0.109	0.249	0.210	0.400	0.325	0.579	0.446	0.697	0.582
	21562.00000	BURLINGTON D RIVER HEADGATE	1,313	5.6%	0.003	0.107	0.101	0.216	0.213	0.345	0.354	0.494	0.512	0.608	0.678
	21698.00000	MILTON RES	139	0.6%	0.0	0.042	0.042	0.087	0.086	0.142	0.144	0.207	0.228	0.251	0.333
	21709.00000	EVANS NO 2 DITCH	9	0%	0.0	0.036	0.033	0.068	0.062	0.104	0.097	0.144	0.136	0.166	0.179
	22239.00000	BURLINGTON D RIVER HEADGATE	115	0.5%	0.0	0.020	0.017	0.038	0.033	0.059	0.053	0.082	0.075	0.096	0.099
	22254.00000	DENVER CONDUIT NO 20	20	0.1%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	22355.00000	HORSE CREEK RES	48	0.2%	0.0	0.120	0.134	0.237	0.359	0.377	0.564	0.538	0.768	0.646	0.991
	22370.00000	MARSTON RES FROM (SEE 0903501)	15	0.1%	0.0	0.263	0.154	0.533	0.338	0.860	0.618	1.240	0.969	1.530	1.515
	25050.21709	EVANS NO 2 DITCH	33	0.1%	0.0	0.191	0.210	0.390	0.556	0.634	0.910	0.921	0.949	1.137	1.193
	46748.00000	CHATFIELD RESERVOIR	137	0.6%	0.040	0.235	0.195	0.445	0.431	0.674	0.670	0.919	0.854	1.117	1.041
	47481.40987	DENVER CONDUIT NO 20	7	0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	48974.00000	BURLINGTON D RIVER HEADGATE	12	0.1%	0.0	0.162	0.136	0.327	0.279	0.525	0.459	0.757	0.616	0.908	0.739

Figures

Watershed Parameters

- 1-square mile "typical" watershed
- Imperviousness 2%, 20%, 35%, 50%, 65%, 80%
- Sub-basin parameters from 2006 Big Dry Creek Northern Tributaries OSP
- Horton infiltration using parameters from USDCM

Climate Data

- Hourly Precipitation
- Daily Min and Max Temperatures
- Wind Speed
- Evaporation/ET calculated by model

Aquifer Parameters

- Porosity
- Field Capacity
- Wilting Point
- Upper/ lower zone water availability for ET

SWMM

Daily Time Series Output from SWMM

- Outflow
- Evaporation/ET
- Storage

Water Rights Accounting

- Streamflow
- Diversion Records
- Return Flows
- Calls

Water Rights Spreadsheet

Output from Water Rights Spreadsheet

Water shortage or water surplus

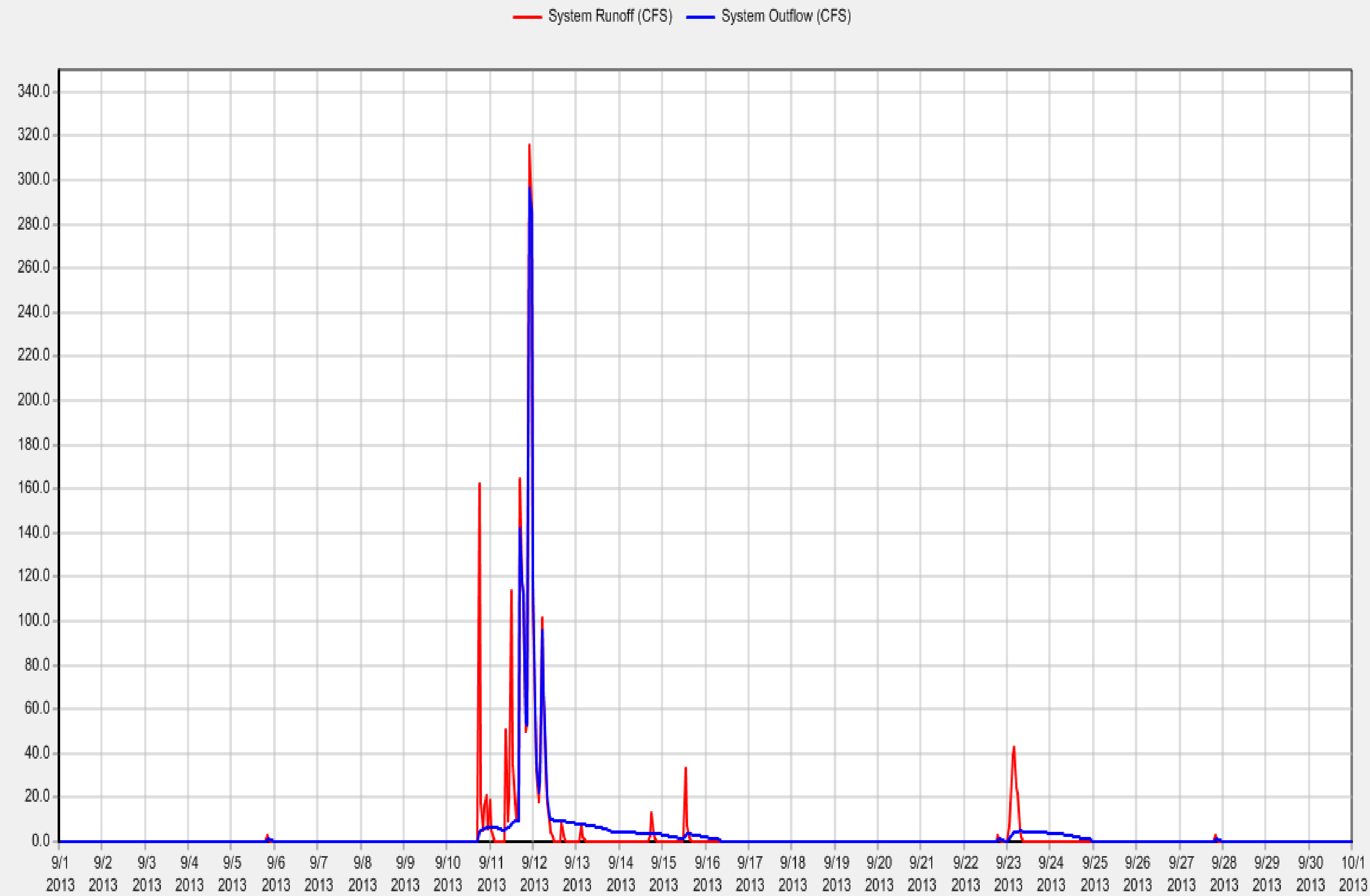


Figure 2. Representative Hydrographs Showing FSD Routing (SWMM output 50%IA + FSD, September 2013)

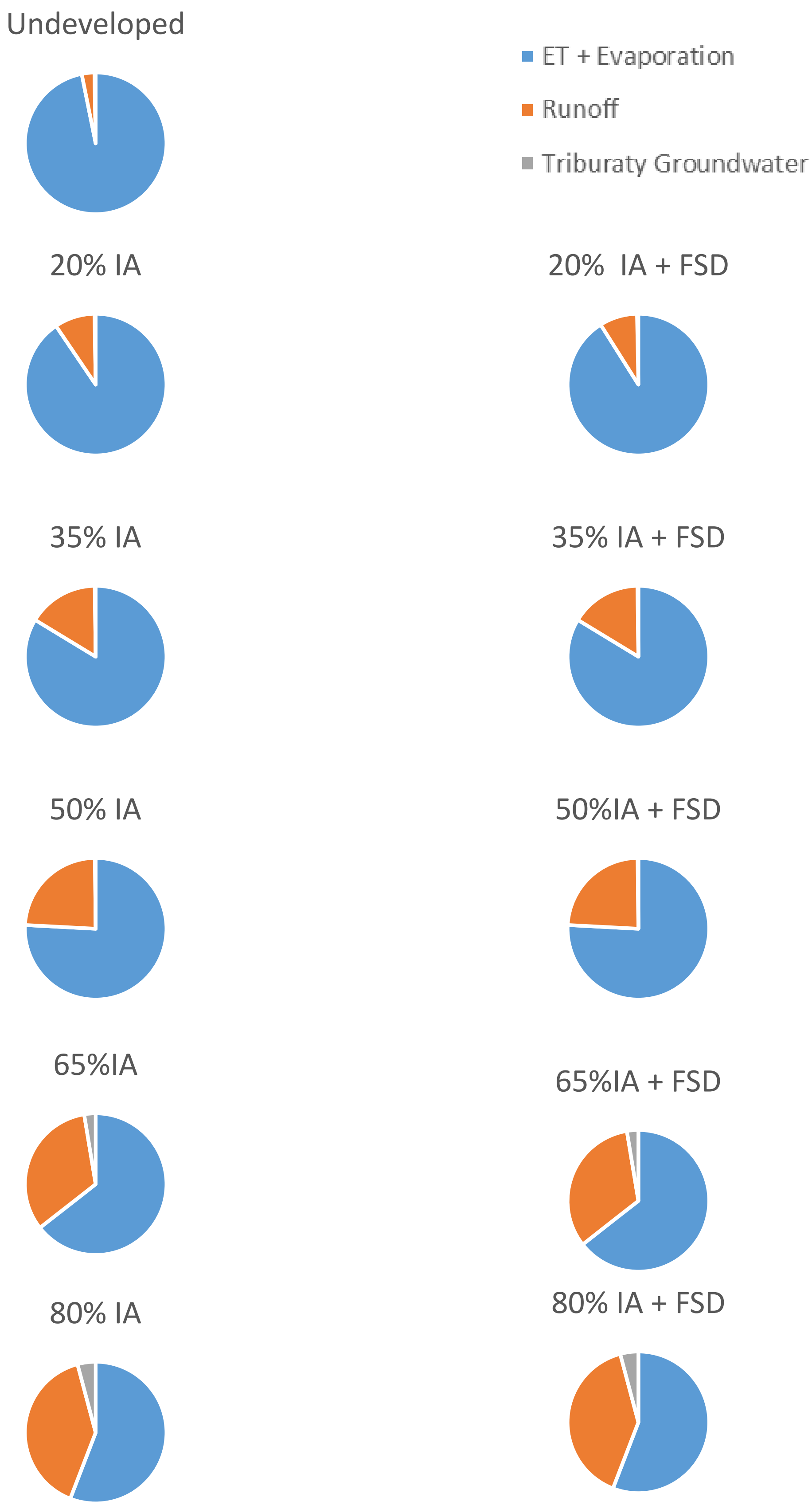


Figure 3. SWMM Water Balance Results for Varying Levels of Imperviousness

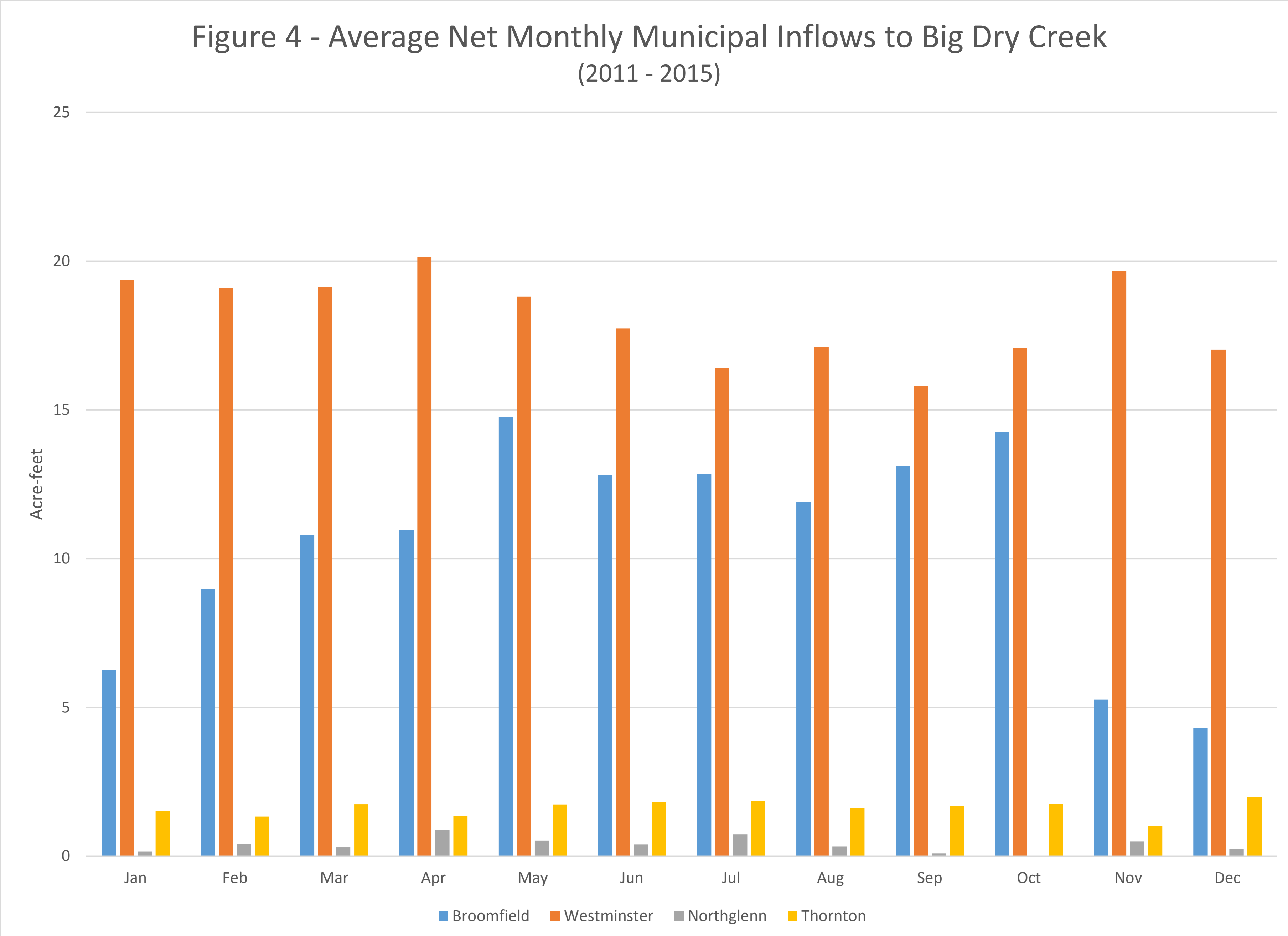


Figure 4 - Average Net Monthly Municipal Inflows to Big Dry Creek
(2011 - 2015)
Acre-feet
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Broomfield
Westminster
Northglenn
Thornton

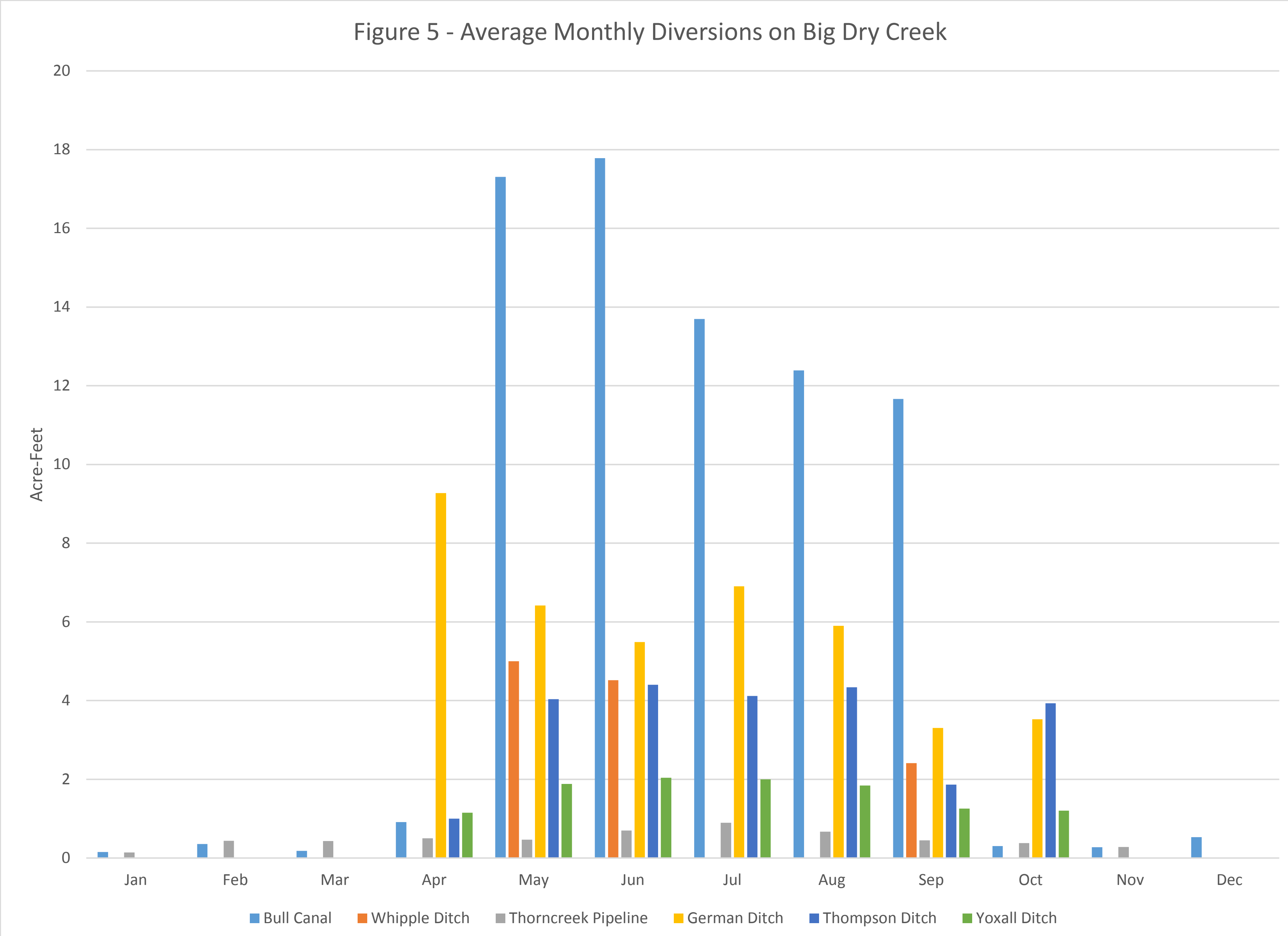
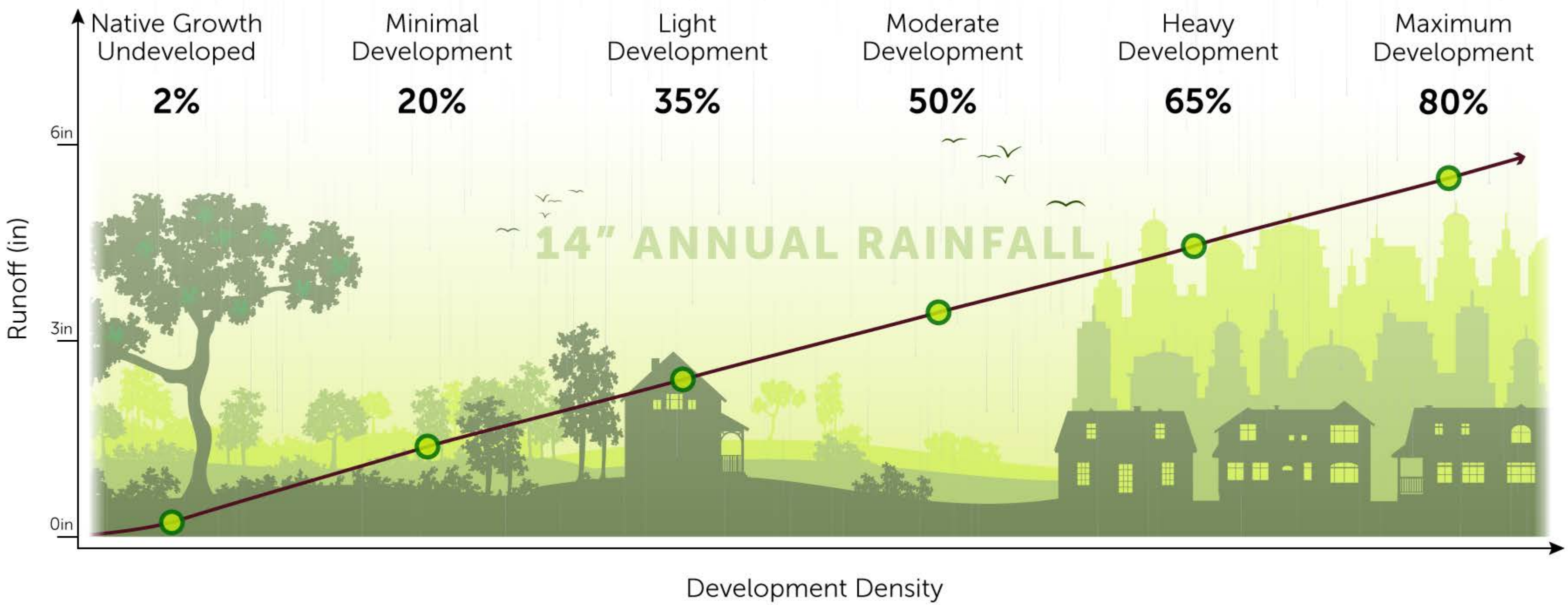


Figure 5 - Average Monthly Diversions on Big Dry Creek
Acre-Feet
0
2
4
6
8
10
12
14
16
18
20
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Bull Canal
Whipple Ditch
Thorncreek Pipeline
German Ditch
Thompson Ditch
Yoxall Ditch

Figure 6. Runoff due to Various Densities of Development



Presentation- UDFCD Annual Conference, April 5, 2016

Full Spectrum Detention and Water Rights

Ken MacKenzie, P.E., UDFCD, Master Planning Program Manager
&
Dr. Andrew Earles, P.E. and Adam Kremers, P.E., Wright Water Engineers, Inc.

April 5, 2016

Overview of Presentation

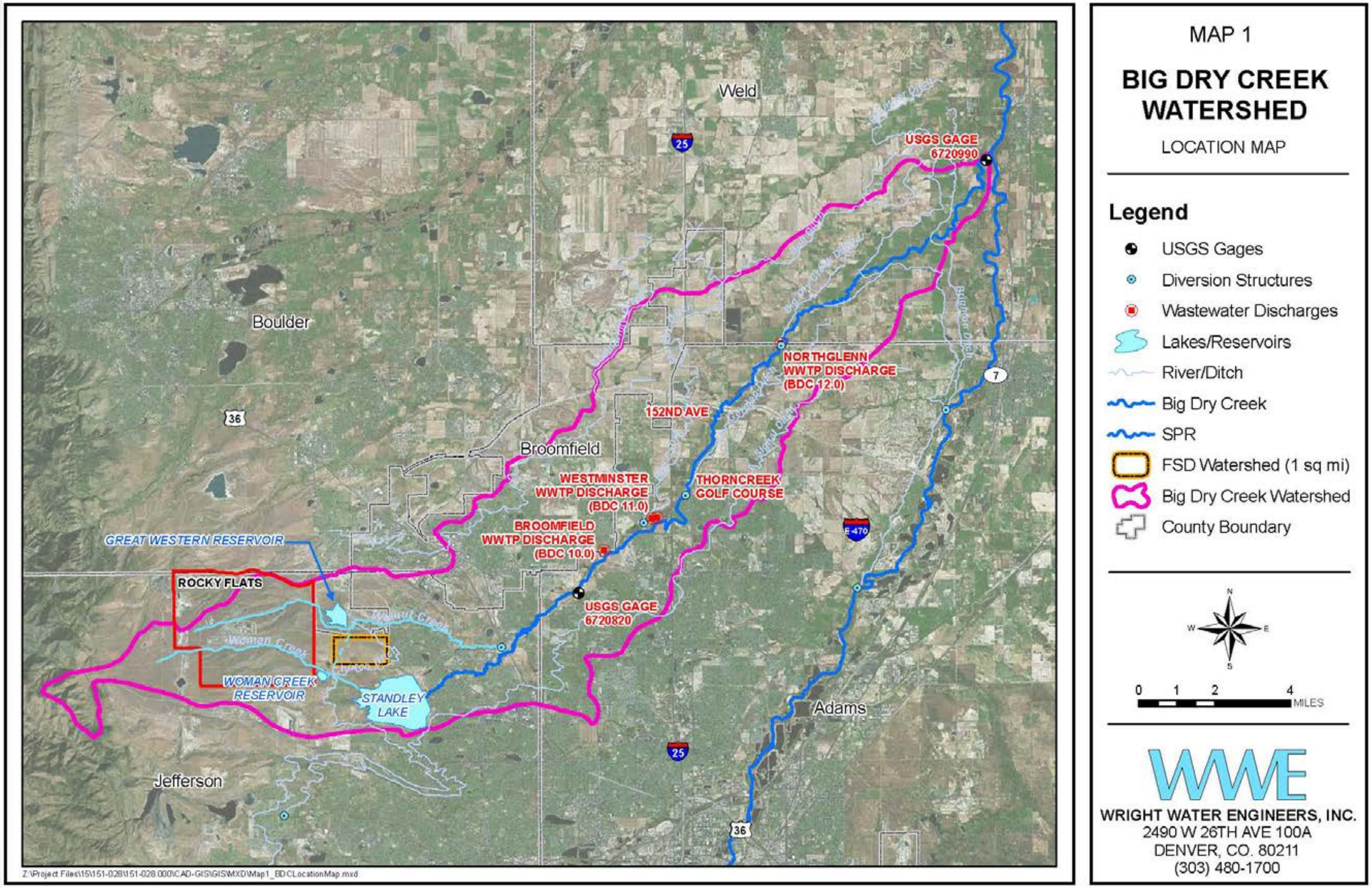
- Objectives and Approach
- SWMM Water Balance Modeling
- Water Rights Analysis
- Conclusions

Colorado Revised Statute (CRS) §37-92-602 (8)

- UDFCD legislative effort in 2015 session
- Provides legal protection for stormwater detention and infiltration facilities meeting criteria:
    1. Owned or operated by a governmental entity or subject to oversight by governmental entity (e.g., required under MS4 permit)
    2. Continuously releases or infiltrates at least 97% of all runoff from a rainfall event < = 5-year storm within 72 hours after the end of the event
    3. Continuously releases or infiltrates as quickly as practicable, but in all cases releases or infiltrates at least 99% of the runoff within 120 hours after the end of events > = 5-year storm
    4. It operates passively and does not subject the stormwater runoff to any active treatment process
    5. If located in Fountain Creek watershed (tributary to the Arkansas River), facility must be required by or operated in compliance with MS4 permit

Objectives

- Conduct long-term water balance analysis to quantify changes to the quantity and timing of water available to water rights users.
- Quantification of water balance differences between undeveloped, developed, and developed with FSD.
- Evaluation of changes in balance (evaporation, ET, infiltration, surface runoff) for varying levels of imperviousness.
- Examine effects of timing of runoff/releases from FSD facilities.
- Evaluate effects on downstream water users.


MAP 1
BIG DRY CREEK WATERSHED
LOCATION MAP
Legend
USGS Gages
Diversion Structures
Wastewater Discharges
Lakes/Reservoirs
River/Ditch
Big Dry Creek
SPR
FSD Watershed (1 sq mi)
Big Dry Creek Watershed
County Boundary
Weld
Boulder
Broomfield
Adams
Jefferson
USGS GAGE 6720990
NORTHGLENN WWTP DISCHARGE (BDC 12.0)
152ND AVE
WESTMINSTER WWTP DISCHARGE (BDC 11.0)
THORNCREEK GOLF COURSE
BROOMFIELD WWTP DISCHARGE (BDC 10.0)
GREAT WESTERN RESERVOIR
ROCKY FLATS
USGS GAGE 6720820
WOMAN CREEK RESERVOIR
STANDLEY LAKE
0 1 2 4 MILES
WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Approach

- Combine hydrology model (SWMM) with water rights model (spreadsheet)
- Model “typical” developments scenarios for hypothetical watershed (range of imperviousness)
- UDFCD spreadsheets for conceptual FSD sizing
- Water Rights model to assess downstream effects of SWMM scenarios

Watershed Parameters

- 1-square mile "typical" watershed
- Imperviousness 2%, 20%, 35%, 50%, 65%, 80%
- Sub-basin parameters from 2006 Big Dry Creek Northern Tributaries OSP
- Horton infiltration using parameters from USDCM

Climate Data

- Hourly Precipitation
- Daily Min and Max Temperatures
- Wind Speed
- Evaporation/ET calculated by model

SWMM

Aquifer Parameters

- Porosity
- Field Capacity
- Wilting Point
- Upper/ lower zone water availability for ET

Daily Time Series Output from SWMM

- Outflow
- Evaporation/ET
- Storage

Water Rights Accounting

- Streamflow
- Diversion Records
- Return Flows
- Calls

Water Rights Spreadsheet

Output from Water Rights Spreadsheet

Water shortage or water surplus

Fundamental Model Assumptions

- One square mile watershed (major drainage scale, typical of large scale development projects)
  - Use Big Dry Creek Northern Tributaries OSP as starting point for "typical" model parameterization
  - 160 acre sub-basins (similar to UDFCD master plan modeling)
  - Assume directly tributary to waterway
- Imperviousness varied from undeveloped (2%) to dense development (80%)
- Climate data (hourly rainfall, temperature, wind speed, etc.) from NOAA GHCN-D climate data files

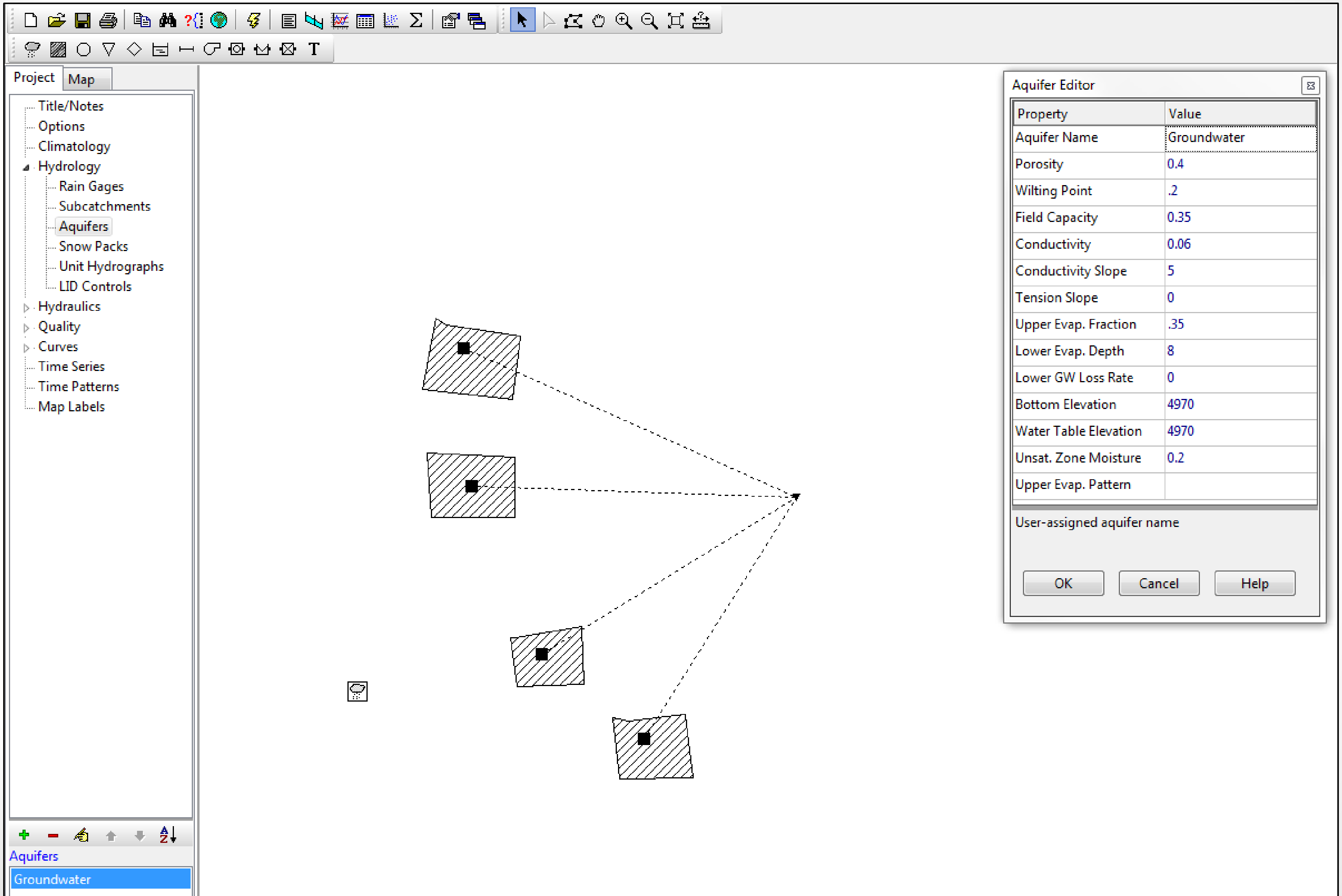
Fundamental Model Assumptions (cont.)

- Horton Loss parameters (guidance from USDCM), assume HSG C.
- Evaporation occurs from surface water (e.g. depression storage, runoff).
- Shallow aquifer beneath site – fraction of water in upper soil zone is available for ET between events:
  - Aquifer is “bucket” and change in aquifer storage represents shallow (tributary) groundwater recharge or depletion
  - Aquifer ET parameters “calibrated” for undeveloped scenario to yield results where ET ~ PET for native plants, with infrequent runoff.
- Snowmelt incorporated for runoff timing effects – not a sensitive parameter.

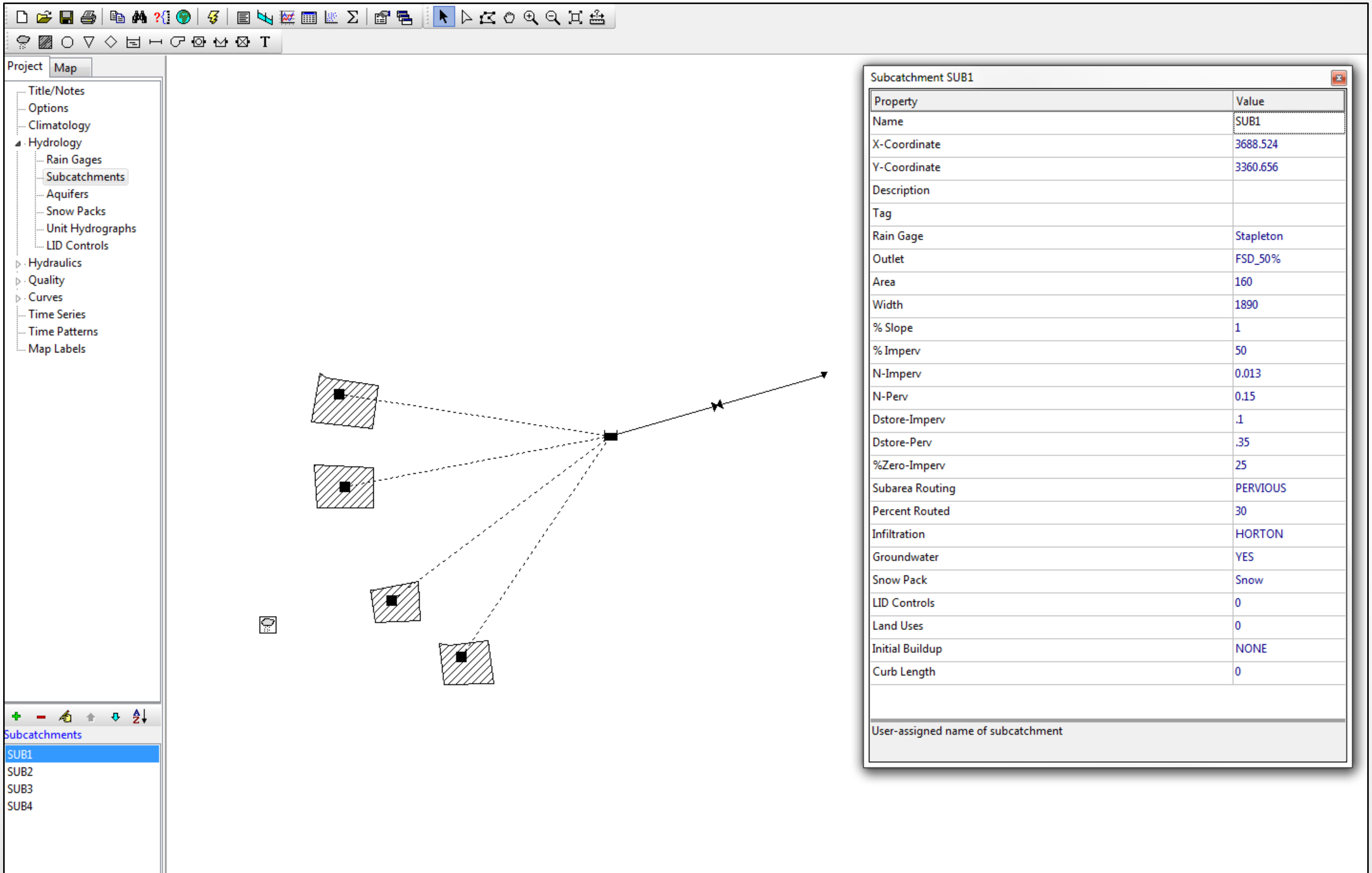
Fundamental Model Assumptions (cont.)

- Assumes dry land/native land use prior to development.
- Additional irrigation water not accounted for in model:
  - Model provides capabilities to evaluate alternate scenarios, including return flows from irrigated land; however, scope of this assessment did not include irrigation.
- Results from 1 square mile are scalable to larger areas.

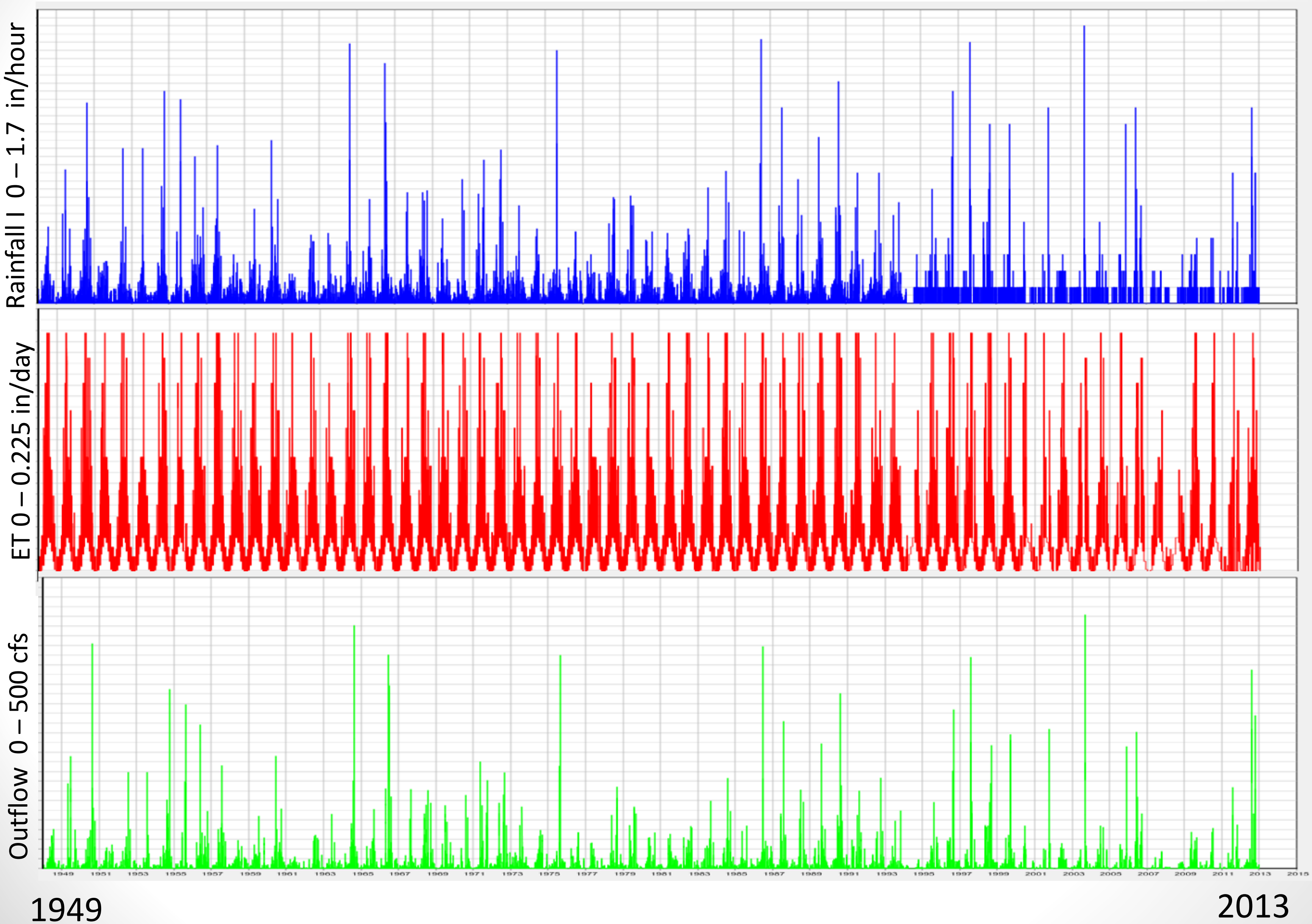
SWMM Layout for Model with No FSD



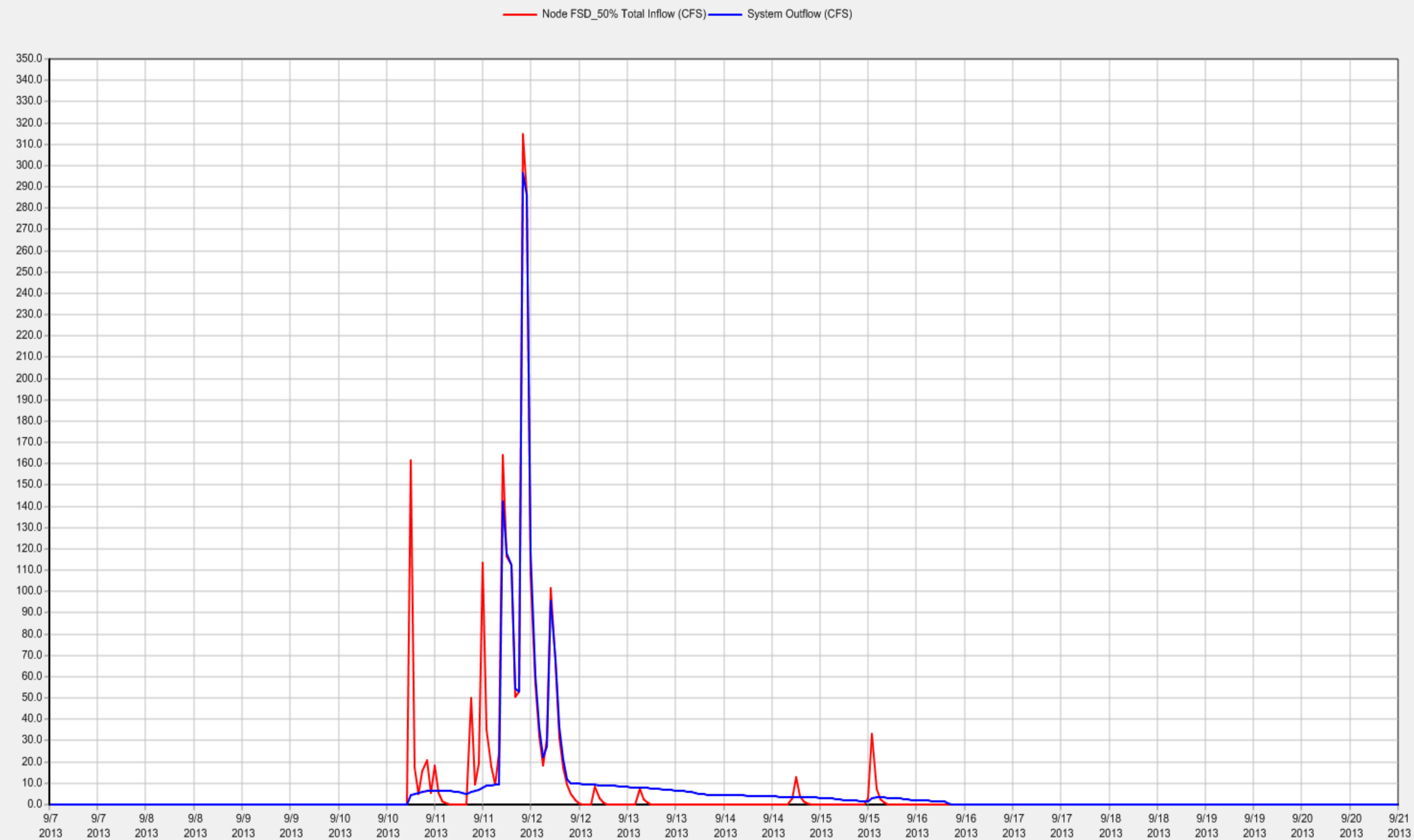
SWMM Model Layout with FSD



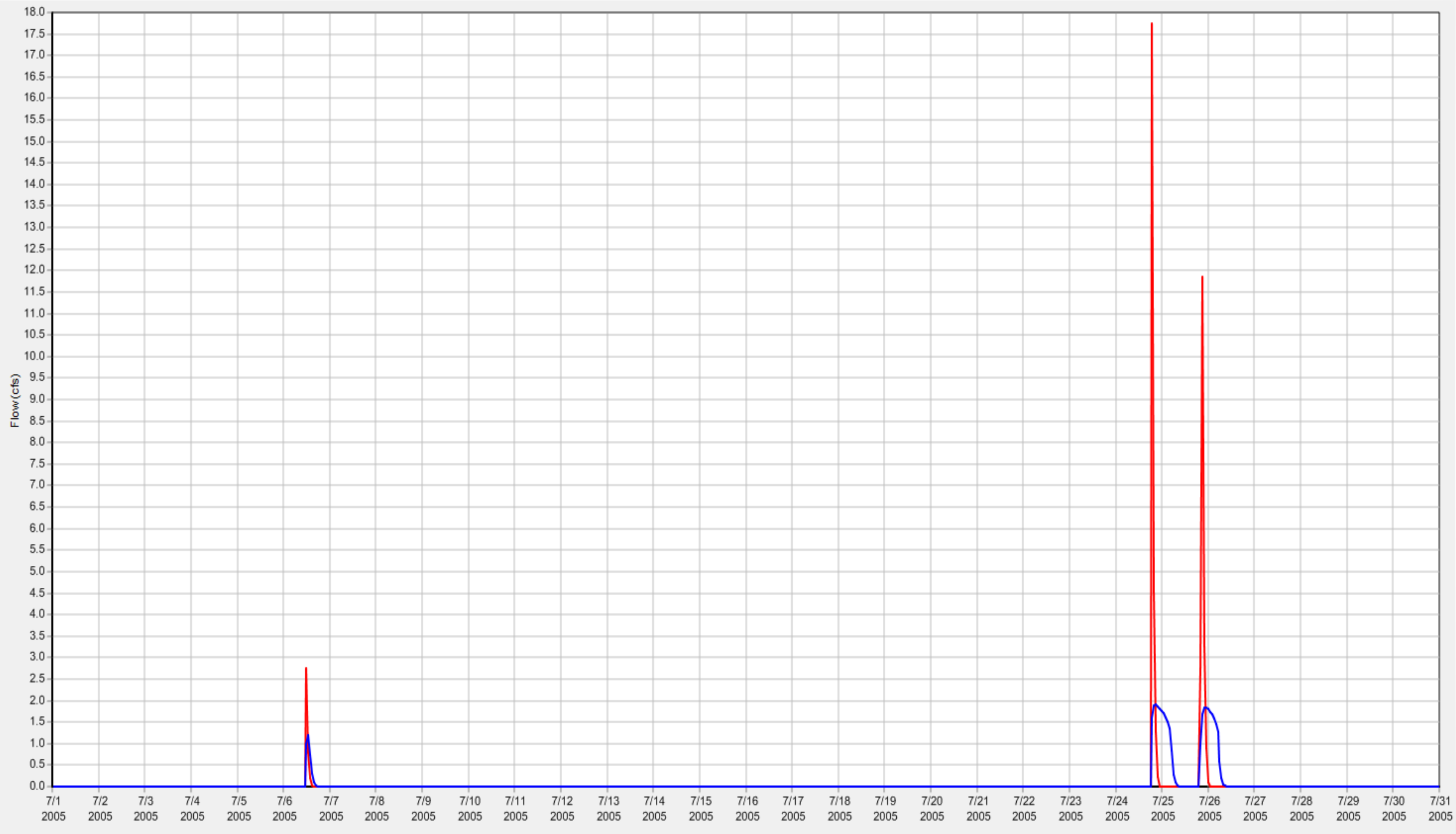
Precipitation, ET & System Outflow, 1949 - 2013

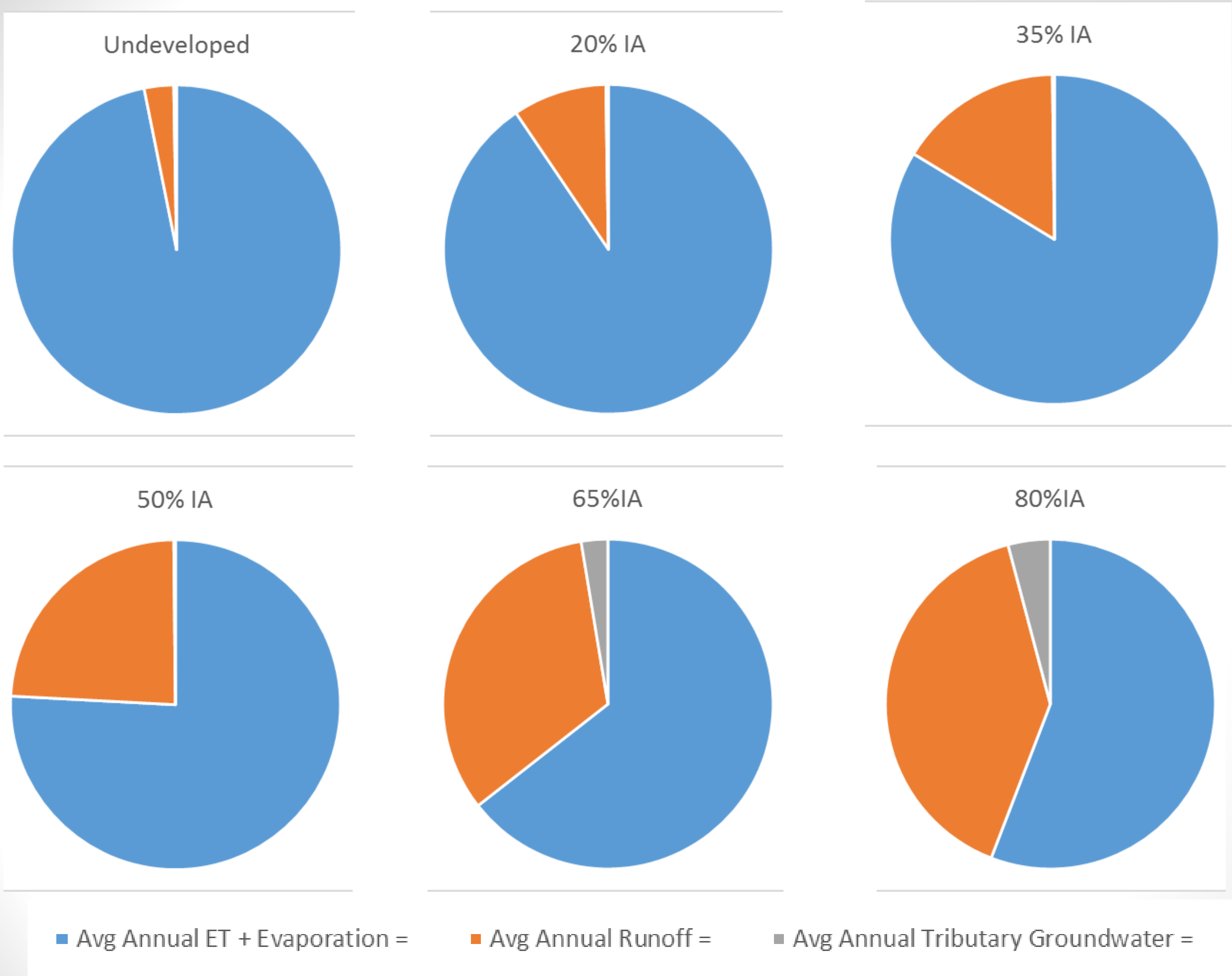


FSD Inflow and Outflow September 2013, 50% IA



Modeled FSD Inflow and Outflow, July 2005, 50% IA




Undeveloped
20% IA
35% IA
50% IA
65%IA
80%IA
Avg Annual ET + Evaporation =
Avg Annual Runoff =
Avg Annual Tributary Groundwater =

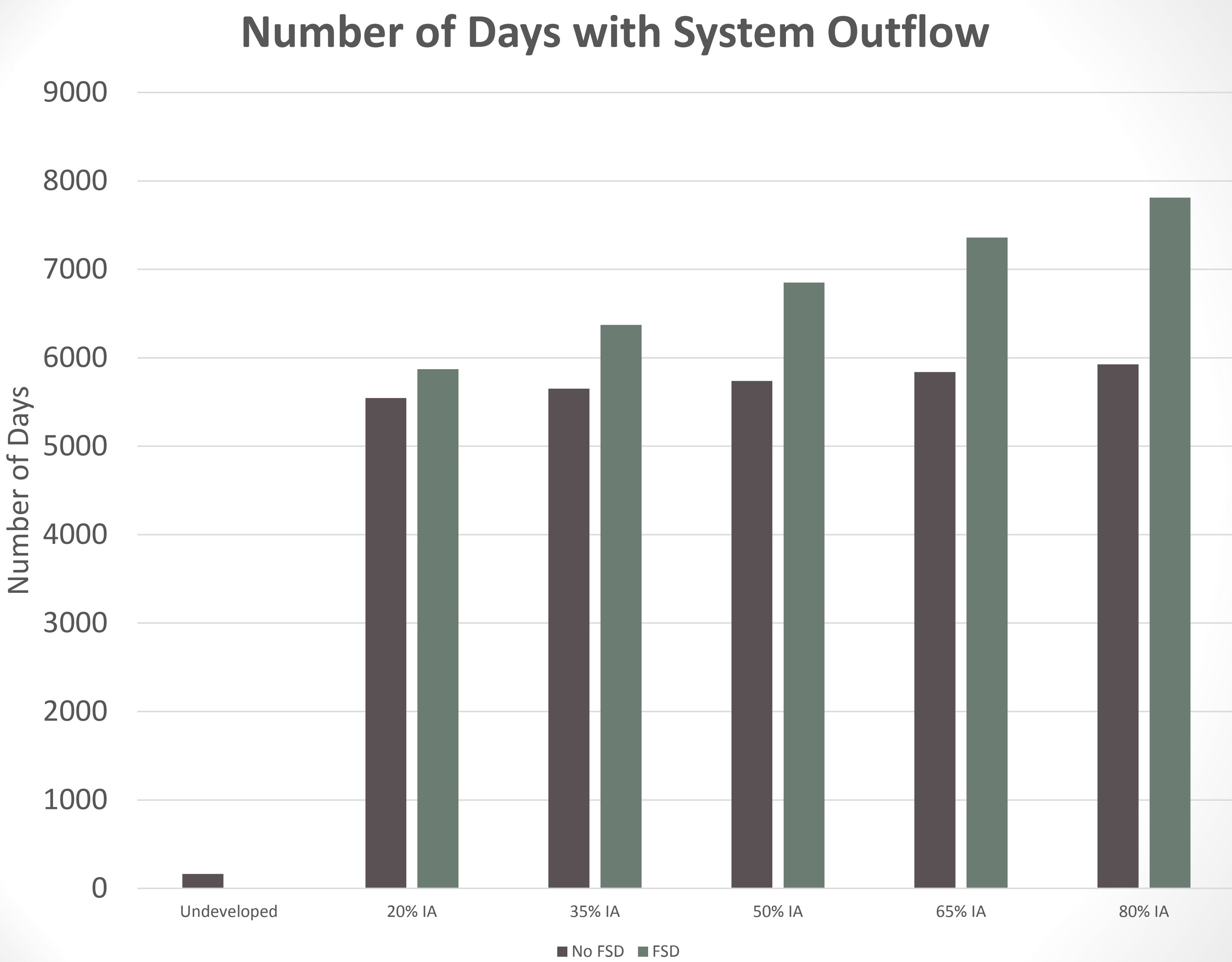
Erosion due to hydromodification

Results – Outflow, Evaporation/ET and Storage

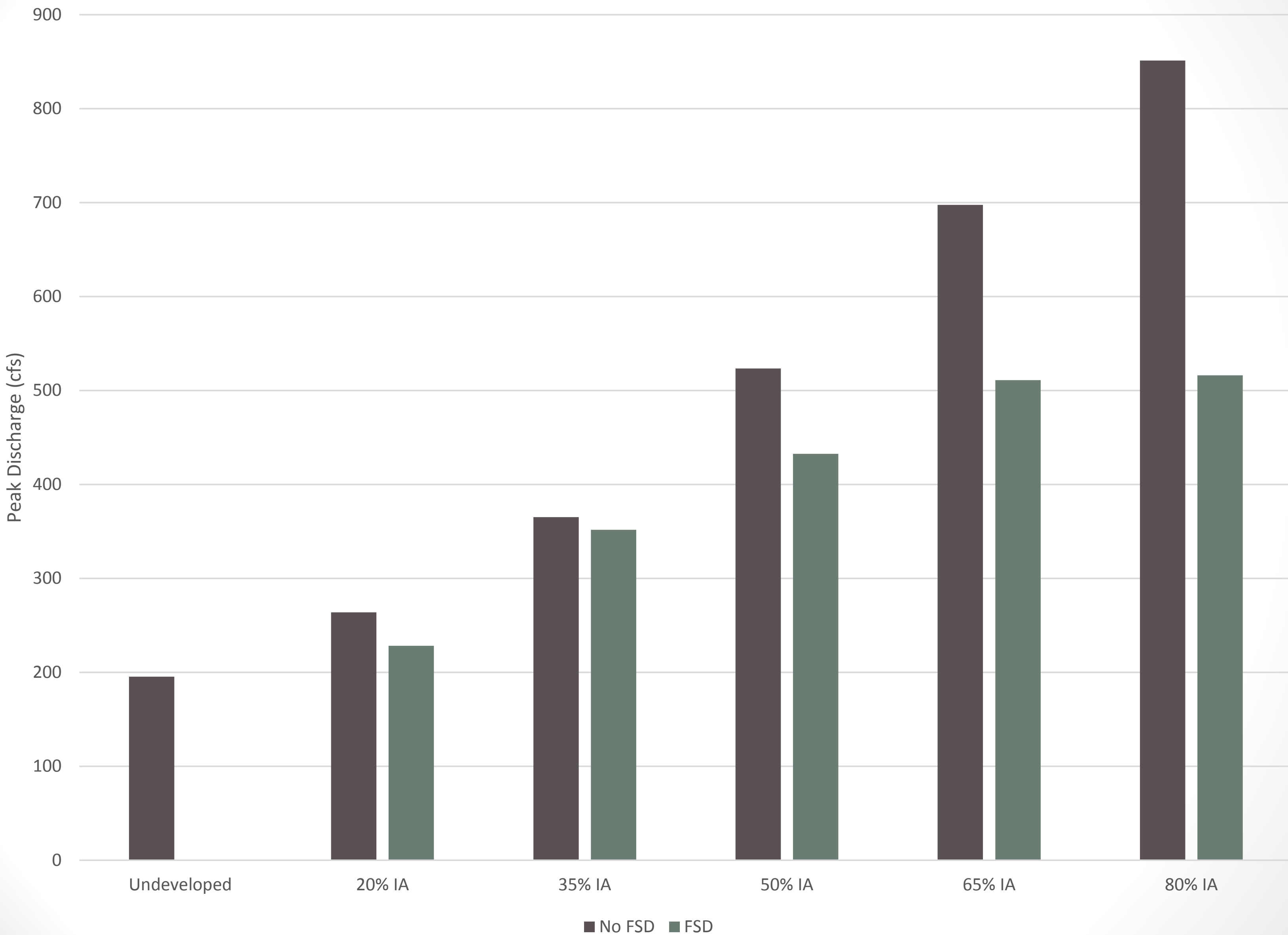
System Outflow											
Variables	**Undev**	**20% IA**	**20% IA + FSD**	**35% IA**	**35% IA + FSD**	**50% IA**	**50% IA + FSD**	**65% IA**	**65% IA + FSD**	**80% IA**	**80% IA + FSD**
Number of Events	163	5545	5871	5652	6372	5738	6852	5838	7361	5927	7812
Mean Daily Outflow (cfs)	12.2	1.3	0.6	2.1	0.9	3.0	1.2	3.9	1.4	4.4	1.7
Peak Daily Outflow (cfs)	196	264	228	365	352	523	433	697	511	851	516
Mean Daily Outflow (ac-ft)	8.9	0.9	0.7	1.5	1.2	2.2	1.7	2.9	2.2	3.5	2.6
Max Daily Outflow (ac-ft)	77	94	72	113	96	129	102	144	125	158	133

Evaporation											
Variables	**Undev**	**20% IA**	**20% IA + FSD**	**35% IA**	**35% IA + FSD**	**50% IA**	**50% IA + FSD**	**65% IA**	**65% IA + FSD**	**80% IA**	**80% IA + FSD**
Number of Events	20689	22032	22833	22443	22443	23529	23529	23707	23707	23707	23707
Daily Mean Evap (in)	0.043	0.036	0.036	0.042	0.042	0.038	0.038	0.038	0.038	0.039	0.039
Peak Daily Evap (in)	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228

Storage											
Variables	**Undev**	**20% IA**	**20% IA + FSD**	**35% IA**	**35% IA + FSD**	**50% IA**	**50% IA + FSD**	**65% IA**	**65% IA + FSD**	**80% IA**	**80% IA + FSD**
Number of Events	0	0	6080	0	6569	0	7044	0	7858	0	7972
Daily Mean Storage (ac-ft)	0	0.0	0.2	0.0	0.6	0.0	1.1	0.0	1.4	0.0	1.9
Daily Peak Storage (ac-ft)	0	0	12	0	23	0	35	0	47	0	59


Number of Days with System Outflow
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Number of Days
Undeveloped
20% IA
35% IA
50% IA
65% IA
80% IA
No FSD
FSD

Peak Outflow Rates with and without FSD

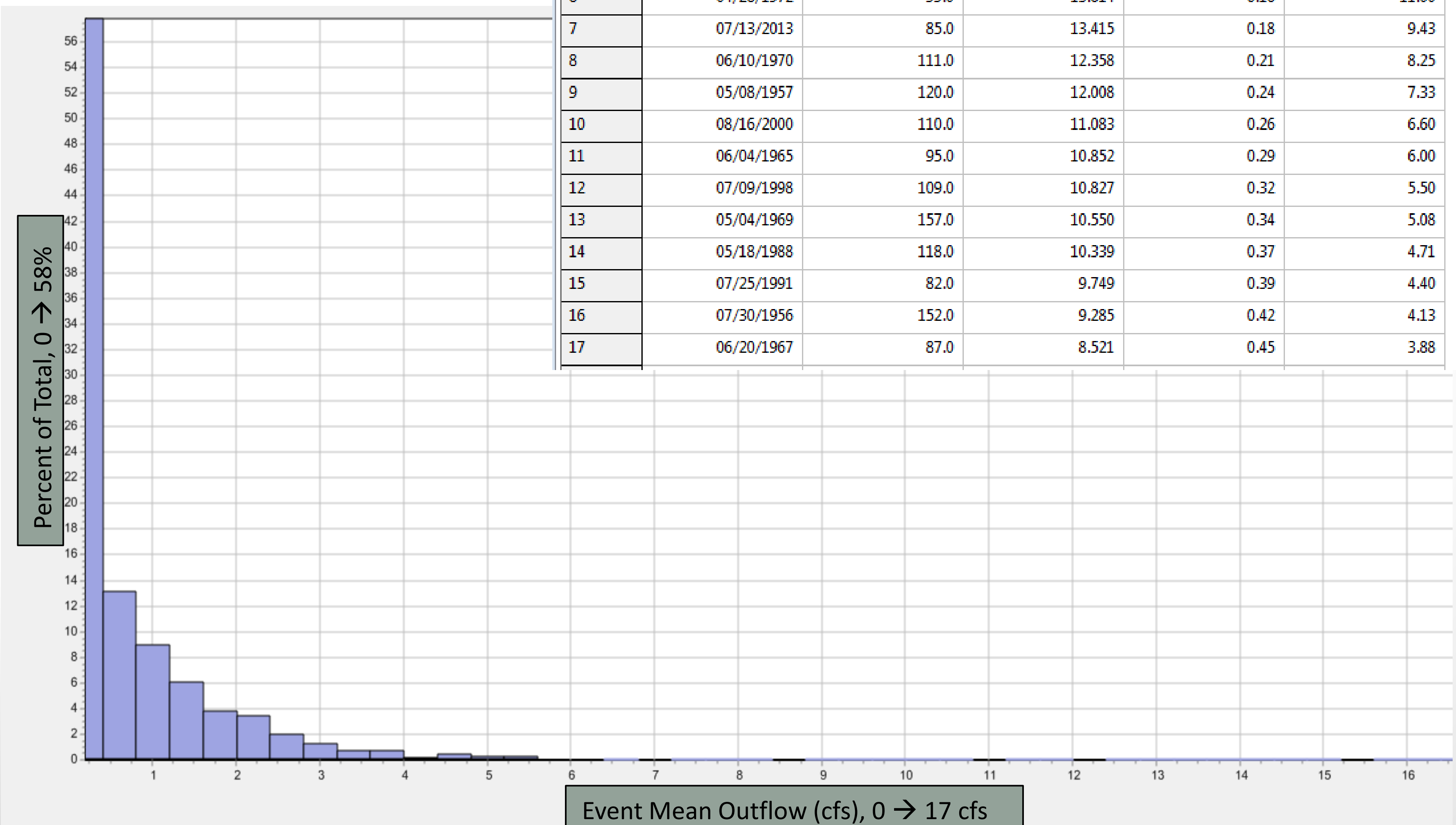


System Outflow Histogram & Data

Σ Statistics - System Outflow

Summary | Events | Histogram | Frequency Plot

Rank	Start Date	Event Duration (hours)	Event Mean (CFS)	Exceedance Frequency (percent)	Return Period (years)
1	08/18/2004	89.0	17.018	0.03	66.00
2	08/02/1951	93.0	16.512	0.05	33.00
3	05/05/1973	105.0	15.584	0.08	22.00
4	09/10/2013	141.0	15.366	0.11	16.50
5	04/13/1967	100.0	14.653	0.13	13.20
6	04/26/1972	99.0	13.614	0.16	11.00
7	07/13/2013	85.0	13.415	0.18	9.43
8	06/10/1970	111.0	12.358	0.21	8.25
9	05/08/1957	120.0	12.008	0.24	7.33
10	08/16/2000	110.0	11.083	0.26	6.60
11	06/04/1965	95.0	10.852	0.29	6.00
12	07/09/1998	109.0	10.827	0.32	5.50
13	05/04/1969	157.0	10.550	0.34	5.08
14	05/18/1988	118.0	10.339	0.37	4.71
15	07/25/1991	82.0	9.749	0.39	4.40
16	07/30/1956	152.0	9.285	0.42	4.13
17	06/20/1967	87.0	8.521	0.45	3.88



WATER RIGHTS ANALYSIS

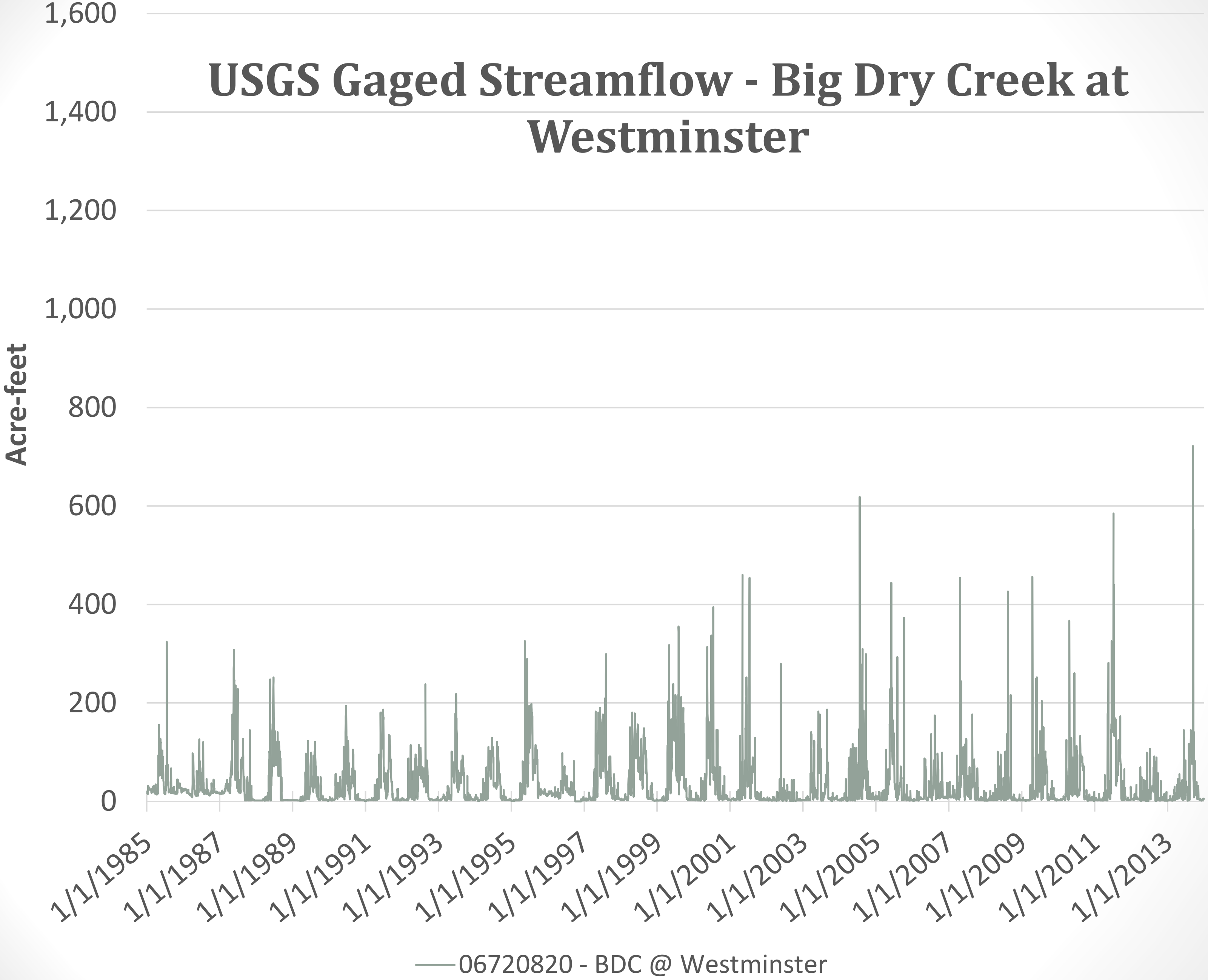
Objectives

- Colorado Water Landscape
- Big Dry Creek
- Historical River Calls
- Water Rights Holders
- Full Spectrum Detention Benefits

Big Dry Creek - Where is the Water?

- Colorado's Decision Support System
- Colorado's Division of Water Resources
- Municipal Imports
- Limitations
- Deliveries

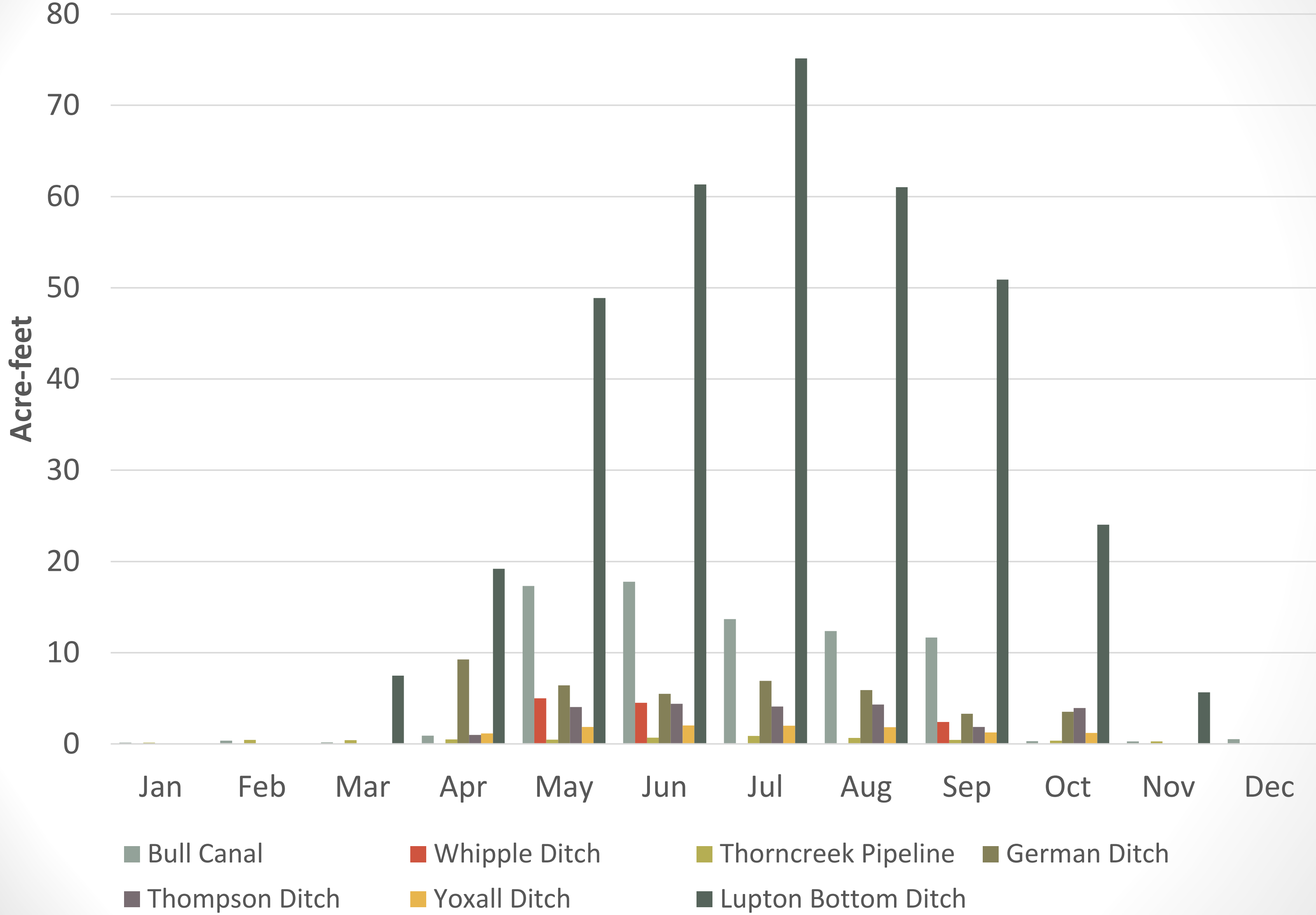
USGS Gaged Streamflow - Big Dry Creek at Westminster



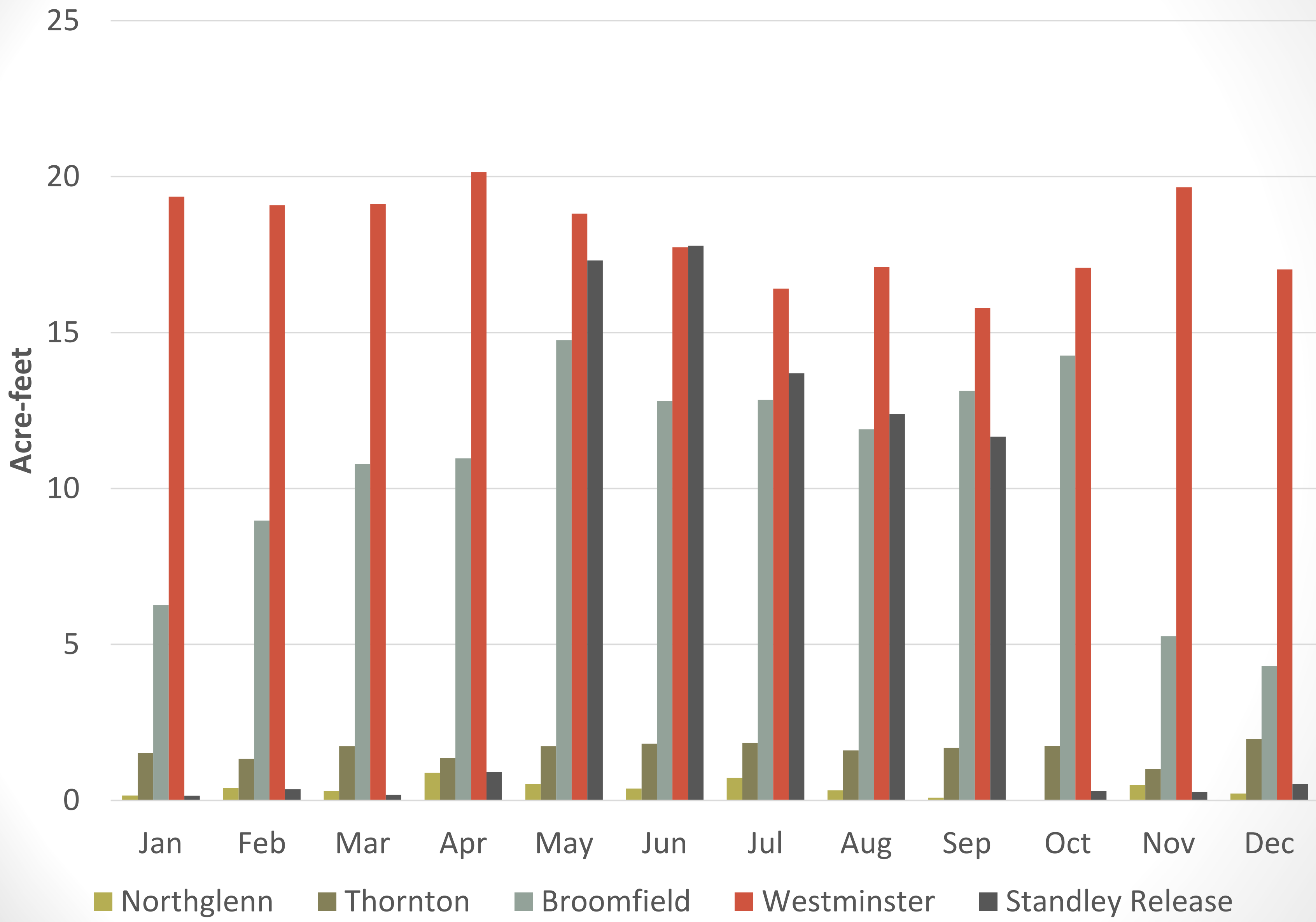
Water Rights on Big Dry Creek

						Decreed Amount (cfs)		
Structure ID	Water Right Name	Appropriation Date	Administration No.	Case No	Decreed Use	Absolute	Conditional	Alternate Point
872	German Ditch	1885-11-30	13118.00000	CA8568	Irrigation	0.99		
871	Bull Canal (Whipple Ditch)	1885-12-31	13149.00000	CA8568	Irrigation	0.99		
871	Bull Canal (Whipple Ditch)	1884-09-01	15895.12663	CA54658	Irrigation	5		
872	German Ditch	1885-11-25	15895.13113	01CW0273	Irrigation	40		
873	Big Dry Creek Ditch	1889-12-15	15895.14594	CA54658	Irrigation	36.66		
874	Yoxall Ditch	1896-07-27	17010.00000	CA40750	Irrigation	16.8		
880	Thornton Golf Course Pipeline	1987-12-10	50382.00000	96CW0244	Irrigation, Recreation, Other Beneficial Uses	5		140
880	Thornton Golf Course Pipeline	1996-12-31	53691.00000	96CW1116	Municipal			130
871	Bull Canal (Whipple Ditch)	2004-11-15	56567.00000	04CW0310	Municipal		31	
871	Bull Canal (Whipple Ditch)	2004-12-20	56602.00000	04CW0310	Municipal			21

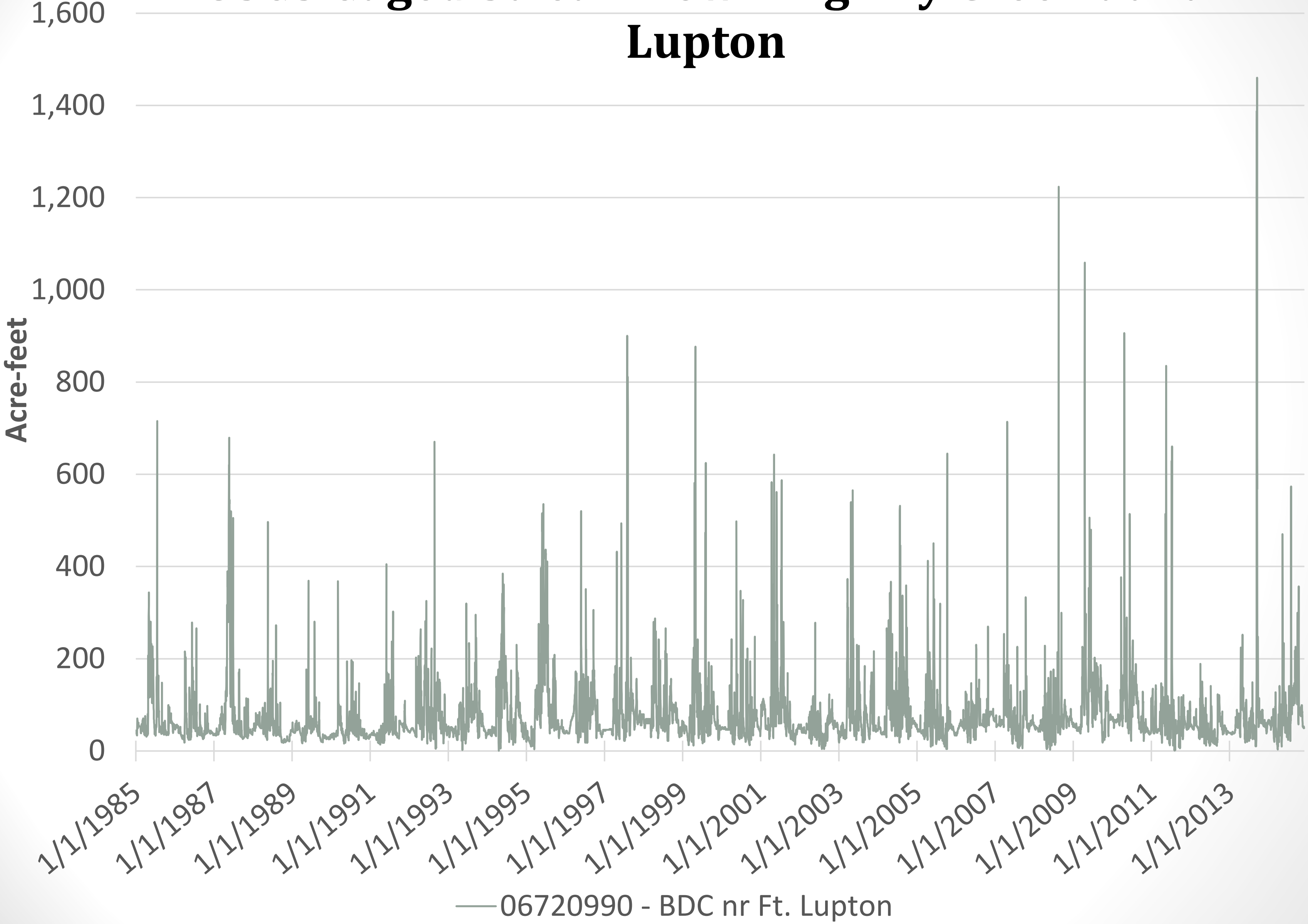
Average Monthly Big Dry Creek Diversions



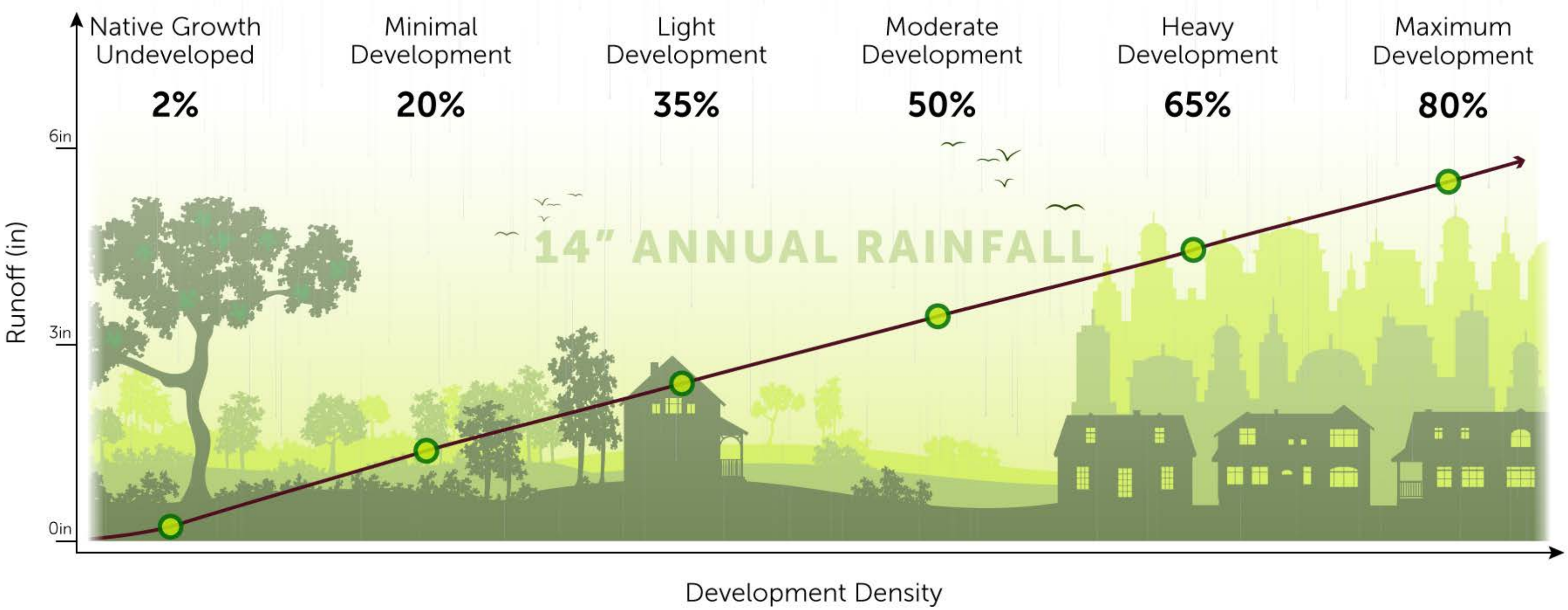
Average Monthly Inflows on Big Dry Creek

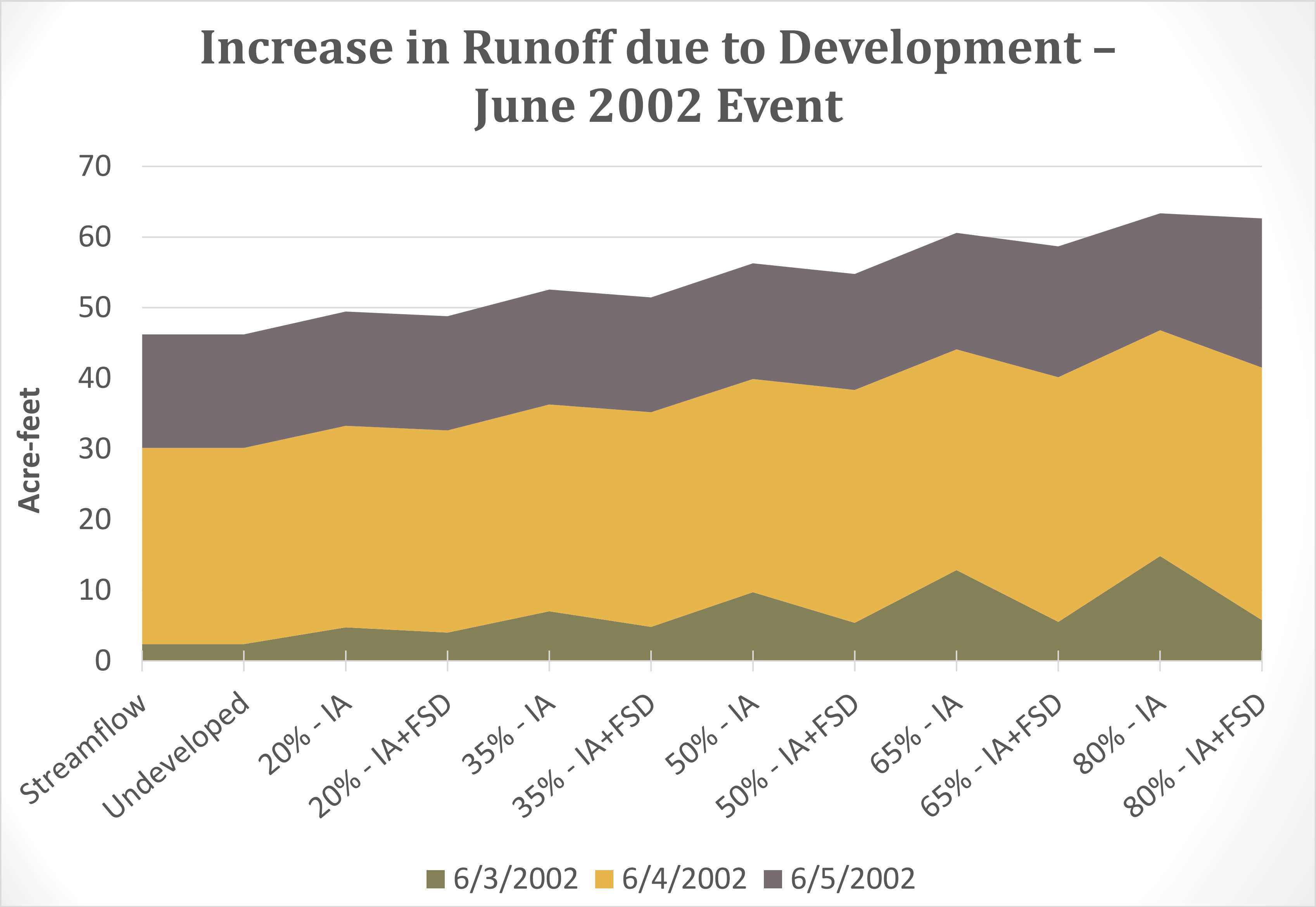


USGS Gaged Streamflow - Big Dry Creek at Ft. Lupton



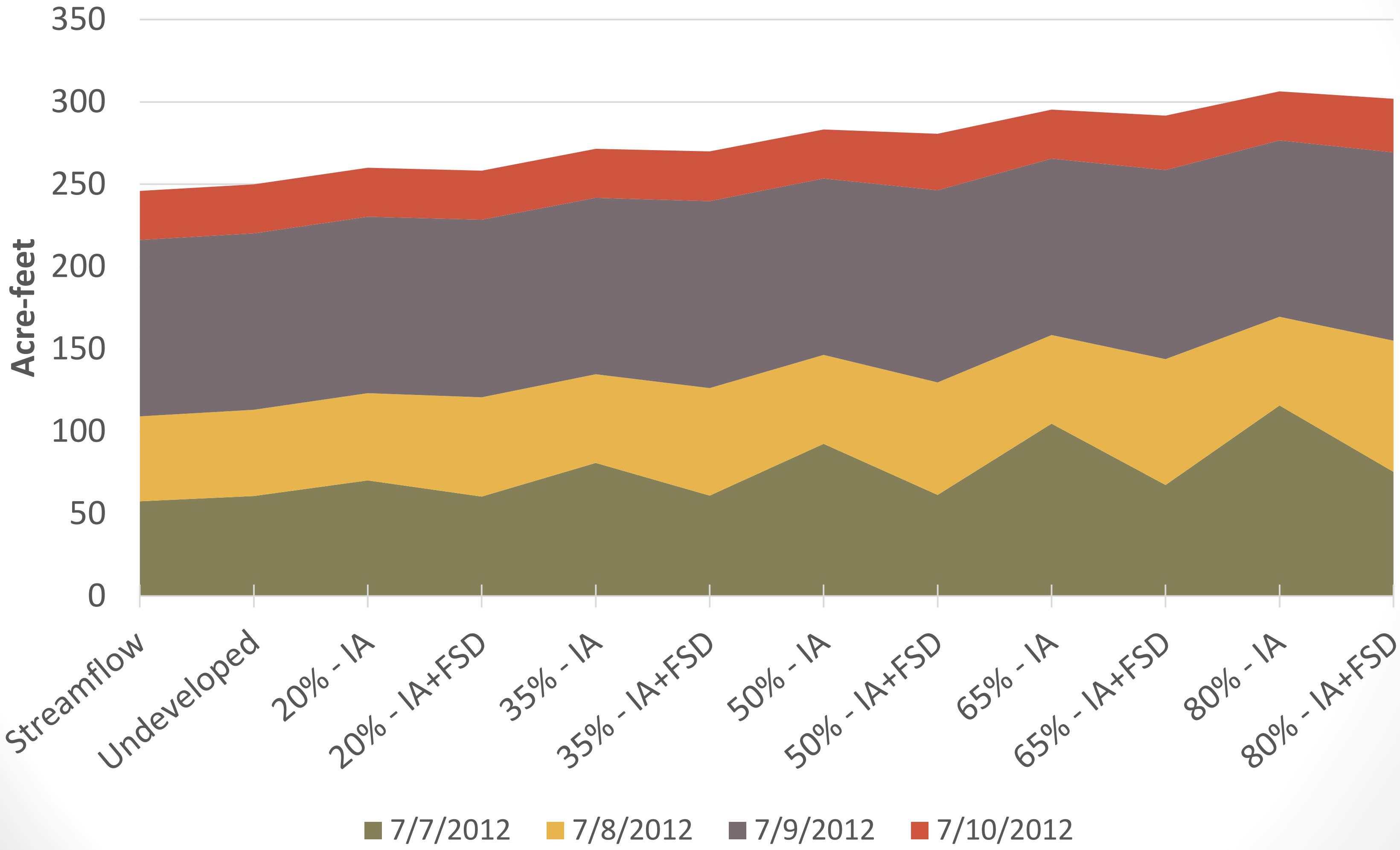
Runoff due to Various Densities of Development



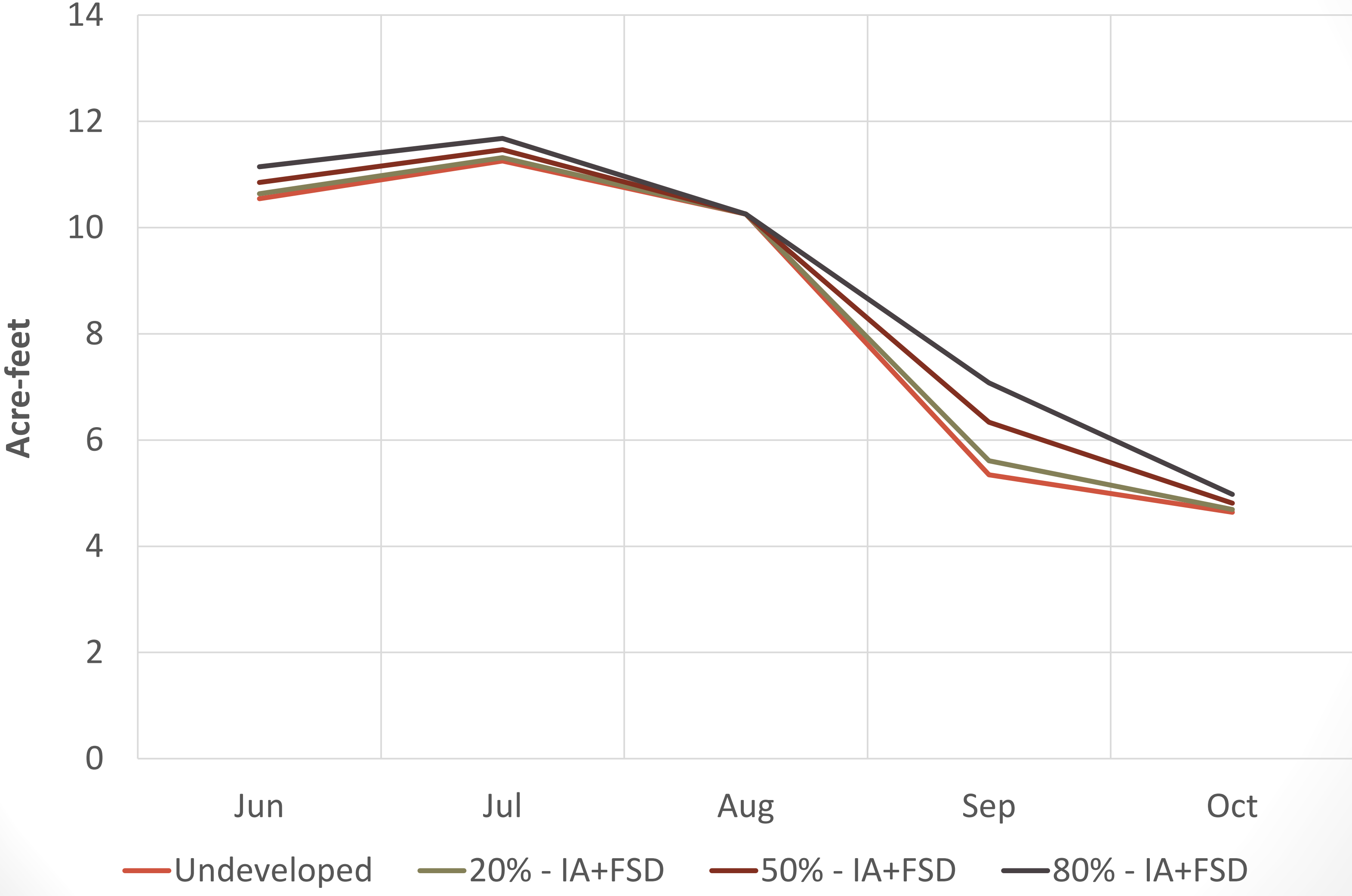


Increase in Runoff due to Development – June 2002 Event
Acre-feet
70
60
50
40
30
20
10
0
Streamflow
Undeveloped
20% - IA
20% - IA+FSD
35% - IA
35% - IA+FSD
50% - IA
50% - IA+FSD
65% - IA
65% - IA+FSD
80% - IA
80% - IA+FSD
6/3/2002
6/4/2002
6/5/2002

Increase in Runoff due to Development – July 2012 Event

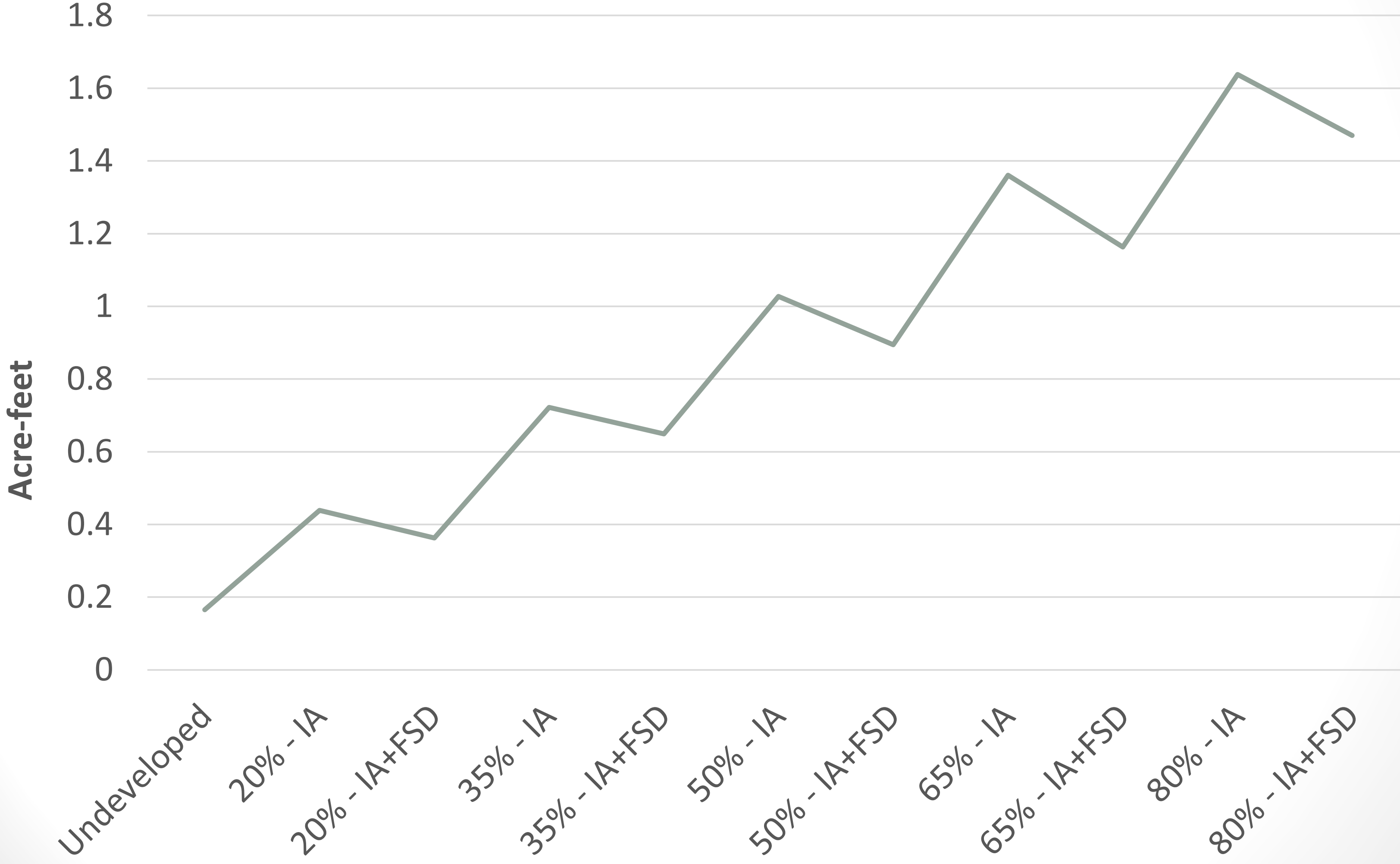


Increase in 2002 Irrigation Season Streamflow as a Result of Development



Average Daily Increase in Runoff during South Platte River Call

Meadow Island Ditch



CONCLUSIONS

Conclusions

- Development increases impervious area which decreases evaporation/ET and increases runoff
- Surface water yield from undeveloped to developed conditions changes dramatically, more so at higher impervious levels
- Evaporation/ET in model is not sensitive to effects of FSD
  - Depression storage following rainfall
  - Soil moisture availability for ET (upper aquifer zone)
- FSD attenuates peak discharges and extends release hydrographs

Conclusions

- SWMM Model trends follow expected patterns with increasing imperviousness
- FSD primarily affects the timing of runoff (relative to same scenario) without FSD, quantity effects are minor
- Increased flow along the Front Range is coveted and will help water rights holders reduce the supply/demand gap
- Following rainfall events in dry years, water rights holders will benefit from increased flow in subsequent days as a result of FSD

Questions & Comments?

DENVER
2490 W. 26th Avenue Suite 100A
Denver, Colorado 80211
Phone: 303.480.1700
Fax: 303.480.1020

GLENWOOD SPRINGS
818 Colorado Avenue
P.O.Box 219
Glenwood Springs, Colorado 81602
Phone: 970.945.7755
Fax: 970.945.9210

DURANGO
1666 N. Main Avenue Suite C
Durango, Colorado 81301
Phone: 970.259.7411
Fax: 970.259.8758

www.wrightwater.com

WWE

Wright Water Engineers, Inc.