# Case Study of the Hydrologic Benefits of On-Site Retention in the Central Coast Region

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**Background:**

The Central Coast Water Board is proposing post-construction stormwater requirements for new and redevelopment projects in the Central Coast Region. The proposed performance requirements on all sites creating or replacing $\geq$22,500 ft$^2$ are as follows:

1. Retain runoff from all storms up to the 95th Percentile Event - Prevent offsite discharge for all days on which accumulated rainfall does not exceed the 95$^{th}$ percentile 24-hr, precipitation total. This volume must be infiltrated, evaporated/transpired, and/or harvested for later use, and
2. Post-development peak flows shall not exceed pre-project peak flows for the 2- through 100-yr storm events.
3. Continuous simulation modeling is required to evaluate the runoff characteristics and evaluate compliance with the performance requirements.

The first requirement is identical to “Option 1” of the EISA Section 438 (2009) requirements for federal facilities. The second requirement is the current Santa Barbara County peak matching requirement. The Water Board recognizes that peak matching does not address flow duration effectively; specifically, requiring facilities to maintain peaks at pre-project levels does not prevent longer duration flows, below the peaks, that result from additional runoff volumes generated by the project. However, the Water Board is interested in knowing whether the peak matching requirement used in combination with the retention requirement affords protection to receiving waters that is comparable to the protections afforded by a flow duration management requirement. In pursuing this question, the first step is to examine the effects of the proposed requirements (i.e. the combination of retention and peak management) on runoff characteristics

Evaluation of runoff characteristics requires an estimation of the amount of retention (item 1, above) that can be achieved on-site under different development scenarios. The retention estimate will then influence the total amount of runoff that will need to be addressed by a detention facility and finally, the discharge characteristics leaving the project site (e.g., flow volumes and duration). While the impacts of altered flow regimes are ultimately of interest to the Water Board, this analysis is intended to isolate and answer the question of how and to what degree the flow regime is affected, rather than what effect those alterations may have on stream conditions.

## Scenarios Modeled

Two development project scenarios were analyzed, each involving the same total project area, one representing single family residential development which was assumed to involve a land use conversion from a pre-developed pasture condition, and the other a commercial redevelopment project. Each project type was assumed to occur on two different soils, NRCS type C soil and NRCS type D soil. Infiltration rates for on-site retention facilities were based on the daily average rates reported in the EISA Section 438 Stormwater guidance document (December, 2009).

## Hydrologic Modeling

HSPF continuous hydrologic modeling was used to generate three components of discharge for each scenario (and each sub-scenario) at project area outlets. The three components modeled were surface runoff (rapidly responding runoff with high peak unit area discharge from impervious and saturated pervious areas), interflow (slower responding subsurface runoff with moderate peak unit area discharge from pervious areas that emerges to the surface at slope breaks and road cuts), and groundwater runoff (long-lasting, very low peak unit area discharge to the drainage system which provides base flow). Urban pervious infiltration rates for a D-soil were characterized in HSPF using an HSPF INFILT parameter value typical of disturbed, low-infiltration soil (0.030 iph). Pre-developed pasture conditions were assumed to have an INFILT value midway between an urban disturbed landscape and undisturbed landscape (0.055 iph). Corresponding INFILT values for C-soils (.19 and .33 iph) were estimated from the ratio of 2-hr average infiltration rates for C and D soils specified by EISA Section 438. Detention facilities were modeled as impermeable storages with assumed flexible outlet controls. The total size and volume-discharge relationship (outlet control) for detention facilities were optimized by trial and error based on matching mitigated developed to pre-developed (100% pasture) peak annual flow frequency curves between the 2-yr and 100-hr quantiles.

## Assumed Routing of Runoff

For the mitigated scenarios, inflows to on-site retention facilities were assumed to include all impervious area runoff and any surface runoff from the residual pervious site area not devoted to retention facilities. Groundwater runoff from residual pervious areas was assumed to leave the site and enter the downstream drainage system. Onsite retention facilities were assumed to infiltrate at the 24-hr average rate specified by EISA 438 for each soil type. Runoff infiltrated in the bioretention facility was route through a groundwater storage reservoir with sufficient storage capacity to assure low, steady release to the stream, typical of a base flow. Overflows from the bioretention facility were routed to a detention facility which was assumed to be off-site (i.e. it did not take up any site area). Interflow from the site pervious area not devoted to bioretention was also routed to the detention facility. Outflow from the detention facility was combined with the groundwater outflow to estimate the total discharge to the drainage system from the site. Figure 1 provides a schematic view of how flow component pathways are conceptualized in the HSPF model for pre-developed, unmitigated developed, and mitigated developed cases.

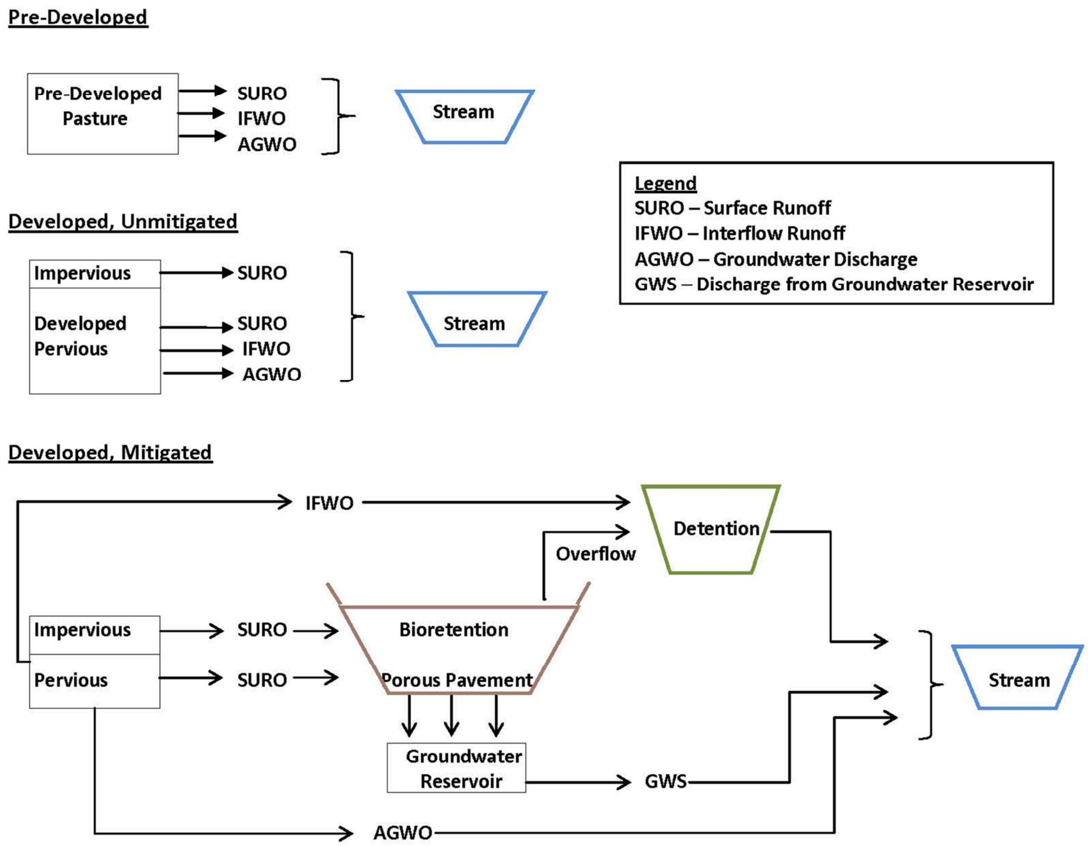



Figure 1. Schematic showing how runoff component pathways are conceptualized in HSPF modeling.

## Hydrometeorological Data Inputs

Continuous hydrologic modeling of all scenarios required long term rainfall and potential evapotranspiration data sets. Chad Helmle (Personal Communication, May 23, 2012) provided a synthesized hourly rainfall record for Santa Cruz derived primarily by spatial correlation of available daily rainfall totals at Santa Cruz (NCDC site 047916) with hourly records at nearby sites (Tetra-Tech, 2011). Daily potential evapotranspiration for the 1950-2010 simulation period was estimated using monthly average values of reference evapotranspiration reported by CMIS for Region 3 (CMIS, 2010).

## Design Rainfall Amount

The design rainfall amount was based on the 61-water year record for Santa Cruz. It was determined following procedures outlined in EISA 438 as follows. All 24-hr rainfall depths greater than 0.1 inches were ranked in descending order. The depth corresponding to the breakpoint between the lower 95% and upper 5% of was identified as the design depth for retention facilities equal to 1.96 inches for the Santa Cruz record.

**Sizing of Bioretention and Detention Facilities**

Bioretention facilities were conceptualized as storage "boxes" with surface areas and volumes consistent with a standard that requires retention of runoff from the 95% non-exceedance, 24 hour rainfall event on-site. For the SFR scenario, sizing retention to the standard was based on estimated surface runoff for the entire developed site impervious and pervious areas. For the commercial redevelopment scenario, sizing to the standard was based on runoff from 50% of the total site impervious.

The procedure to determine the area and storage volume necessary to meet the stated retention standard applied a conservative approach that assured retention and infiltration of runoff from the design event regardless of the time distribution of rainfall within the 24-hr period. The approach was based on the following key concepts:

- The facility is assumed to infiltrate at the average 24-hr rate for the soil class specified by EISA 438
- The facility must have storage capacity equal to the runoff volume from the site plus the volume of rain on the facility surface
- If the facility's drainage time of the runoff volume from the 24 hour design storm exceeds 24 hours and the storage area is fixed, then facility volume must be increased commensurate with the runoff volume and rainfall from the 95% non-exceedance storm with a longer duration equal to the drainage time for 24-hour runoff volume.

The steps followed in sizing bioretention for the residential case were:

1. Estimate surface runoff volume (ac-in) to the bioretention facility based on the 95% non-exceedance, 24-hr rainfall amount per EISA 438 direct method (i.e. daily rainfall – interception/depression storage-infiltration depth).
2. Determine the potential 24-hr infiltrated volume per acre for C or D soil based on EISA 438 average daily infiltration depth. (ac-in/ac)
3. Divide result 1 by result 2 to arrive at initial facility area in acres.
4. If the result of 3 is less than 50% of pervious area on-site, then it represents the bioretention area to be modeled with an assumed storage depth (before any surface spill occurs) equal to result 1 divided by result 3. Both area and storage volume to meet criterion are assumed to be met. If this is not the case, then go on to steps 5 - 10
5. If result 3 is greater than 50% of the site pervious area, assume the site is "area-constrained" and set the bioretention area to an area equal to 50% of the site pervious area.
6. Compute the drainage volume in 24 hrs (ac-in) by multiplying the result of 5 by the average daily infiltration rate.
7. Determine the hours to drain the 95% 24-hr runoff volume by dividing 1 by 6 and multiplying by 24. The result will be greater than 24 hours by definition.

8. Perform frequency analysis on hourly rainfall to determine the 95% non-exceedance rainfall amount for the storm duration determined in step 7.
9. Use the result of in lieu of the 24-hr, 95 percent non-exceedance rainfall to estimate runoff volume (ac-in). This is the estimated storage required in the bioretention facility to assure no overflow of the 95%, 24-hr storm runoff from the site.
10. Divide result of step 9 (ac-in) by result of step 5 (ac) to arrive at required storage depth for an area-constrained bio-retention facility.

For the commercial case, the porous pavement and bioretention areas are specified in advance therefore, the steps are as follows:

1. Estimate surface runoff volume (ac-in) to the bioretention facility based on the 95% non-exceedance, 24-hr rainfall amount per EISA 438 direct method and the assumption that 50% of the impervious area must be mitigated. In this calculation, it is assumed that the porous pavement area first removes a portion of that runoff volume consistent with its area and the average daily infiltration rate. It has no storage capacity.
2. Compute the potential bioretention drainage volume in 24 hrs (ac-in) by multiplying the pre-specified area by the average daily infiltration rate.
3. Follow steps 6-10 as described for the residential case to determine the bioretention storage volume and depth.

An example of the bioretention design calculation is provided below for the Single Family Residential, D-Soil case [3.04 ac site, 45% impervious (1.33 ac), 55% pervious (1.71 ac) with assumed maximum limit to bioretention area of 50% of site pervious = 0.86 acres.]

1. Estimate runoff volume to facility (initial abstractions and average daily infiltration rates from EISA 438)
    a. Volume = impervious runoff + pervious runoff
        i. Impervious runoff =(rainfall – initial abstraction)* impervious area
           Impervious runoff = (1.96 in - .10 in) * 1.33 ac = 2.47 ac-in
        ii. Pervious runoff = (rainfall – initial abstraction – infiltration)*pervious area
           Pervious runoff = (1.96 in - .20 in - .77 in) * 1.71 ac = 1.69 ac-in
        iii. Total runoff volume = 2.47 + 1.69 = 4.16 ac-in

2. Determine 24-hr infiltrated volume per acre of bioretention
   24-hr average infiltration depth = 0.77 in (EISA 438, p. 60) = 0.77 ac-in/ac

3. Estimate Initial Facility Size Runoff Volume/(Infiltrated volume/ac)
   4.16/0.77 = 5.4 acres
4. 5.4 ac is much greater than assumed upper limit of bioretention area = 1.71/2 = 0.86 ac
5. Therefore the site is area-constrained and bioretention area = 0.86 acres
6. 24 hour drainage volume for 0.86 ac bioretention = 0.86 ac * 0.77 ac-in/ac = 0.66 ac-in
7. Estimate hours to drain runoff volume = 24*4.16/0.66 = 152 hours
8. Perform frequency analysis to determine 95% non-exceedance rainfall amount for a duration of 152 hours (per EISA 438 procedure except using 152 hour totals instead of 24 hour totals. This amount is approximately 3.0 inches.
9. Compute runoff volume except for 3.0 inches over 152 hours instead of 24 hours
   Volume = impervious runoff + pervious runoff

i. Impervious runoff =(rainfall – initial abstraction)* impervious area
    Impervious runoff = (3.0 in - .10 in) * 1.33 ac = 3.86 ac-in
ii. Pervious runoff = (rainfall – initial abstraction – infiltration)*pervious area
    Pervious runoff = (3.0 in - .20 in - .77*152/24 in) * 1.71 ac <0, however, assume storage required for rain on pool = 3 in *.86 ac = 2.58 ac-in
iii. Storage required in facility = 3.86 ac-in + 2.58 ac-in = 6.44 ac-in or 0.54 ac-ft

10. Required storage depth with 100% void space = 0.54 ac-ft/0.86 ac = 0.62 ft = 7.5 inches

Detention facilities for both SFR and Commercial scenarios were sized to fully mitigate peak flows ranging from the 2-yr to 100-yr for 100% of the developed sites by matching the frequency curve in this range determined for a 100% pasture condition on the site.

**Simulation Cases for Each Land Use Scenario**

The simulation cases for each land use scenario (Single Family Residential (SFR) Development and Commercial Redevelopment (COMM) are summarized in Tables 1 and 2 respectively. Note that for the residential scenario, there are a total of six cases, three for each soil class: 1) developed with no retention or detention, 2) developed with retention and detention and 3) pre-developed 100% pasture. For each case the volume and area required for retention facilities and the detention volume necessary to meet the 2-100 peak control standard are reported.

For the commercial scenario, 8 cases are shown in Table 2; however, the 2 pre-developed cases (C and D soil with 100% pasture) are identical to cases in the SFR scenario. Therefore, there are really only 6 unique cases; 3 for each soil class. These cases include “no mitigation”, “detention mitigation only” and “combined detention and retention”. The two mitigation scenarios show the marginal amount of detention volume required to meet the standard if retention is not implemented.

***Table 1. Single Family Residential Development from Pasture, Land Cover and Mitigation Summary (C-Soil and D-Soil)***

Total site area for all cases = 3.04 acres

| *CASES* | *PASTURE (AC)* | *IMPERVIOUS (AC)* | *GRASS (AC)* | *ON-SITE BIORETENTION (AC)* | *ON-SITE BIORETENTION STORAGE VOLUME[1] (AC-FT)* | *DETENTION VOLUME[2] (AC-FT)* |
|---|---|---|---|---|---|---|
| *No Mitigation **C&D- Soil*** | - | 45% | 55% | - | - | - |
| *On-Site Retention and Detention **C-Soil*** | - | 45% | 31% | 24% | *0.21* | *0.85* |
| *On-Site Retention and Detention **D-Soil*** | | 45% | 27.5% | 27.5% | *0.54* | *0.38* |
| *Pasture Reference **C&D-Soil*** | *100%* | - | - | - | - | - |

| **Table 2. Commercial Redevelopment, C-Soil and D-Soil Scenarios** (total site area = 3.04 acres for all cases) | | | | | | | |
|---|---|---|---|---|---|---|---|
| CASES | PASTURE (AC) | IMPERVIOUS (AC) | GRASS (AC) | POROUS PAVEMENT[3] (AC) | ON-SITE BIORETENTION[4] (AC) | BIORETENTION STORAGE VOLUME[1] (AC-FT) | DETENTION VOLUME[2] (AC-FT) |
| No Mitigation ***C&D- Soil*** | - | 87% | 13% | - | - | - | - |
| Detention Only, **C-Soil** | - | 87% | 13% | - | - | - | 1.60 |
| Detention Only, **D-Soil** | - | 87% | 13% | - | - | - | 0.62 |
| On-Site Retention and Detention, **C-Soil** | - | 78% | - | 9% | 13% | 0.19 | 1.25 |
| On-Site Retention And Detention, **D-Soil** | - | 78% | - | 9% | 13% | 0.91 | 0.42 |
| Pasture Reference ***C&D-Soil*** | 100% | - | - | - | - | | |

**[1]SIZED TO MITIGATE RUNOFF FOR 95%-NON EXCEEDANCE 24-HR EVENT FOR 50% OF REDEVELOPED IMPERVIOUS (SCENARIO ASSUMES FULL REDEVELOPMENT)**

**[2]SIZED TO MATCH 2-YR TO 100-YR PEAK ANNUAL FLOW QUANTILES FOR PASTURE REFERENCE CONDITION**

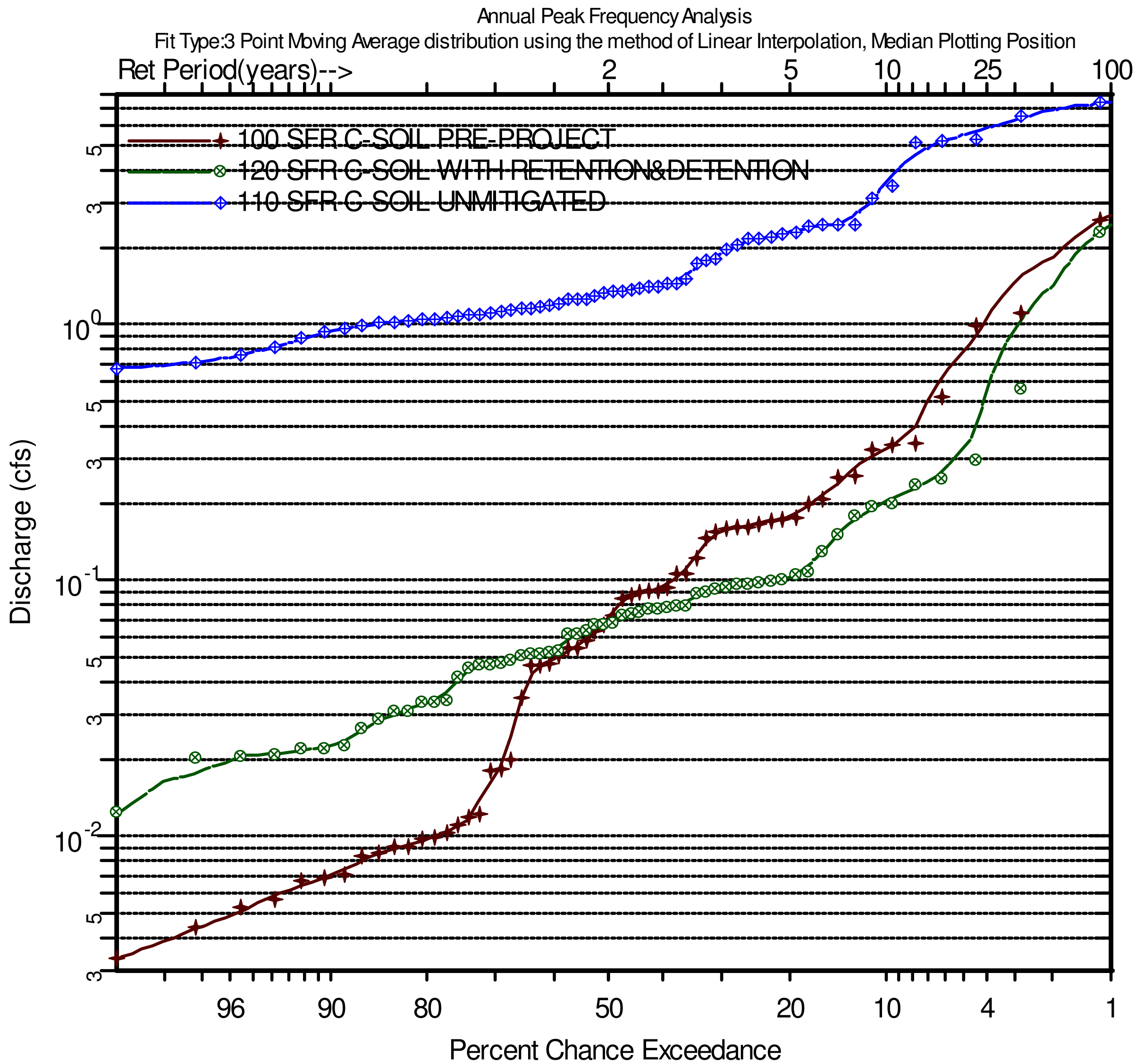
**[3]AREA FIXED AT 10% OF TOTAL SITE IMPERVIOUS**

**[4]AREA FIXED AT 13% OF TOTAL SITE AREA**

**Results for Single Family Residential Scenario for C and D Soils**

Single Family Residential Development, C-Soil

Flood Frequency Comparison

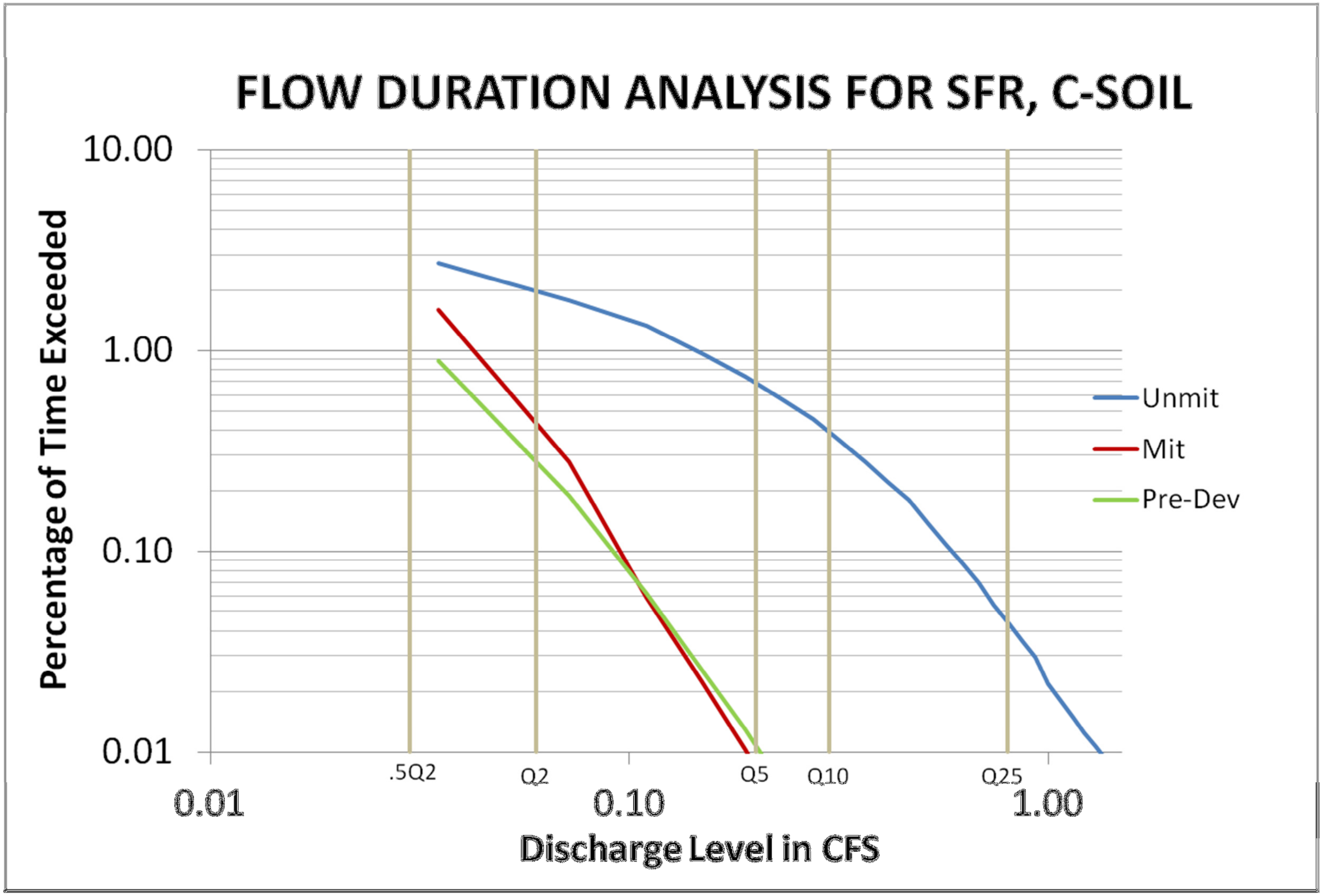



| Table 3. Peak Annual Flood Frequency Curve Data for C-Soil, SFR | | | | | | |
|---|---|---|---|---|---|---|
| Average Recurrence Interval (years) | 2 | 5 | 10 | 25 | 50 | 100 |
| | Quantiles (cfs) | | | | | |
| | | | | | | |
| Pre-Dev, C-Soil | 0.07 | 0.18 | 0.33 | 1.14 | 1.85 | 2.70 |
| SFR- no R/D- C-Soil | 1.33 | 2.31 | 3.74 | 5.96 | 6.94 | 7.45 |
| SFR w R/D, C-Soil[1] | 0.07 | 0.10 | 0.21 | 0.63 | 1.45 | 2.48 |

**Peak Annual Flow Frequency Discussion, Single Family Residential Development, C-Soil**

A total of 1.06 ac-ft of combined bioretention and detention storage is required to meet the 2-100-yr standard for residential development. Note that the detention seems to over-mitigate for some intermediate quantiles; however, in the case of the C-soil, it is difficult to match both the 2-yr and 100-yr peaks without over mitigating for intermediate peak quantiles.

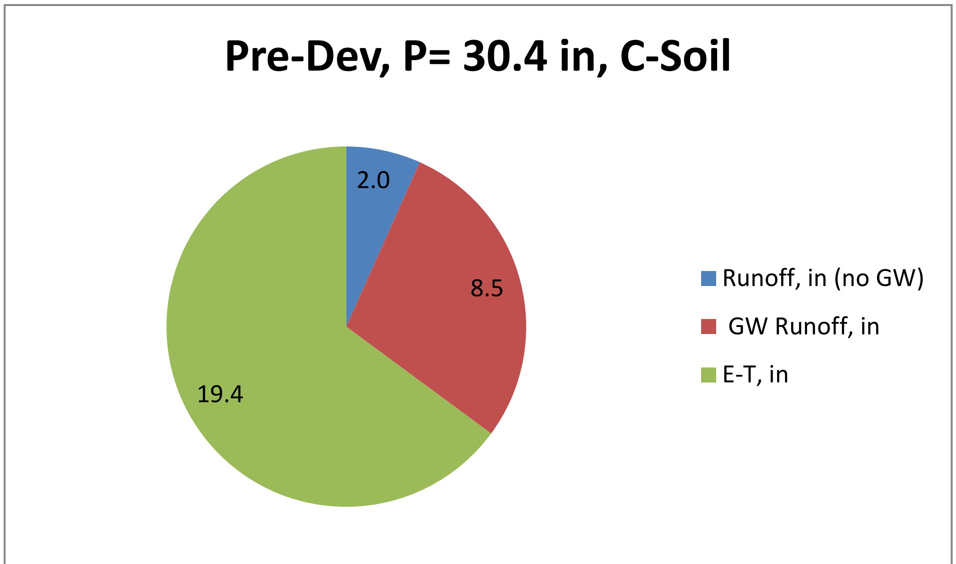
Durational Analysis

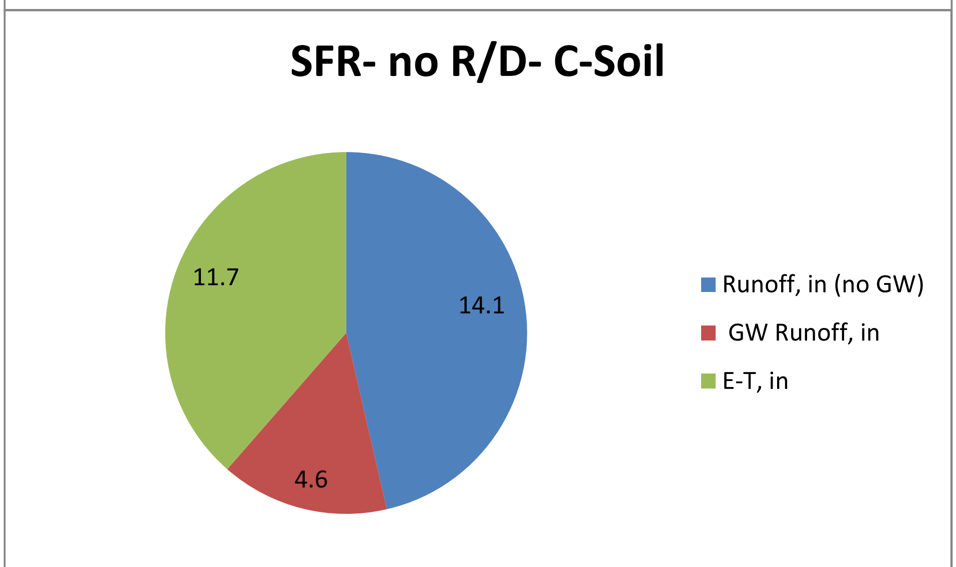


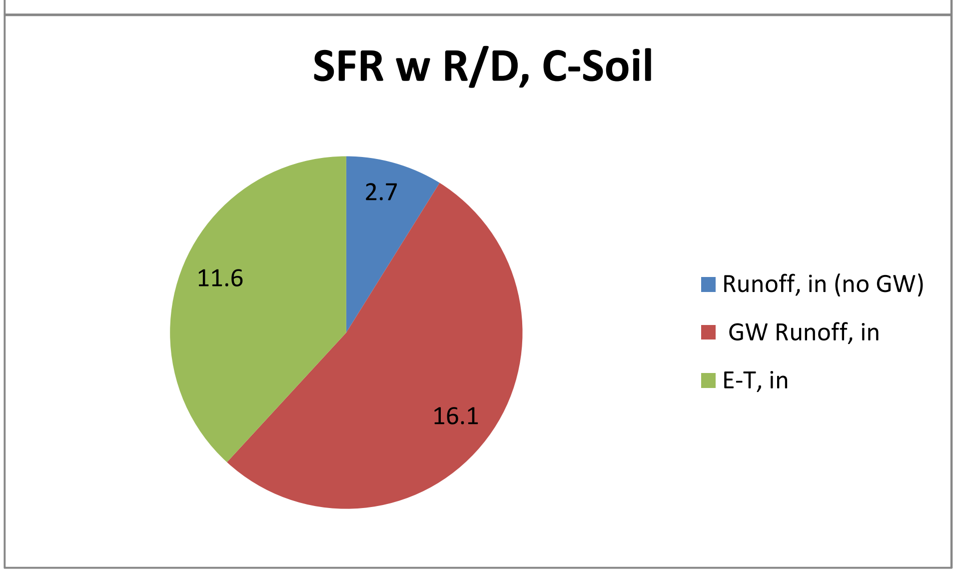
**Flow Duration Discussion, Single Family Residential Development, C-Soil**

Duration analysis was performed for total runoff (surface and interflow) leaving the site. For cases with detention facilities, the analysis was performed on discharges from these facilities. For flow thresholds between 50% of the pasture 2-yr and the pasture 10-yr peak, the combined facilities mitigate approximately 92% of the increase in high flow durations for the single family residential development on the C-soil.

Water Balance Results- SFR, C-Soil



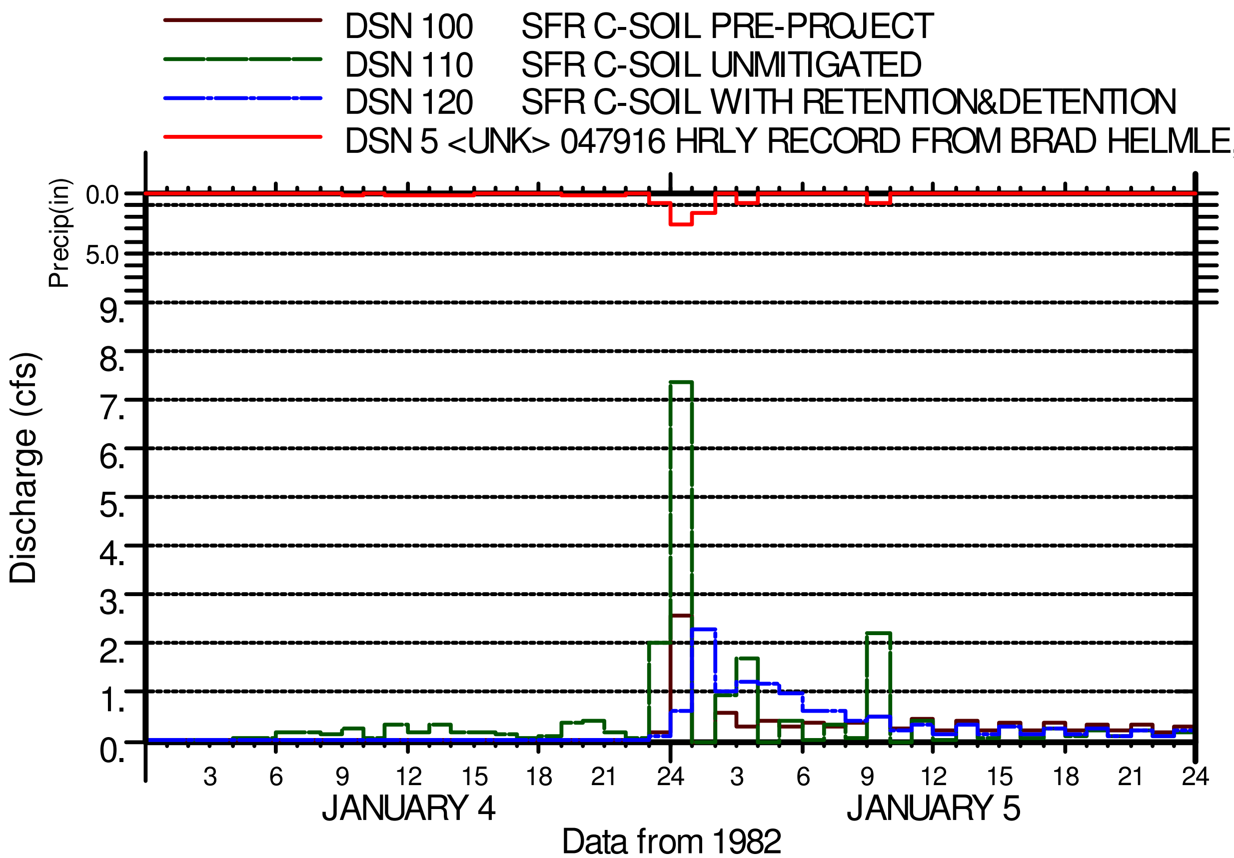



**Water Balance Discussion, Single Family Residential Development, C-Soil**

A bioretention area (.73 ac) taking up 44% of the pervious portion and 24% of the total site area with a storage depth of 3.5 inches infiltrates (and therefore provides some water quality treatment) 81% of the runoff from impervious and landscaped areas. This percentage is calculated from the difference of the unmitigated and retained runoff amounts (14.1 – 2.7 = 11.5 inches) and dividing by the unmitigated runoff amount (14.1). The average runoff volume (surface runoff and interflow) with retention is moderately higher (35%) than for the pre-developed, pasture runoff volume, but E-T is 40% less than the pre-developed case. Groundwater loading is increased by a factor of 3.4 due to storage and subsequent infiltration in the bioretention facility. The detention facility is assumed to be impermeable, located off-site and not part of the site water balance.

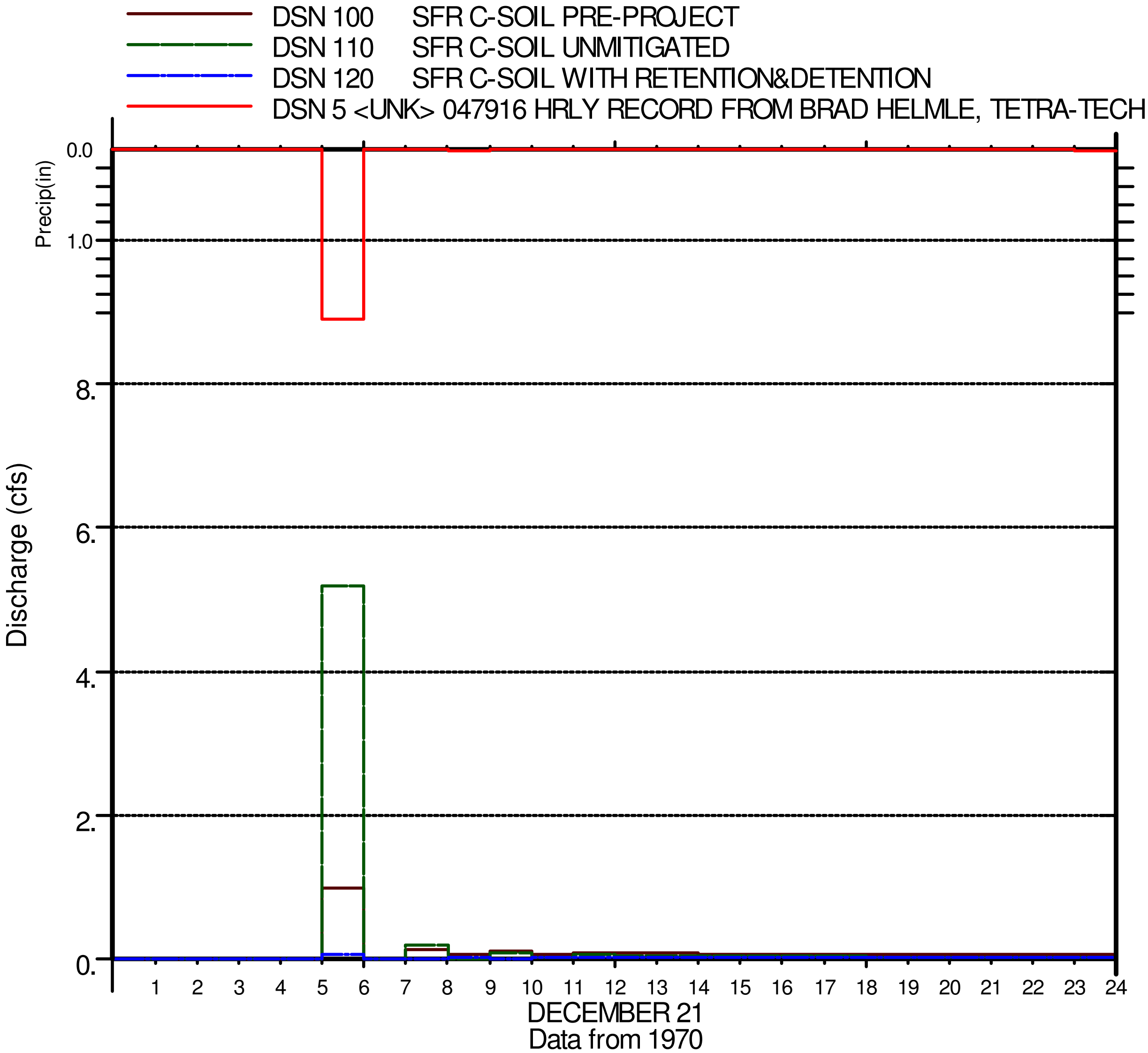
**Sample Hydrographs, Single Family Residential Development, C-Soil**

Storm of record (60 years), January 5, 1982

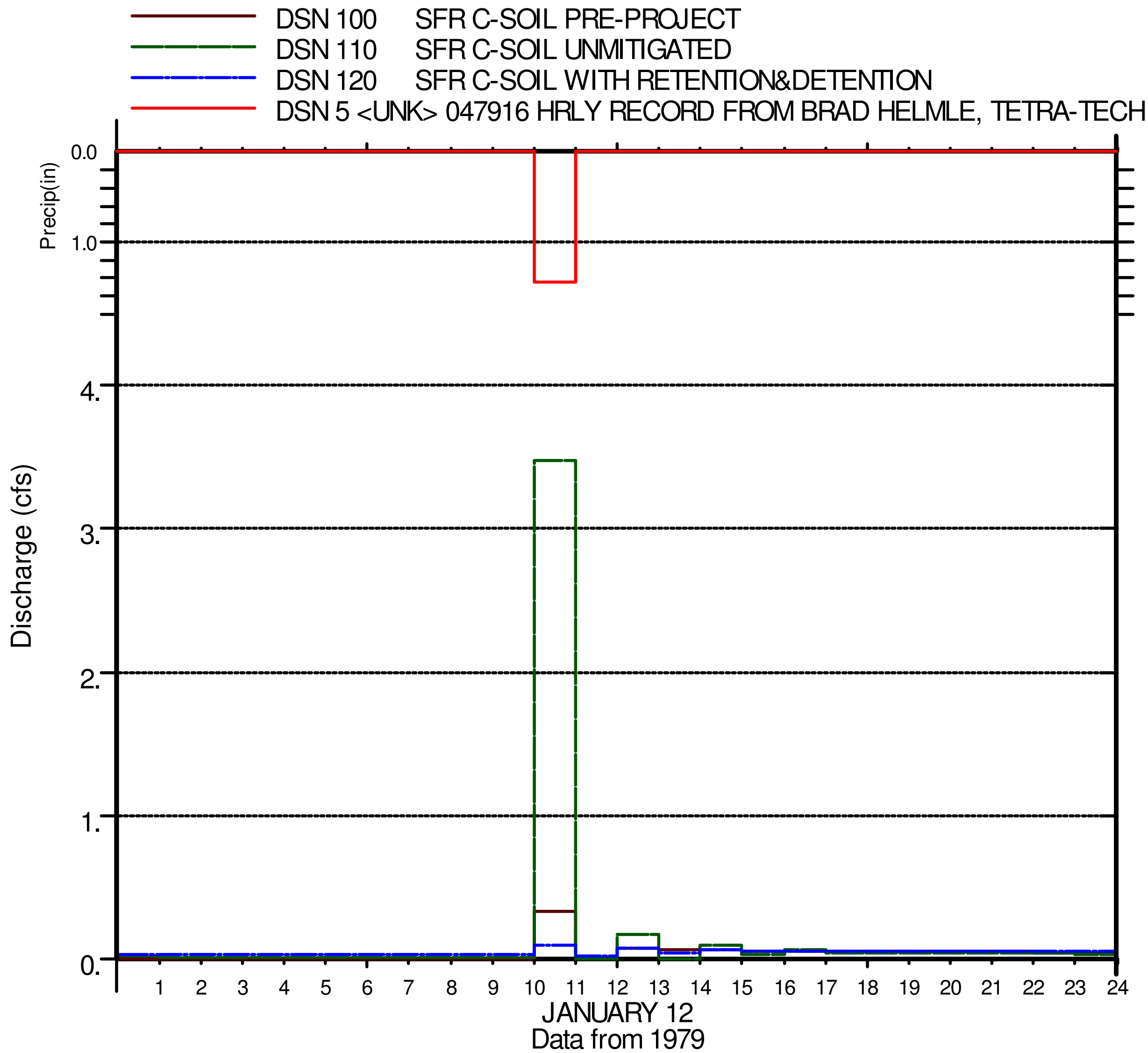


25 yr Peak Annual Flow Event (pre-developed and unmitigated), December 21, 1970.

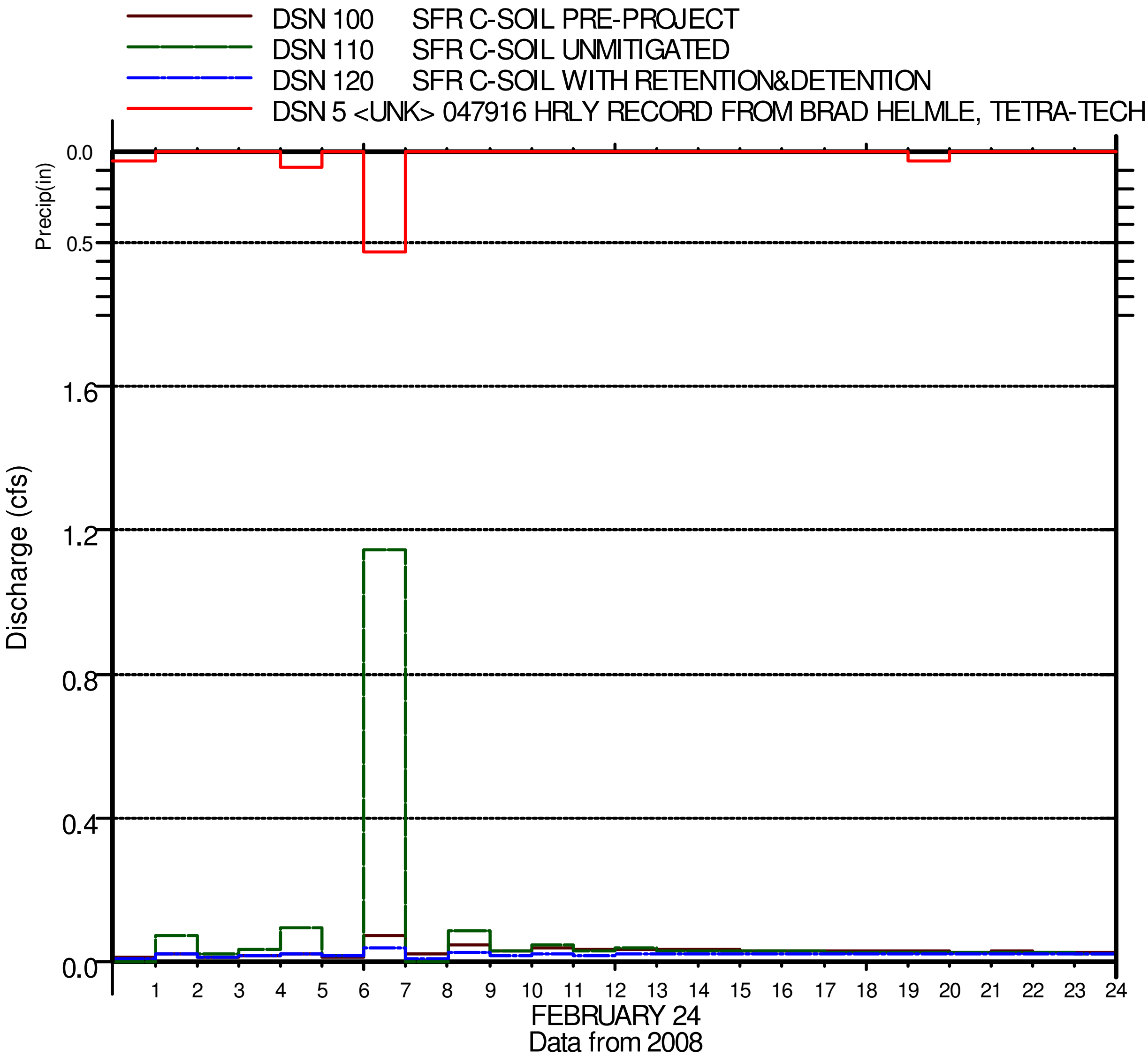
Note that that bioretention is able to absorb this event because there it is a relatively isolate burst of rainfall. Therefore, it does not produce a peak for the mitigated scenario.



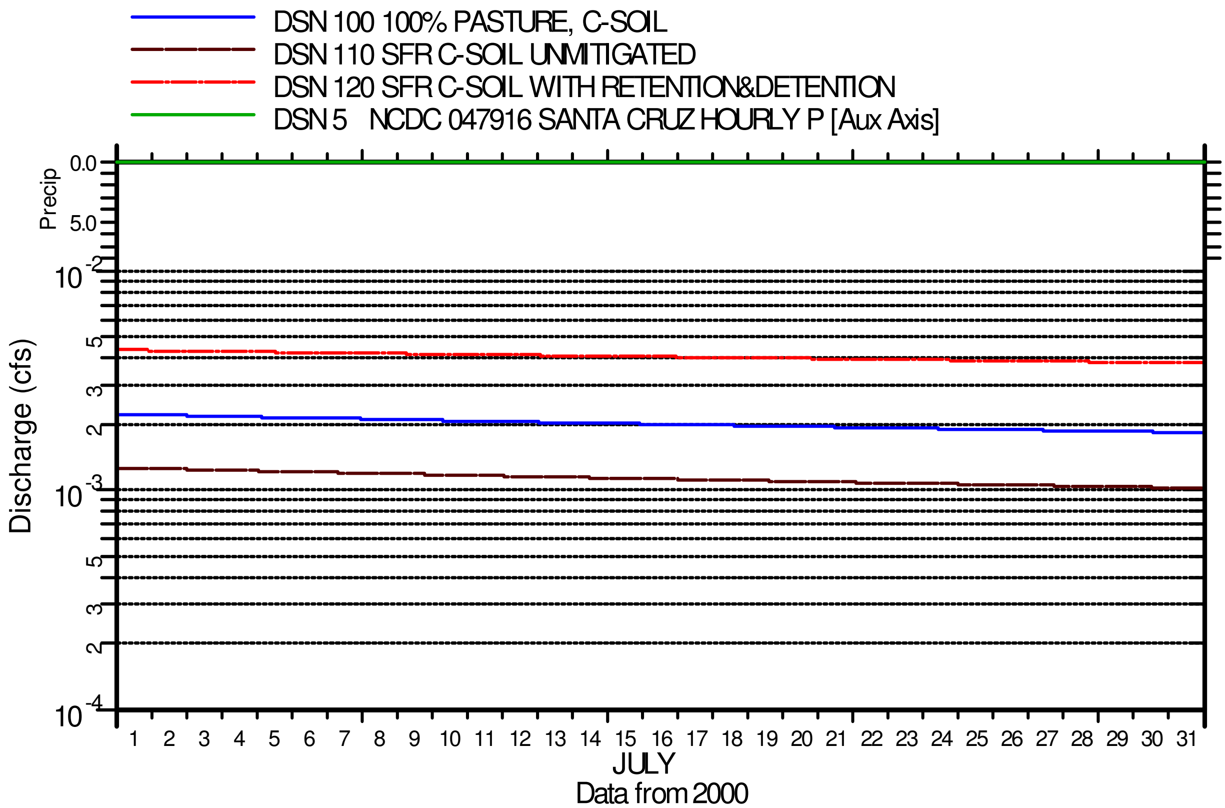
~10 yr Peak Annual Flow Event, January 12, 1979



~2 yr Peak Annual Flow Event, February 24, 2008

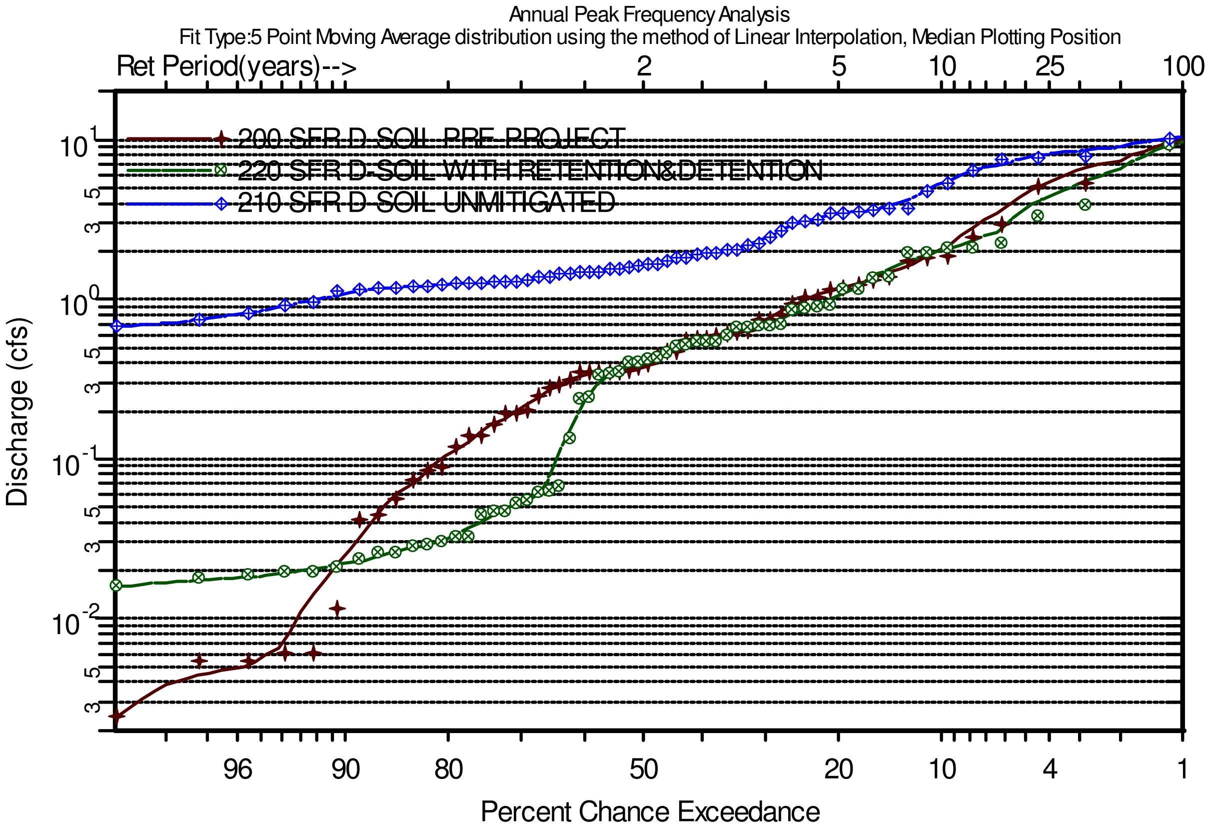


Summer Base Flow, July, 2000-  a month with zero precipitation




July, 2000 was a month of zero rainfall which was preceded by a month with only .2 inches. Thus, the graph above compares summer base flows under very dry conditions.  As shown in the graph above, without on-site retention (brown line), the base flow is approximately cut in half compared to the pre-developed, 100% pasture case (blue line).  In contrast, the developed project with bioretention (red line) maintains base flow during dry conditions above the pre-developed level.

Single Family Residential Development, D-Soil

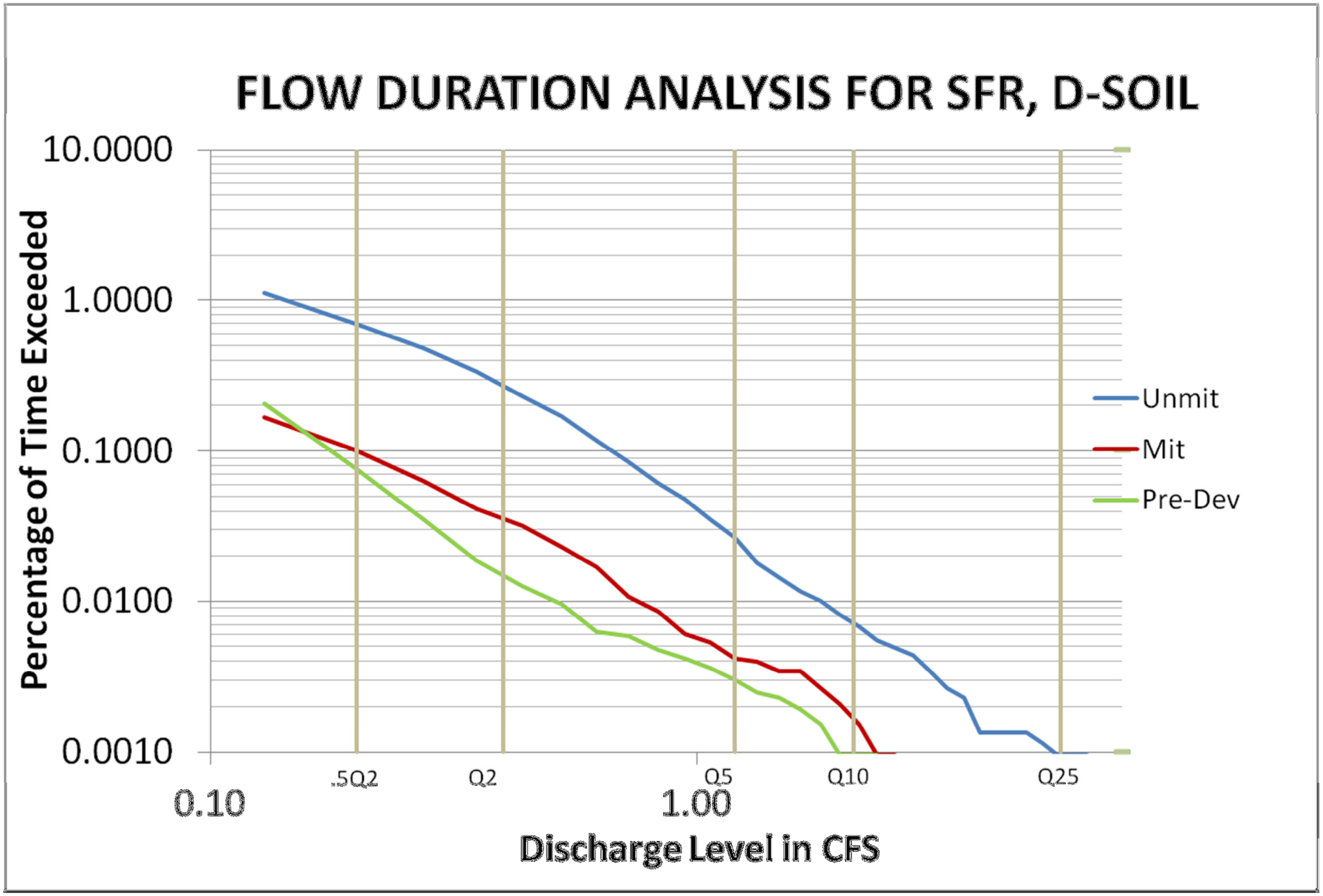



| Table 4. Peak Annual Flood Frequency Curve Data for D-Soil, SFR | | | | | | |
|---|---|---|---|---|---|---|
| Average Recurrence Interval (years) | 2 | 5 | 10 | 25 | 50 | 100 |
| | Quantiles (cfs) | | | | | |
| | | | | | | |
| Pre-Dev, C-Soil | 0.4 | 1.2 | 2.1 | 5.6 | 7.5 | 10.0 |
| SFR- no R/D- D-Soil | 1.6 | 3.4 | 5.5 | 8.3 | 9.1 | 10.5 |
| SFR w R/D, D-Soil | 0.4 | 1.1 | 2.0 | 4.6 | 6.6 | 9.8 |

**Peak Annual Flow Frequency, Single Family Residential Development, D-Soil**

A total of .96 ac-ft of combined bioretention and detention storage is required to meet the 2-100-yr standard for residential development on a D-soil. In contrast to the development on the more infiltrative C-soil, the required bioretention volume is greater than the volume required for detention and peak flow control. However, it should be noted that the relatively small size of the detention facility is partly due to the peak and volume reduction action of the upstream bioretention facility.

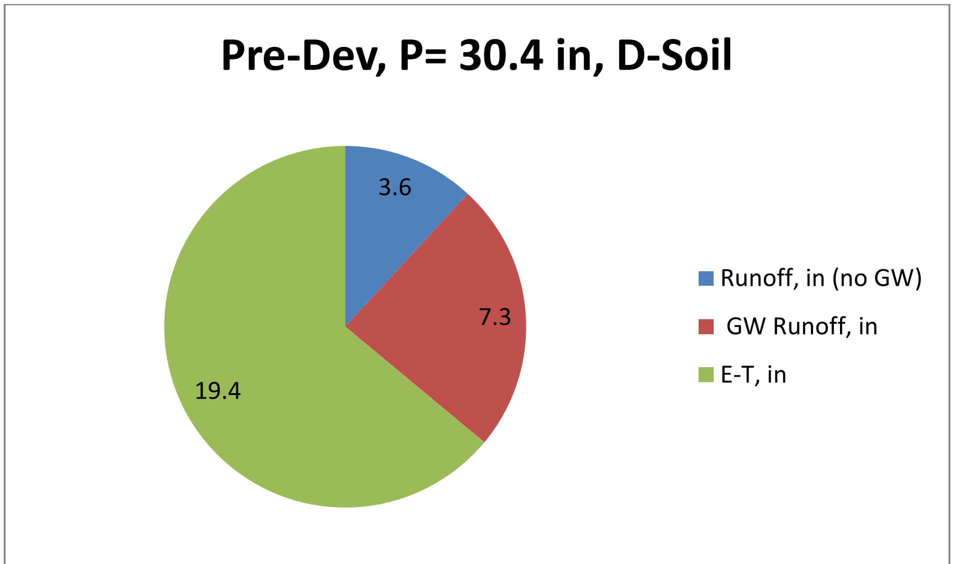
**Flow Duration Analysis- SFR, D-Soil**

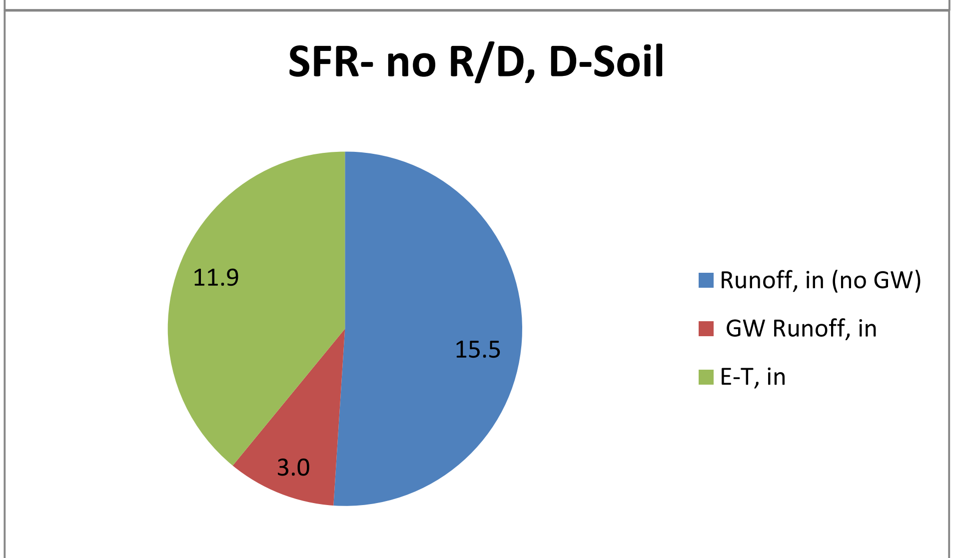


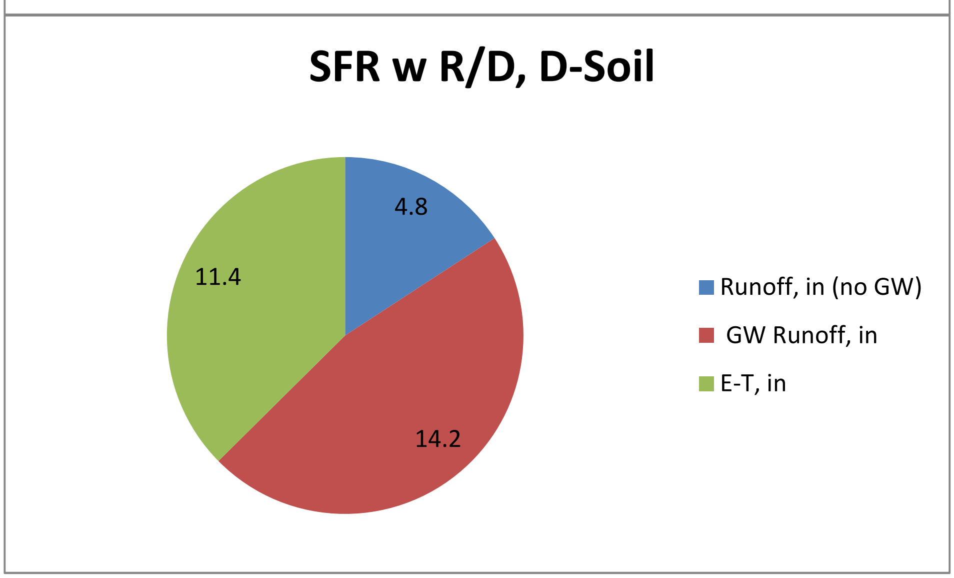
**Durational Analysis Discussion, Single Family Residential Development, D-Soil**

For the single family residential development on the D-soil, the combination of retention and detention facilities reduced increases in high flow durations ranging from 50% of the pasture 2-yr to the pasture 10-yr peak by 91%.

Water Balance Results- Single Family Residential, D-Soil.  As shown, the bioretention


Pre-Dev, P= 30.4 in, D-Soil
3.6
7.3
19.4
Runoff, in (no GW)
GW Runoff, in
E-T, in


SFR- no R/D, D-Soil
11.9
15.5
3.0
Runoff, in (no GW)
GW Runoff, in
E-T, in

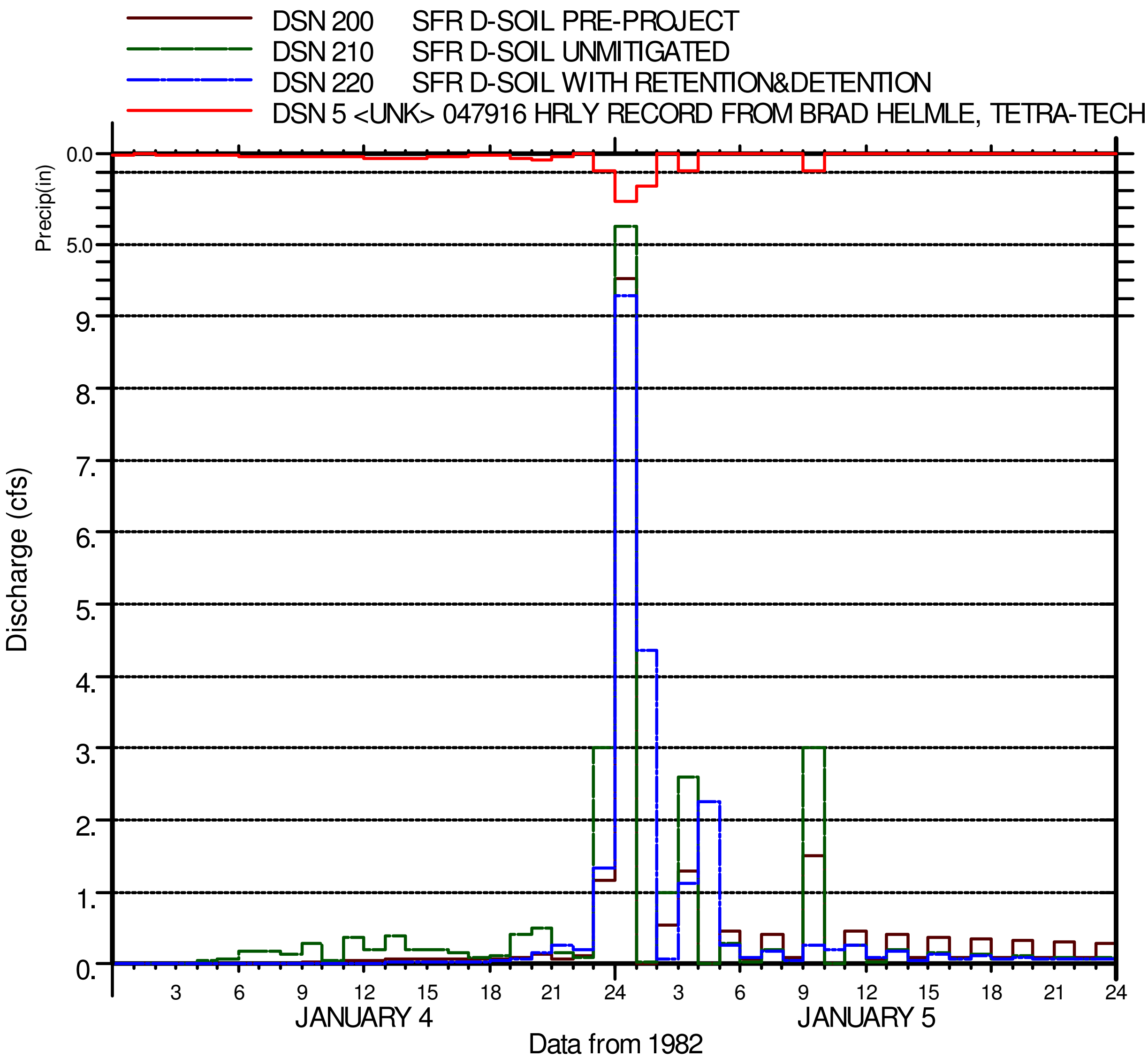

SFR w R/D, D-Soil
4.8
11.4
14.2
Runoff, in (no GW)
GW Runoff, in
E-T, in

**Water Balance Discussion, Single Family Residential Development, D-Soil**

The bioretention area (.84 ac) takes up 50% of the pervious portion and 27% of the total site area. It has a storage depth of 8 inches. Because the infiltration rate is lower for a D soil than a C soil by more than a factor of four, more storage is required to assure retention of runoff from the 24-hr, 95-percentile rainfall amount. The retention facilities reduce the average runoff volume from 15.5 inches (430% of the pasture value) to 4.8 inches (133% of the pasture value). The bioretention facility accomplishes significant water quality treatment by infiltrating 69% of runoff from the developed site (10.7 inches out of 15.5 inches. The detention facility is assumed to be impermeable and to play no role in infiltrating or treating site runoff.

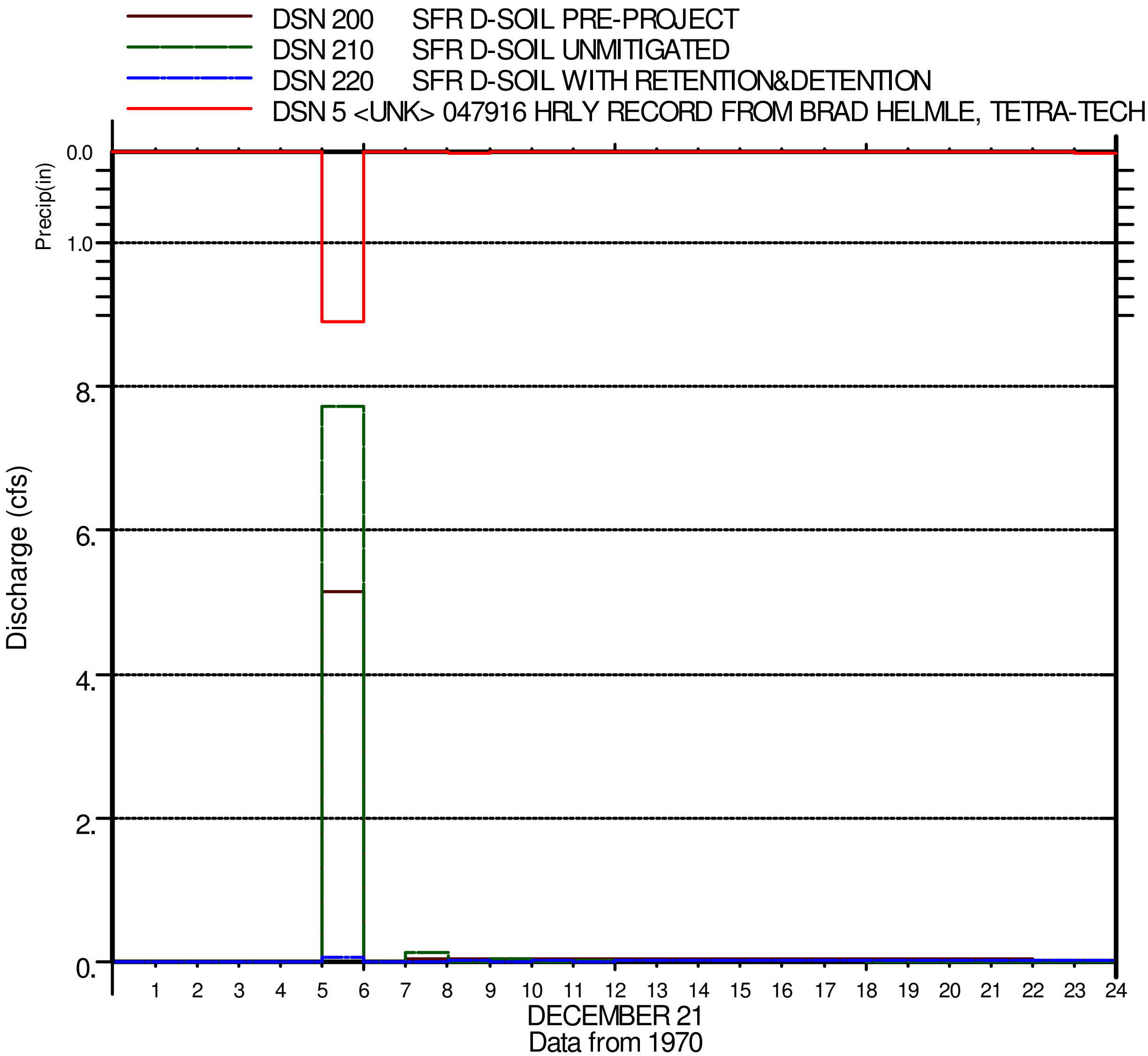
**Sample Hydrographs, Single Family Residential, D-Soil**

Peak Flow Event of record, 50-100 yr event (all scenarios), January 4-5, 1982

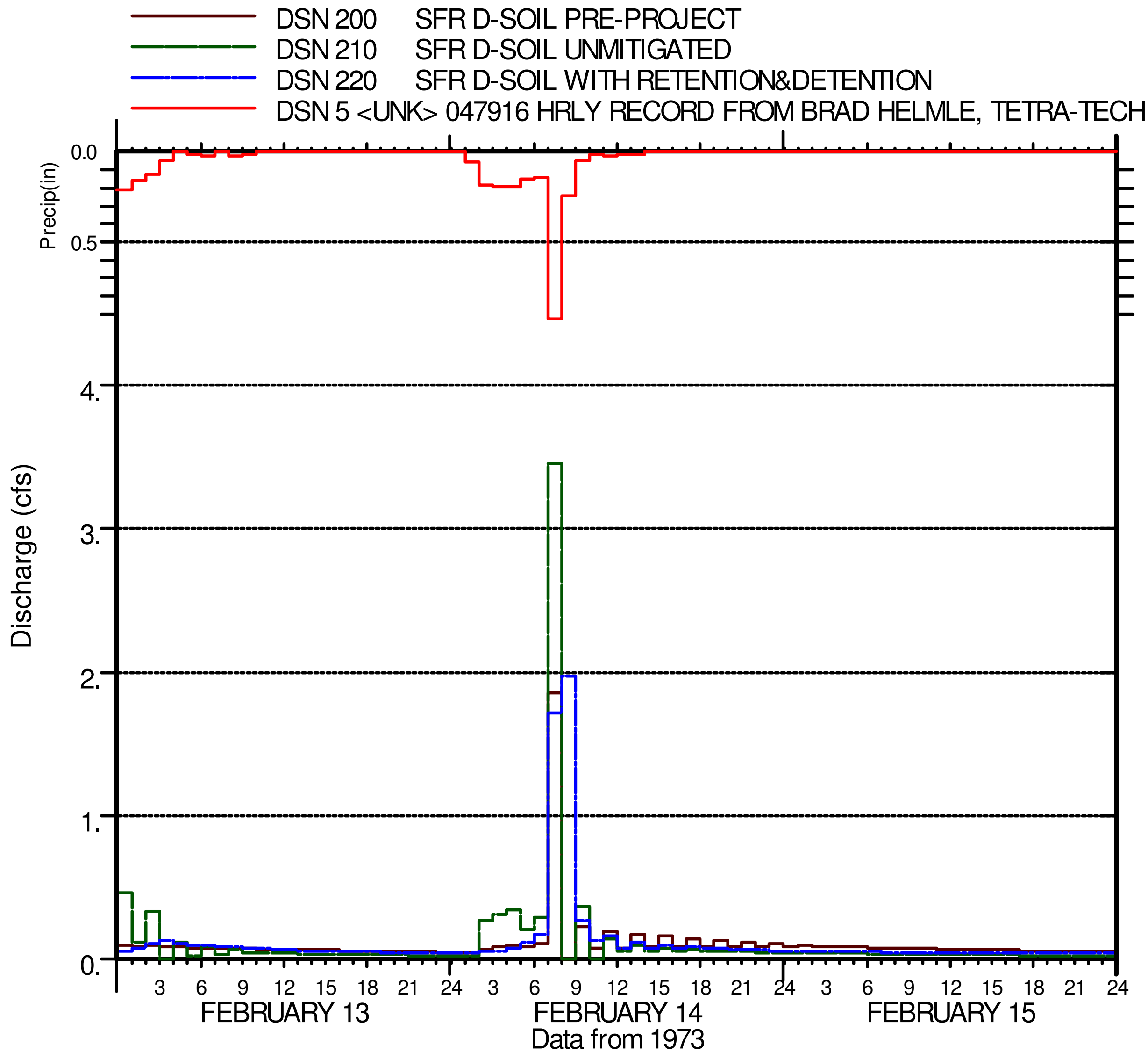


25 yr Peak Annual Flow Event (pre-developed and unmitigated), December 21, 1970.

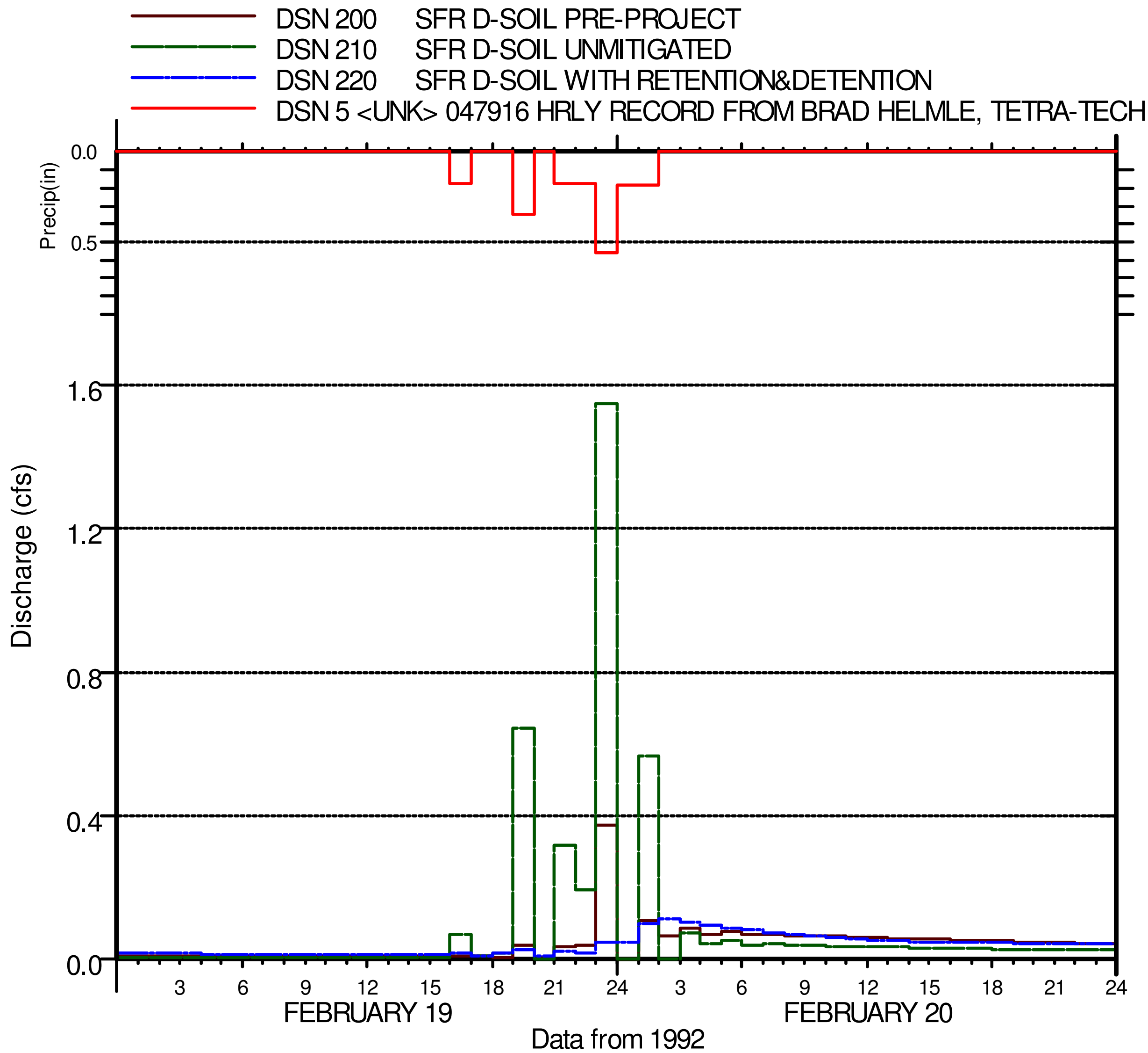
Note that that bioretention is able to absorb this event because there it is a relatively isolate burst of rainfall. Therefore, it does not produce a peak for the mitigated scenario.

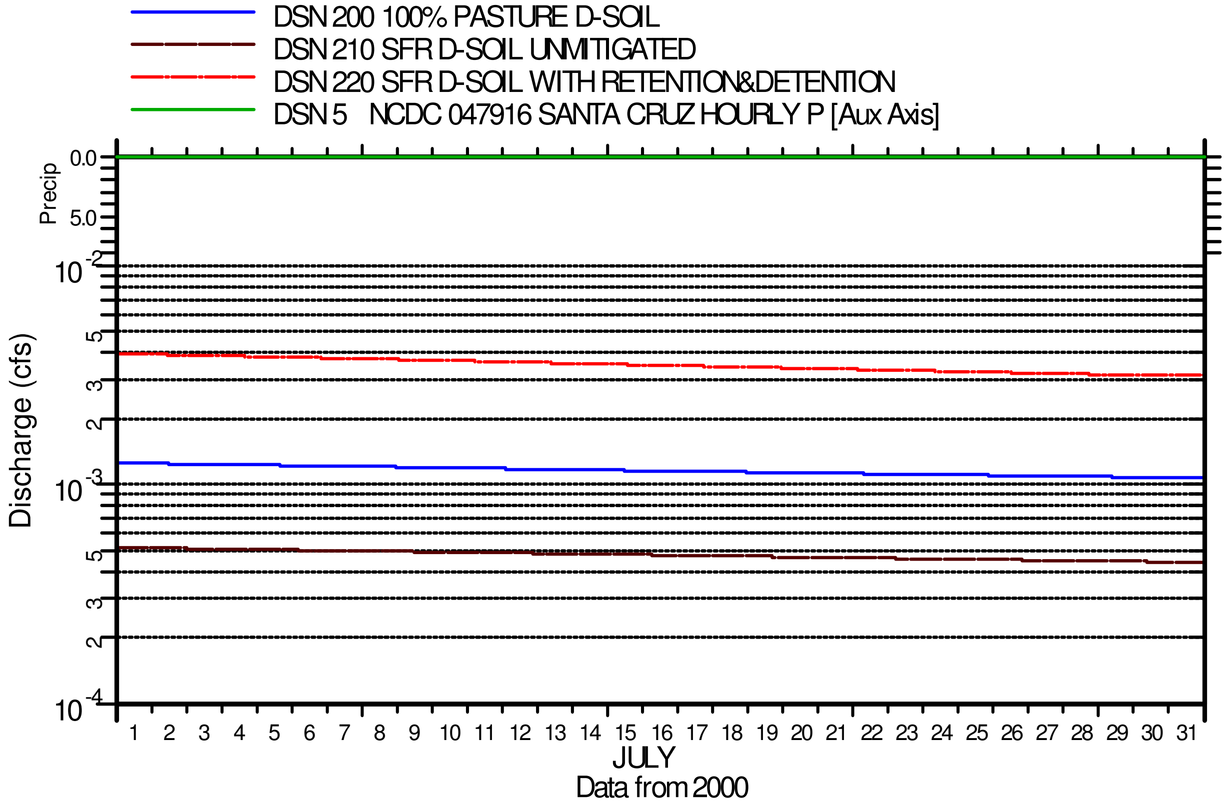


~10 yr Peak Annual Flow Event (pre-developed and mitigated), February 14, 1973



~2 yr Peak Annual Flow Event (pre-developed and unmitigated), February 19-20, 1992



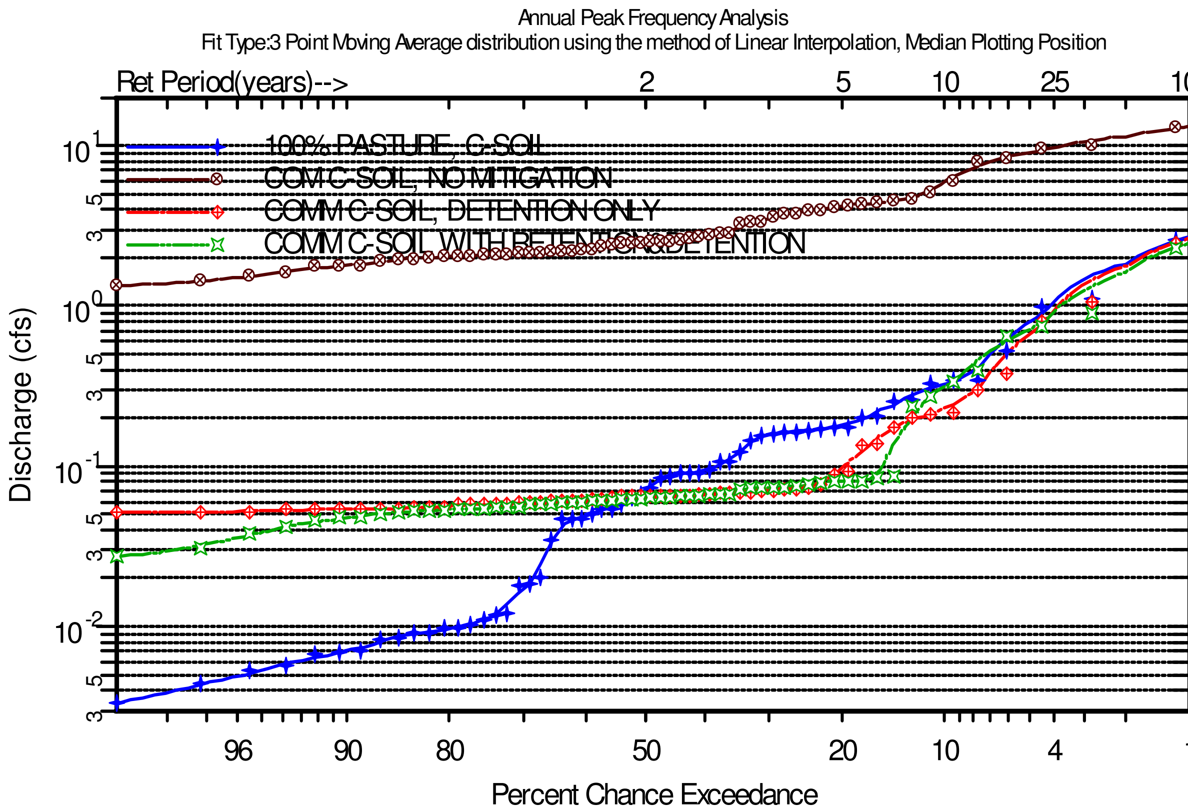



The base flow results for very dry summer conditions for the SFR D-soil are similar to the SFR C-Soil case. The developed site without on-site retention (brown line) exhibits a base flow that is less than 50% of the pre-developed, 100% pasture condition (blue line) while the developed project with bioretention (red line) maintains base flows above the pre-developed level by a substantial margin.

## Results for Commercial Case with C and D Soils

Commercial Redevelopment, C-Soil

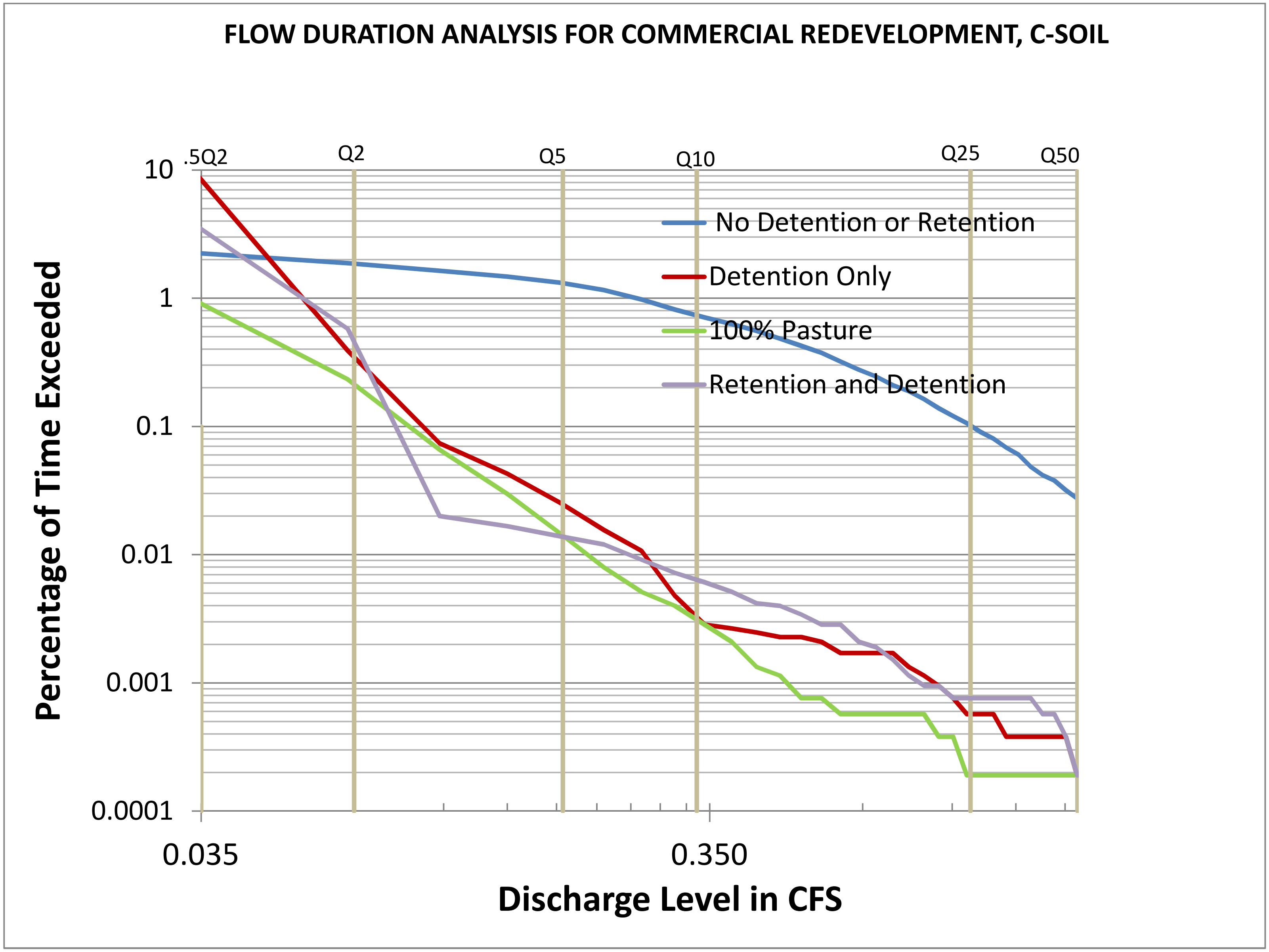
Flood Frequency Comparison




| Table 5. Peak Annual Flood Frequency Curve Data for C-Soil, Commercial | | | | | | |
|---|---|---|---|---|---|---|
| Average Recurrence Interval (years) | 2 | 5 | 10 | 25 | 50 | 100 |
| | Quantiles (cfs) | | | | | |
| Pre-Dev (Pasture), | 0.07 | 0.18 | 0.33 | 1.14 | 1.85 | 2.70 |
| Detention Only | 0.07 | 0.10 | 0.24 | 1.02 | 1.78 | 2.62 |
| On-Site Retention and Detention | 0.06 | 0.08 | 0.32 | 0.99 | 1.62 | 2.45 |
| NO MITIGATION | 2.50 | 4.19 | 6.14 | 9.87 | 11.43 | 13.18 |

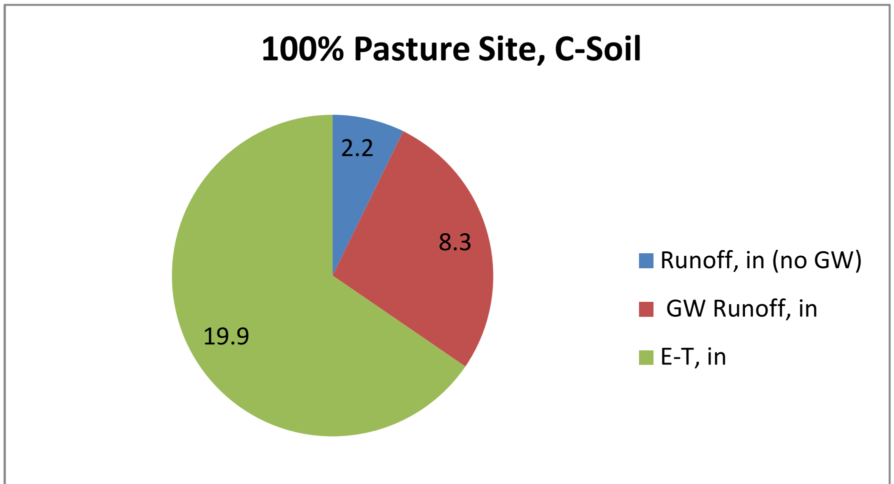
## Peak Annual Flow Frequency Discussion, Commercial Redevelopment, C-Soil

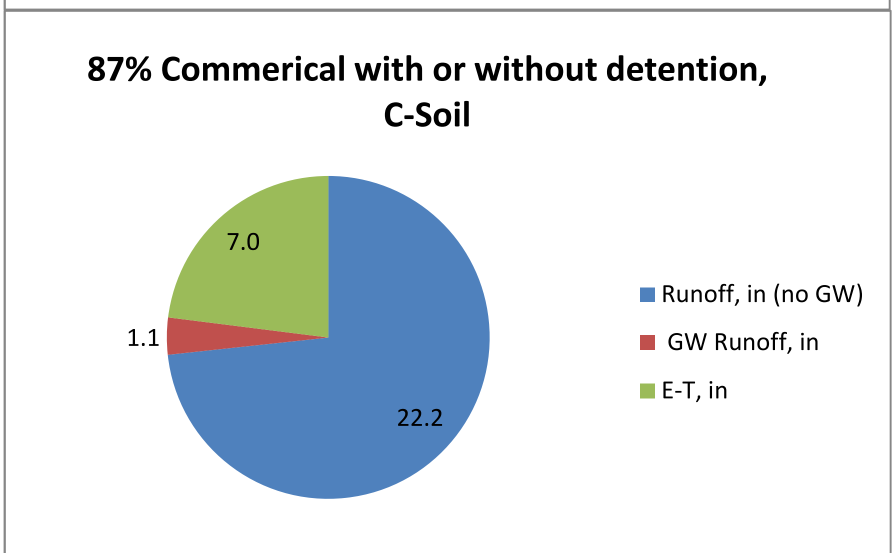
For the commercial development on a C-soil, matching of the pre-developed (100% pasture) frequency curve between the 2-yr and 100-yr quantiles is achieved either with a detention facility with 1.60 ac-ft with no on-site retention, or with a detention facility of 1.25 ac-ft and on-site facilities consisting of 0.26 ac of porous pavement and 0.40 acres of bioretention with 6 inches of available storage.

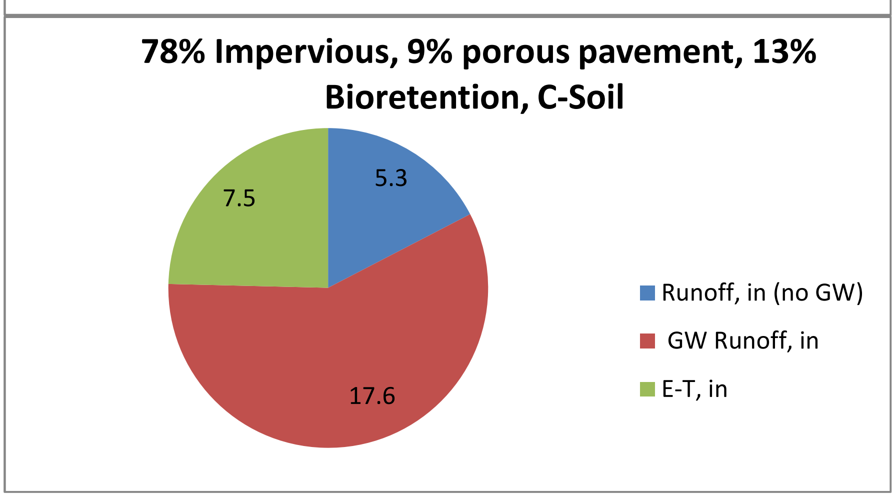

FLOW DURATION ANALYSIS FOR COMMERCIAL REDEVELOPMENT, C-SOIL
Percentage of Time Exceeded
10
1
0.1
0.01
0.001
0.0001
.5Q2
Q2
Q5
Q10
Q25
Q50
No Detention or Retention
Detention Only
100% Pasture
Retention and Detention
0.035
0.350
Discharge Level in CFS

**Flow Duration Discussion, Commercial Redevelopment, C-Soil**

Over range from 50% of the 2-yr to the 10-yr peak, the average reduction in high flow durations is 79% for the combined retention-detention case, and 35% for the detention-only case.   For flows at or above the 2-year flow, average performance for both cases is at the 96% level; however, for the more frequent sub-2-yr peaks, durations are clearly much higher and even exceed the un-mitigated level which drags the average performance down.


100% Pasture Site, C-Soil
2.2
8.3
19.9
Runoff, in (no GW)
GW Runoff, in
E-T, in


87% Commerical with or without detention, C-Soil
7.0
1.1
22.2
Runoff, in (no GW)
GW Runoff, in
E-T, in

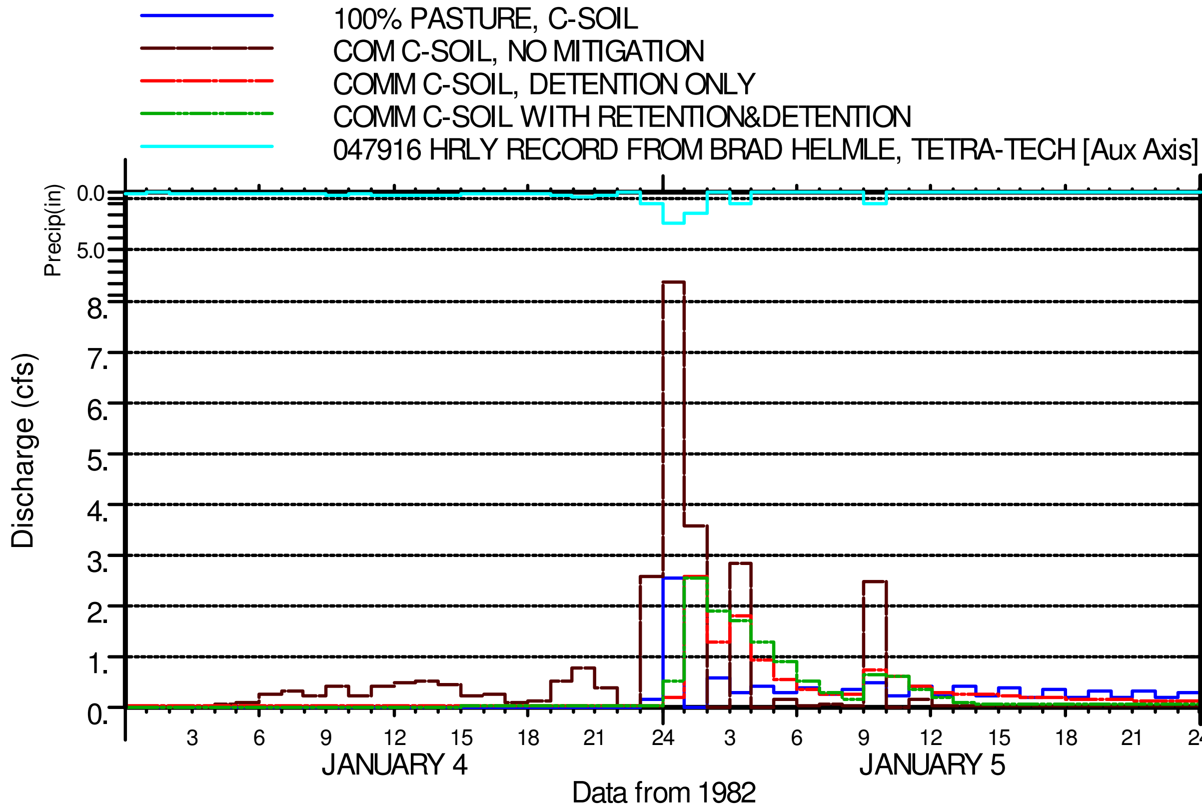

78% Impervious, 9% porous pavement, 13% Bioretention, C-Soil
5.3
7.5
17.6
Runoff, in (no GW)
GW Runoff, in
E-T, in

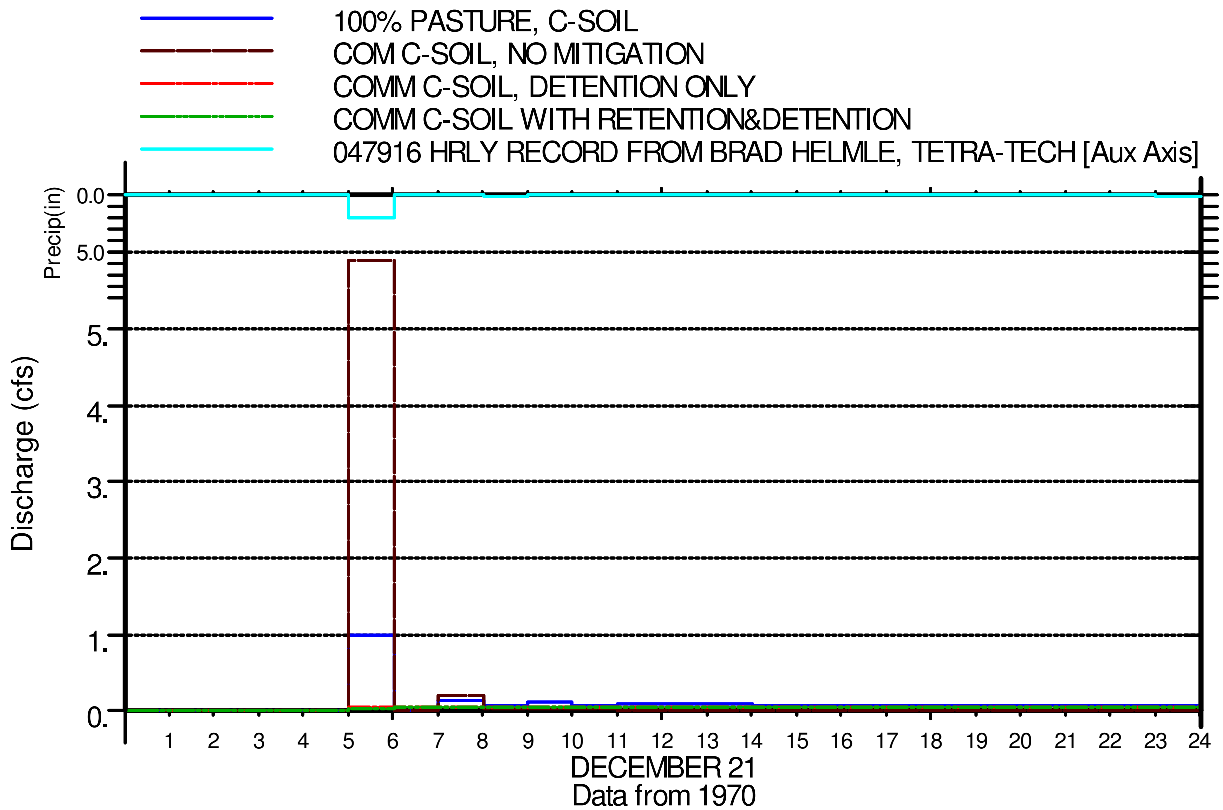
**Water Balance Discussion, Commercial Redevelopment, C-Soil**

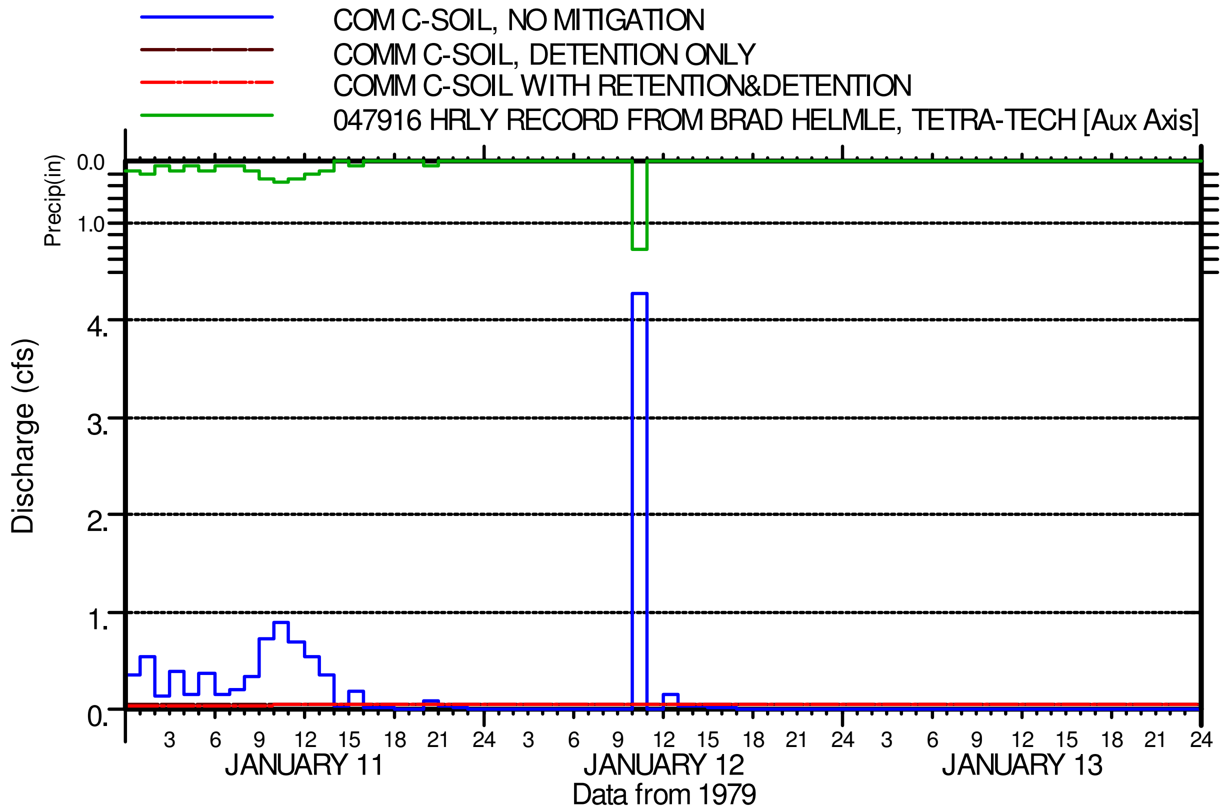
On-site retention facilities consist of 0.26 acres of porous pavement and 0.40 acres of bioretention taking up 10% of the impervious area and 100% of the pervious area on-site. Both facilities are assumed to infiltrate at a constant rate typical of a C-soil. Porous pavement is assumed to have zero storage, while bioretention must have 0.19 acre-ft of volume (5.7 inches in the bioretention facility) in order meet the retention design requirement for 50% of the replaced impervious area.

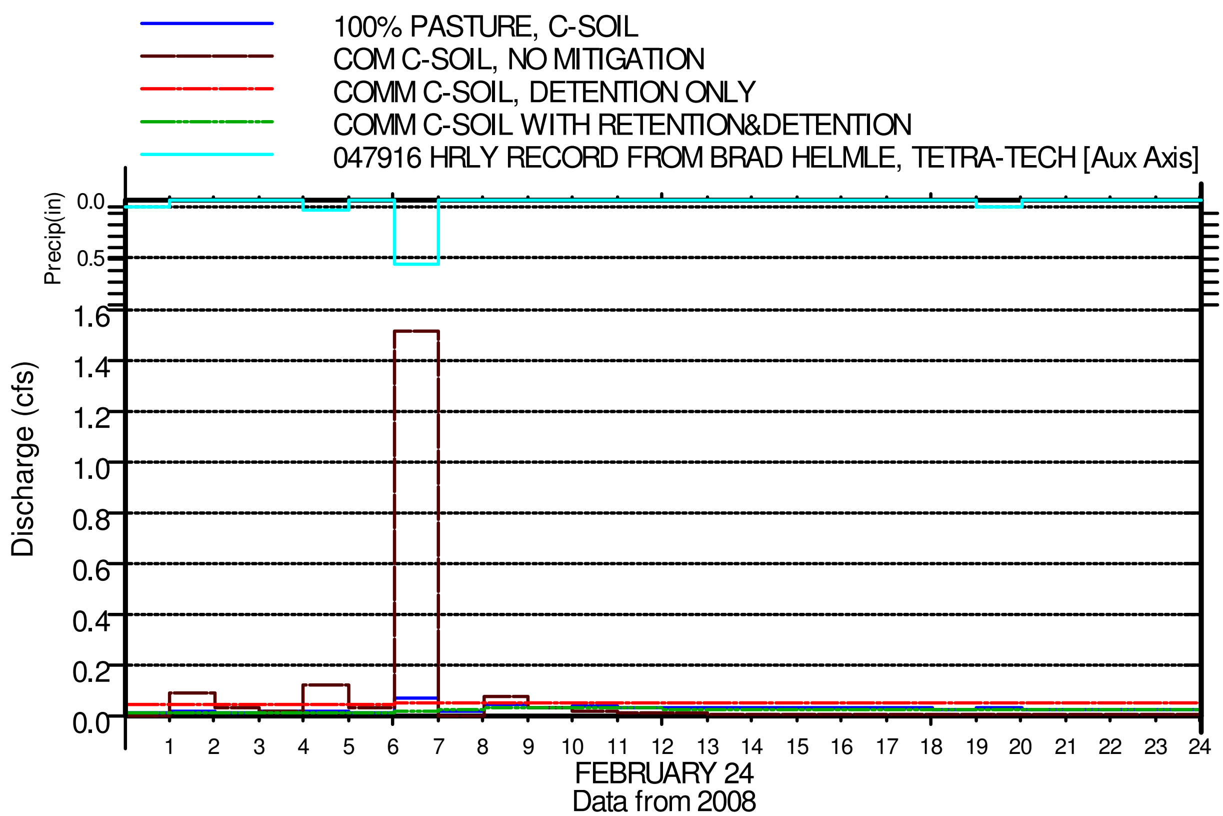
The average runoff volume (surface runoff and interflow) with on-site retention is over double the runoff for pasture conditions; however, the retention facilities treat 76% of the runoff from the site. Groundwater loading is more than doubled compared to pasture conditions and increased by a factor of sixteen compared to developed conditions with no retention facilities. Detention is assumed to play no role in affecting the developed water balance. It is assumed to be off-site with zero infiltration capacity.

**Sample Hydrographs, Commercial Redevelopment, C-Soil**

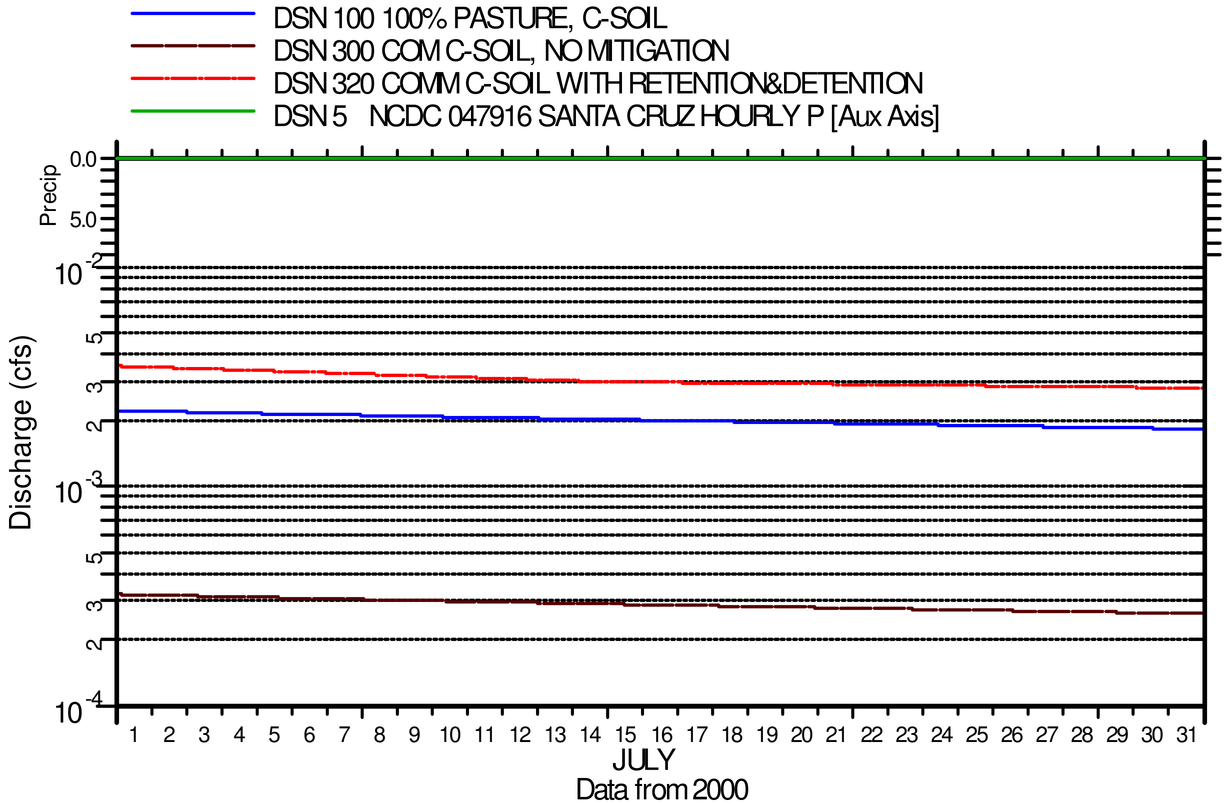



100% PASTURE, C-SOIL
COM C-SOIL, NO MITIGATION
COMM C-SOIL, DETENTION ONLY
COMM C-SOIL WITH RETENTION&DETENTION
047916 HRLY RECORD FROM BRAD HELMLE, TETRA-TECH [Aux Axis]
Precip(in)
0.0
5.0
Discharge (cfs)
5.
4.
3.
2.
1.
0.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
DECEMBER 21
Data from 1970


COM C-SOIL, NO MITIGATION
COMM C-SOIL, DETENTION ONLY
COMM C-SOIL WITH RETENTION&DETENTION
047916 HRLY RECORD FROM BRAD HELMLE, TETRA-TECH [Aux Axis]
Precip(in)
0.0
1.0
Discharge (cfs)
4.
3.
2.
1.
0.
3 6 9 12 15 18 21 24 3 6 9 12 15 18 21 24 3 6 9 12 15 18 21 24
JANUARY 11
JANUARY 12
JANUARY 13
Data from 1979

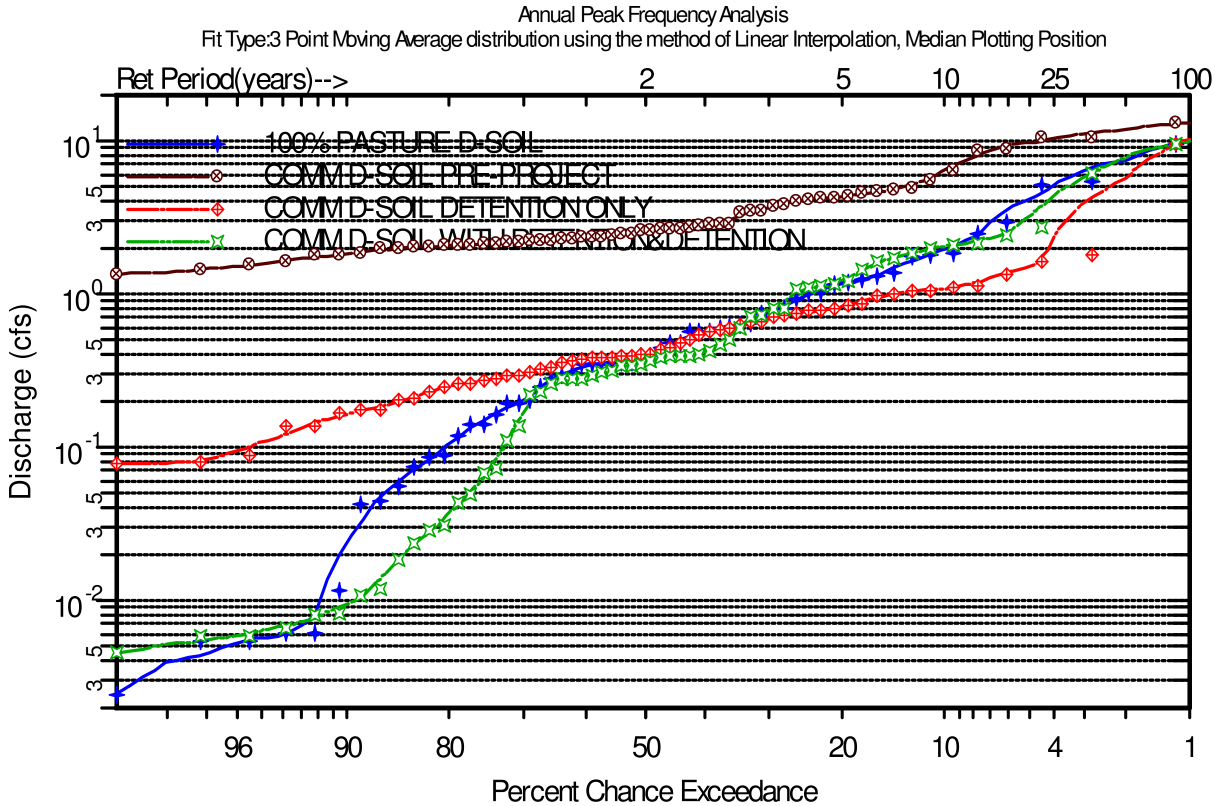


100% PASTURE, C-SOIL
COM C-SOIL, NO MITIGATION
COMM C-SOIL, DETENTION ONLY
COMM C-SOIL WITH RETENTION&DETENTION
047916 HRLY RECORD FROM BRAD HELMLE, TETRA-TECH [Aux Axis]
Precip(in)
0.0
0.5
Discharge (cfs)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
FEBRUARY 24
Data from 2008




The base flow results for very dry summer conditions for the Commercial C-soil are similar to results for the residential scenario except that the base flow depletion for developed conditions is far more extreme. The developed site without on-site retention (brown line) is roughly seven times lower than the pre-developed, 100% pasture condition (blue line) while the developed project with bioretention (red line) maintains base flows above the pre-developed level.

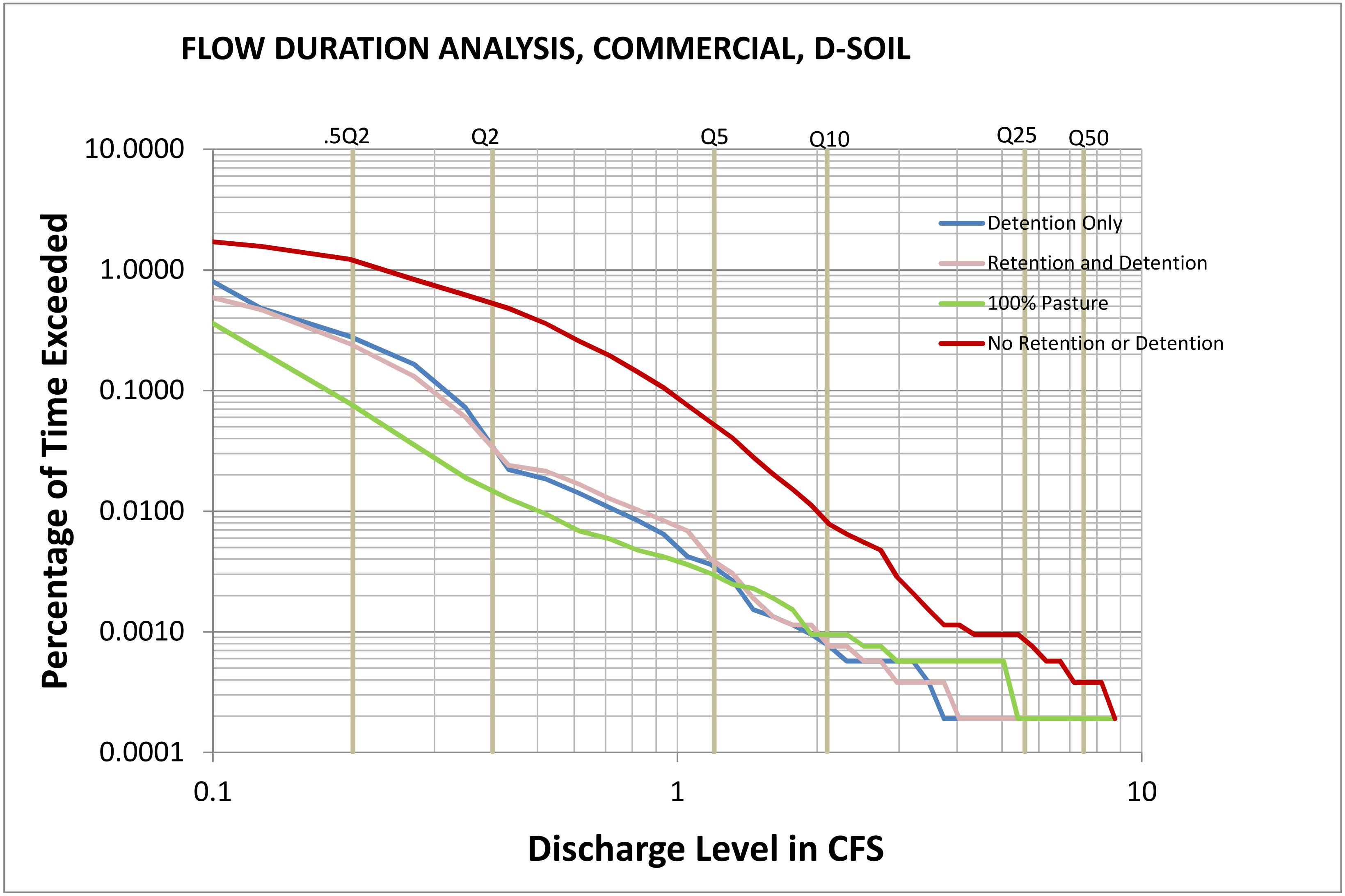
## Commercial Redevelopment, D-Soil




| Table 6. Peak Annual Flood Frequency Curve Data for D-Soil, Commercial | | | | | | |
|---|---|---|---|---|---|---|
| Average Recurrence Interval (years) | 2 | 5 | 10 | 25 | 50 | 100 |
| | Quantiles (cfs) | | | | | |
| Pre-Dev (Pasture), | 0.39 | 1.17 | 2.00 | 5.34 | 7.50 | 9.95 |
| Detention Only | 0.41 | 0.83 | 1.09 | 2.64 | 5.72 | 10.26 |
| On-Site Retention and Detention | 0.36 | 1.24 | 2.05 | 4.63 | 7.84 | 9.93 |
| NO MITIGATION | 2.57 | 4.35 | 6.62 | 10.43 | 11.73 | 13.11 |

## Peak Annual Flood Frequency, Commercial Redevelopment, D-Soil

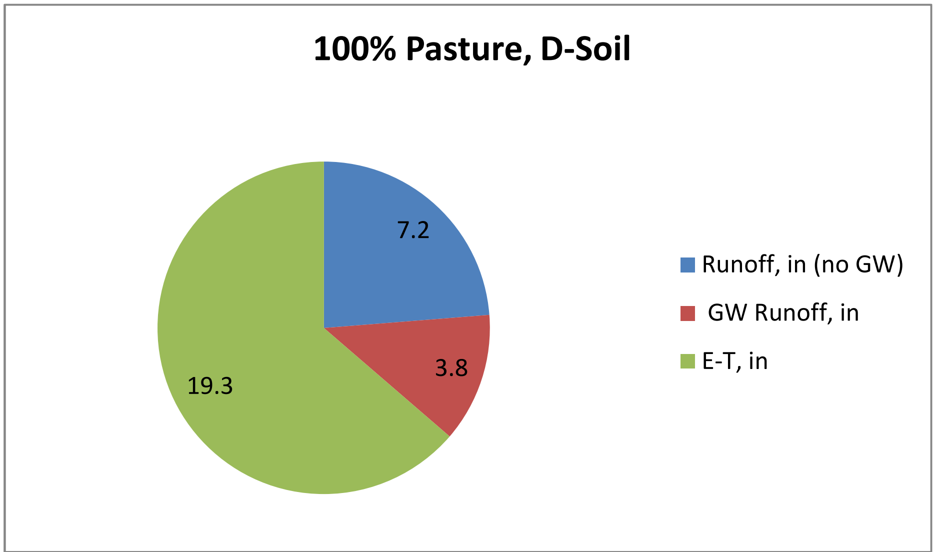
For the commercial development on a D-soil, matching of the pre-developed (100% pasture) frequency curve between the 2-yr and 100-yr quantiles is achieved either with a detention facility with 0.62 ac-ft with no on-site retention, or with a detention facility of 0.42 ac-ft and on-site facilities consisting of 0.26 ac of porous pavement and 0.40 acres of bioretention with 27 inches of available storage.

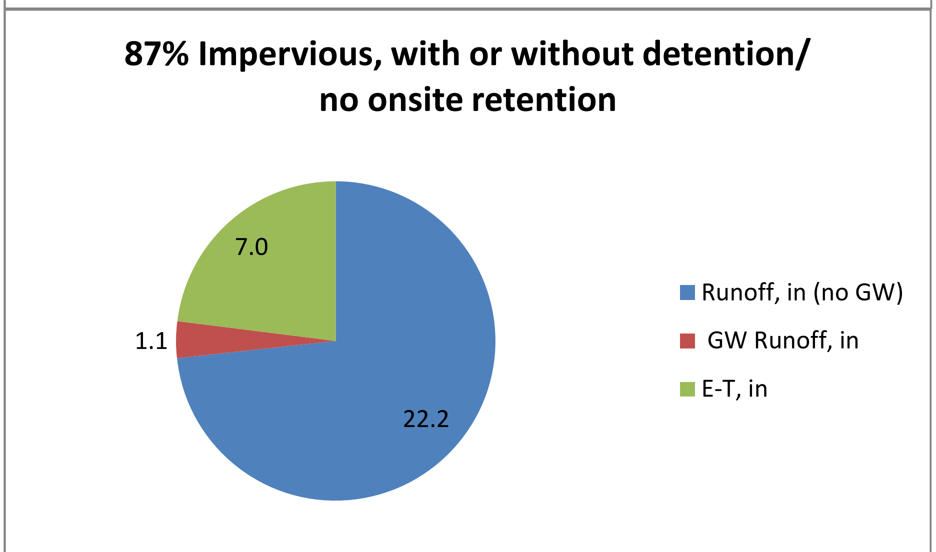


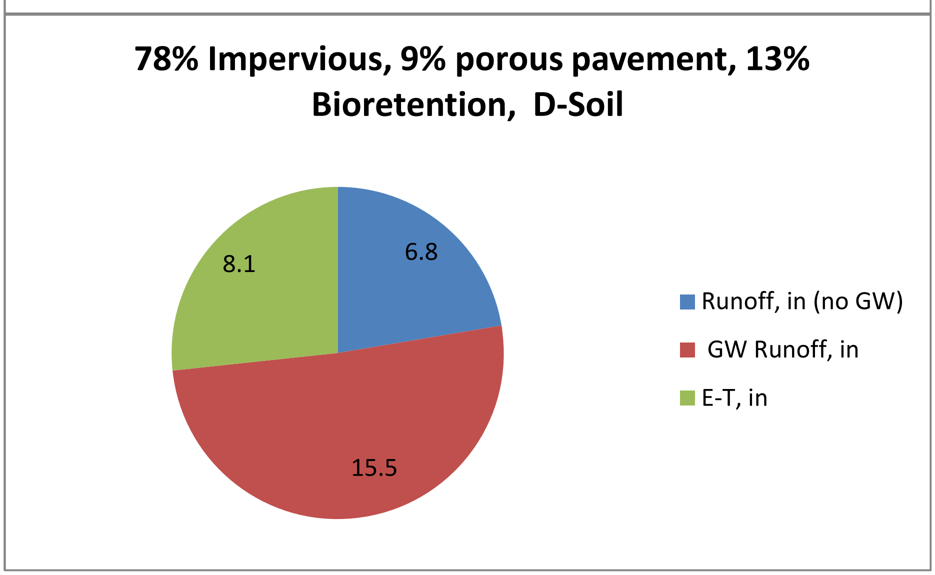
FLOW DURATION ANALYSIS, COMMERCIAL, D-SOIL
.5Q2
Q2
Q5
Q10
Q25
Q50
10.0000
1.0000
0.1000
0.0100
0.0010
0.0001
Percentage of Time Exceeded
Detention Only
Retention and Detention
100% Pasture
No Retention or Detention
0.1
1
10
Discharge Level in CFS

## Flow Duration Discussion, Commercial Redevelopment, D-Soil

Both mitigation scenarios (commercial with 2-100 yr detention and commercial with detention plus retention designed for 50% of the impervious area runoff) reduce increases in high flow durations resulting from the unmitigated case by 96%. With no on-site retention facilities, the detention necessary to meet the peak flow standard is 0.62 ac-ft compared to 0.42 ac-ft for the case of a retention facility with 0.91 ac-ft of storage. These results indicate that on a less infiltrative D-soil, is not as effective as detention for controlling high runoff durations.


100% Pasture, D-Soil
7.2
3.8
19.3
Runoff, in (no GW)
GW Runoff, in
E-T, in


87% Impervious, with or without detention/ no onsite retention
7.0
1.1
22.2
Runoff, in (no GW)
GW Runoff, in
E-T, in

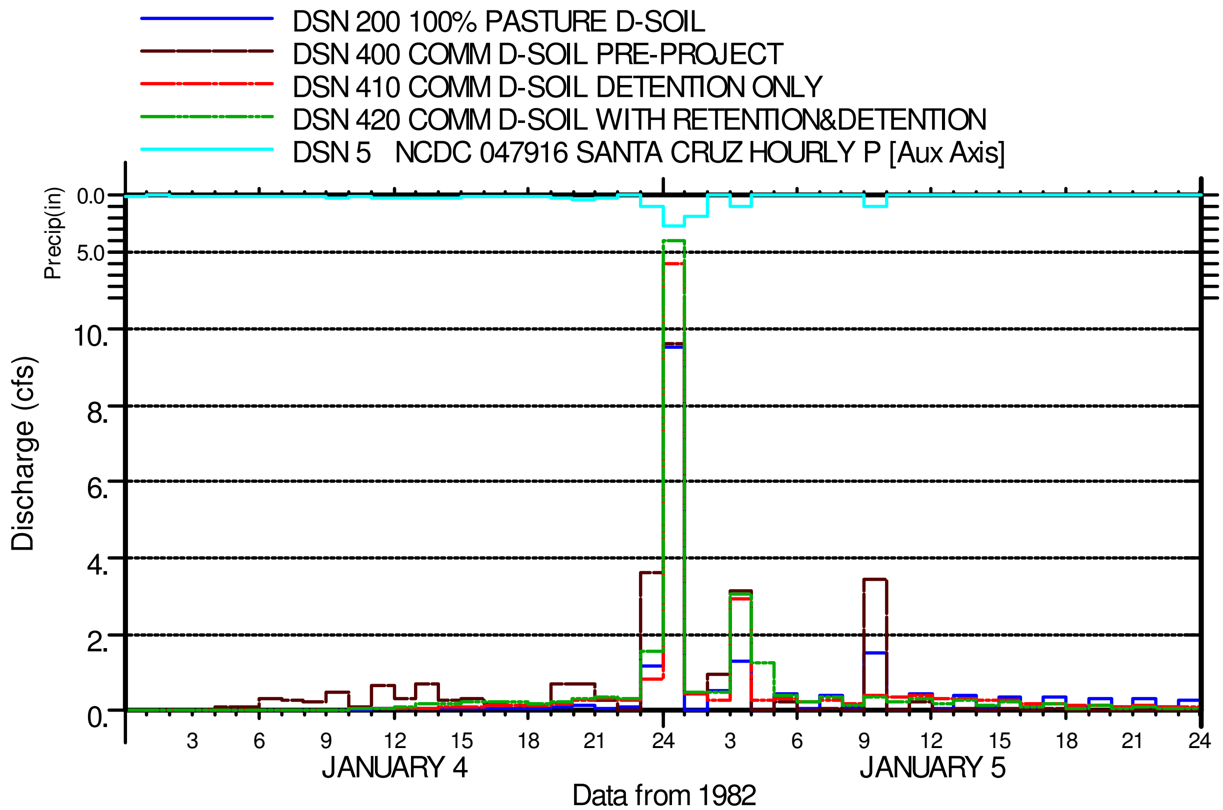

78% Impervious, 9% porous pavement, 13% Bioretention, D-Soil
8.1
6.8
15.5
Runoff, in (no GW)
GW Runoff, in
E-T, in

**Water Balance Discussion, Commercial Redevelopment, D-Soil**

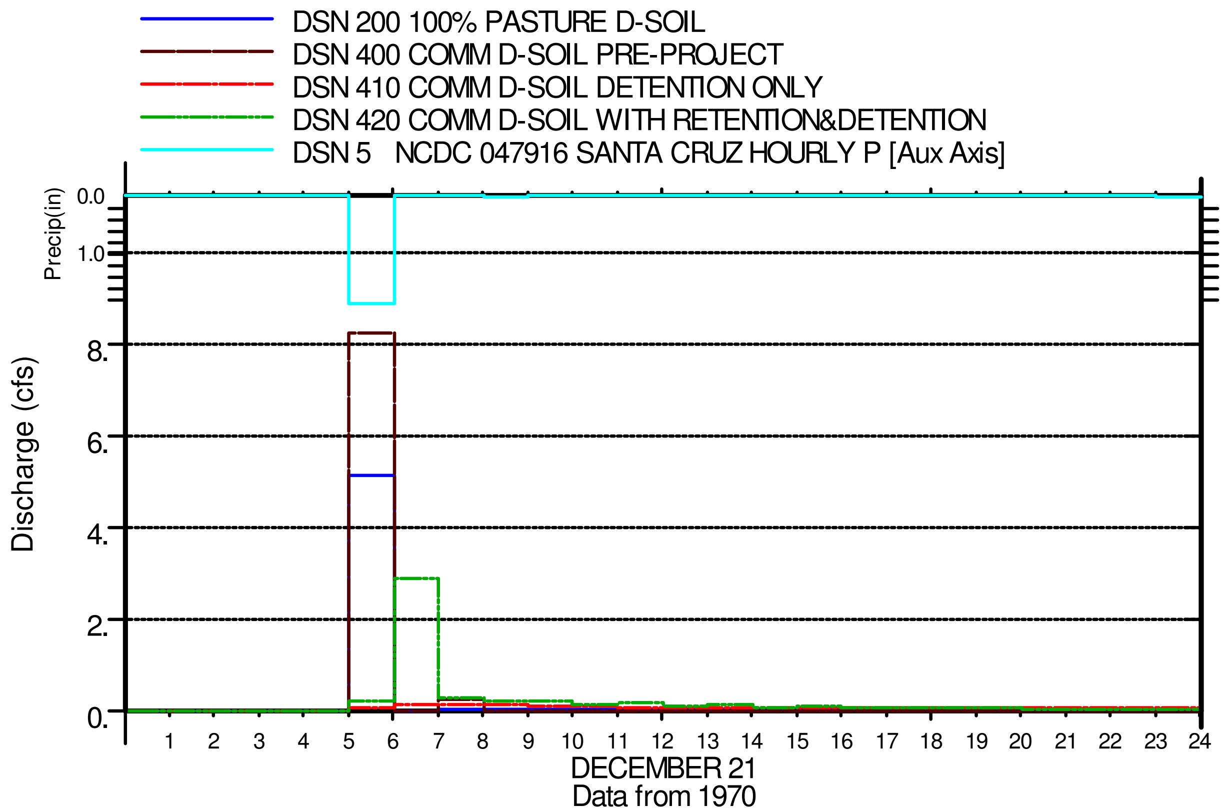
On-site retention facilities takes up the same areas as for the commercial redevelopment on the C-soil, i.e. 0.26 acres of porous pavement and 0.40 acres of bioretention taking up 10% of the impervious area and 100% of the pervious area on-site respectively. Both facilities are assumed to infiltrate at a constant rate typical of a D-soil. Porous pavement is assumed to have zero storage, while bioretention must have 0.91 acre-ft of volume (27.3 inches in the bioretention facility) in order meet the retention design requirement for 50% of the replaced impervious area. Such a large storage depth may be infeasible.

The average runoff volume (surface runoff and interflow) with on-site retention is slightly less than for pasture conditions. Retention infiltrates and provides quality treatment to approximately 70% of runoff from developed site surfaces. Groundwater loading is increased by a factor of four compared to pasture conditions and by a factor of fourteen compared to developed conditions with no retention facilities. Detention is assumed to play no role in affecting the developed water balance. It is assumed to be off-site with zero infiltration capacity.

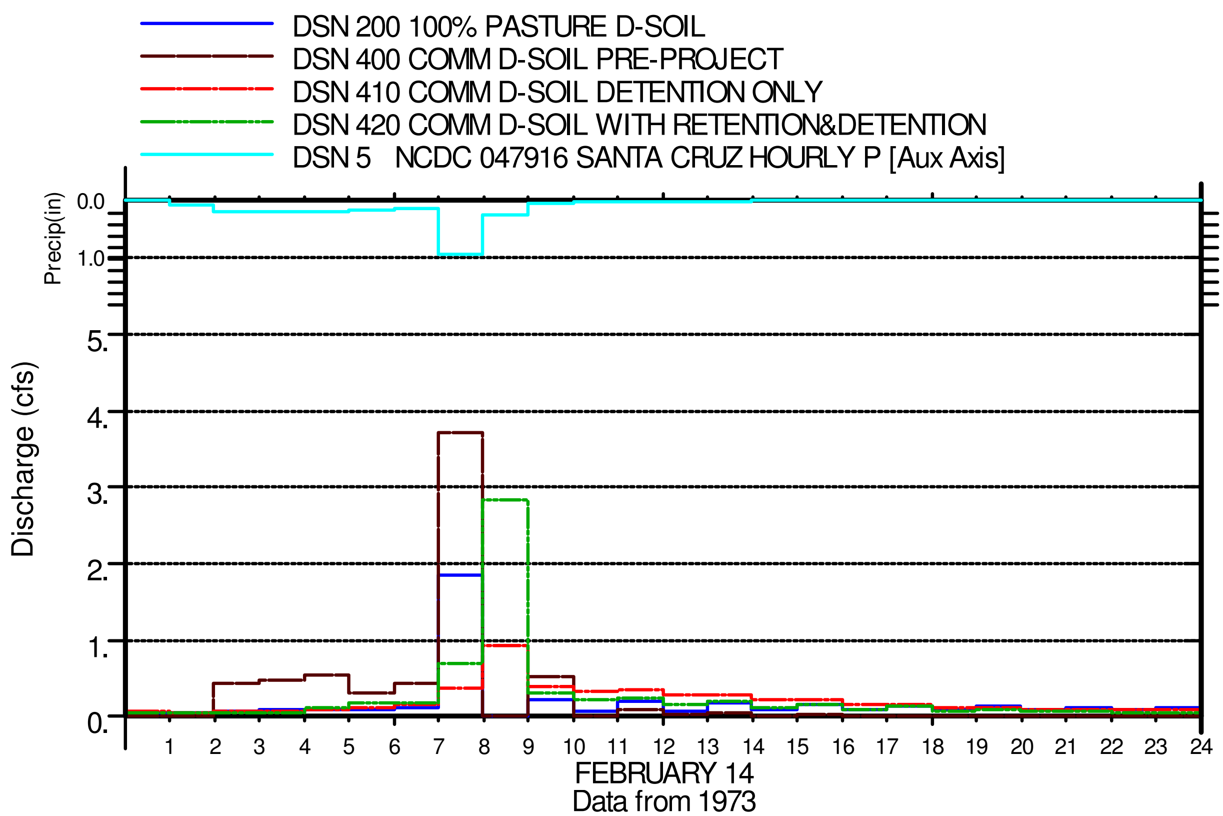
## Sample Hydrographs, Commercial Redevelopment, D-Soil

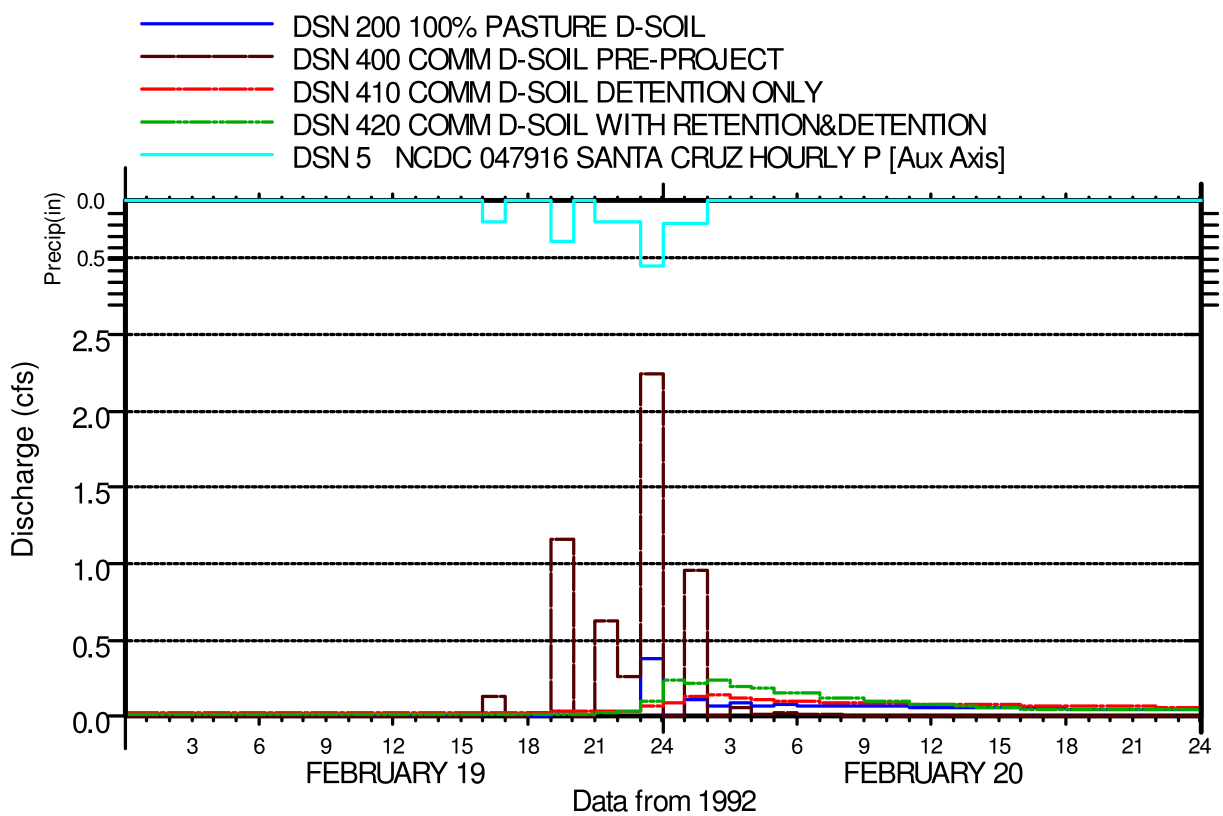


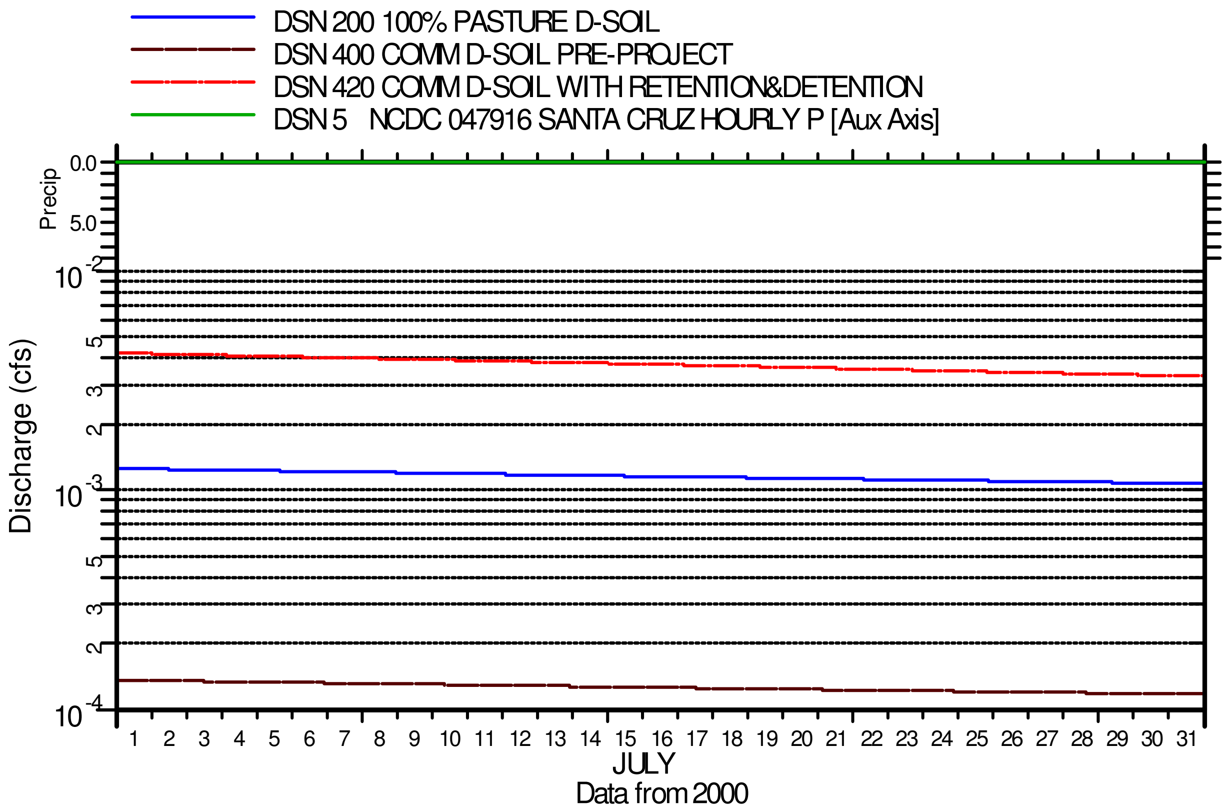
DSN 200 100% PASTURE D-SOIL
DSN 400 COMM D-SOIL PRE-PROJECT
DSN 410 COMM D-SOIL DETENTION ONLY
DSN 420 COMM D-SOIL WITH RETENTION&DETENTION
DSN 5 NCDC 047916 SANTA CRUZ HOURLY P [Aux Axis]
Precip(in)
0.0
5.0
Discharge (cfs)
10.
8.
6.
4.
2.
0.
3 6 9 12 15 18 21 24 3 6 9 12 15 18 21 24
JANUARY 4
JANUARY 5
Data from 1982

DSN 200 100% PASTURE D-SOIL
DSN 400 COMM D-SOIL PRE-PROJECT
DSN 410 COMM D-SOIL DETENTION ONLY
DSN 420 COMM D-SOIL WITH RETENTION&DETENTION
DSN 5 NCDC 047916 SANTA CRUZ HOURLY P [Aux Axis]
Precip(in)
0.0
1.0
Discharge (cfs)
8.
6.
4.
2.
0.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
DECEMBER 21
Data from 1970


DSN 200 100% PASTURE D-SOIL
DSN 400 COMM D-SOIL PRE-PROJECT
DSN 410 COMM D-SOIL DETENTION ONLY
DSN 420 COMM D-SOIL WITH RETENTION&DETENTION
DSN 5 NCDC 047916 SANTA CRUZ HOURLY P [Aux Axis]
Precip(in)
0.0
1.0
Discharge (cfs)
5.
4.
3.
2.
1.
0.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
FEBRUARY 14
Data from 1973


DSN 200 100% PASTURE D-SOIL
DSN 400 COMM D-SOIL PRE-PROJECT
DSN 410 COMM D-SOIL DETENTION ONLY
DSN 420 COMM D-SOIL WITH RETENTION&DETENTION
DSN 5 NCDC 047916 SANTA CRUZ HOURLY P [Aux Axis]
Precip(in)
0.0
0.5
Discharge (cfs)
2.5
2.0
1.5
1.0
0.5
0.0
3 6 9 12 15 18 21 24 3 6 9 12 15 18 21 24
FEBRUARY 19
FEBRUARY 20
Data from 1992




The base flow results for very dry summer conditions for the Commercial D-soil are similar to results for the Commercial C-Soil case. The developed site without on-site retention (brown line) is roughly four times lower than the pre-developed, 100% pasture condition (blue line) while the developed project with bioretention (red line) maintains base flows above the pre-developed level.

**Summary of Results**

**Peak Flows**

<u>Unmitigated Cases</u>

For unmitigated development (no retention or detention facilities), factors of increase in peak flow above the baseline of 100% pasture ranged from about 3 to 19 times. These factors were computed by averaging quantile values for 2-, 5-, 10-, 25-, 50- and 100-yr peak annual flows and taking the ratio of each unmitigated value to baseline value for 100% pasture.

As shown in Table 7, factors of increase in peak flows were greater on the C-soil which exhibits very little surface runoff under pasture conditions. In contrast D-soils are more prone to surface runoff, therefore ratios of increase are less pronounced but still very significant. Differences in the peak flow ratios between residential and commercial for a given soil, are not as great as the differences between the two soils for the same development scenario.

| Table 7. Average Factor of Increase in 100% Pasture Peak Annual Flows with No Retention or Detention | | |
|---|---|---|
| | C-Soil | D-Soil |
| SFR Development | 11.3 | 2.8 |
| Commercial Development | 18.6 | 3.3 |

Mitigated and Partially Mitigated Cases

For all scenarios that included a detention facility, peak annual flow frequency quantiles were match to the 100% pasture conditions quantiles over the range of 2-yr to 100-yr peaks. The only difference in these scenarios was in the total amount of retention and detention storage required to match the pasture condition frequency curve. A summary of the required storage amounts is shown in Table 8.

| Table 8. Total Volume of Facilities Required to Match 100% Pasture Condition Peak Annual Flow Quantiles | | |
|---|---|---|
| | Total Storage Required* C-Soil (ac-ft) | Total Storage Required* D-Soil (ac-ft) |
| Residential with Retention & Detention | 1.06 | 0.94 |
| Commercial with Detention Only | 1.66 | 0.75 |
| Commercial with Retention & Detention | 1.54 | 1.51 |

*Detention volume plus any additional volume from bioretention

The total active storage volume within both retention and detention facilities is similar for C- and D-Soil cases in both the development scenarios. This is a result of the higher volume required for retention facilities on D-soils than on C-soils. As evidenced by the commercial case in which only detention is applied with no retention, if matching peak flows to pre-developed, pasture conditions is the only concern, it requires less detention storage on a D-soil than on a C-soil because the baseline or target condition on a lower infiltration soil is hydrologically closer to the developed condition. In the case of retention sizing, the standard requiring prevention of runoff from 95% non-exceedance, 24 hour rainfall does not account for differences in pre-developed runoff frequency that might be expected from soils with different infiltration characteristics.

**High Flow Durations**

The flow duration performance of the fully mitigated and partially mitigated simulation is characterized by an average reduction in high flow durations at four pasture condition peak flow quantile values, 50% of the 2-yr, 2-yr, 5-yr and 10-yr. For each of these flow levels a percent reduction was calculate as follows:

$$(T_u - T_i) / (T_u - T_p) \times 100\%$$

in which T is the flow duration, and the subscripts u, i, and p correspond to unmitigated, the current simulation case being evaluated, and pasture respectively. This calculation is made for each of the four quantiles and resulting percentages were averaged to represent the approximate duration mitigation performance of the simulation case over the range of flows listed above. Results this calculation for the six cases with different combinations of soil and facilities are shown in Table 9.

**Table 9. Average Percentage Reduction in High Flow Durations from 50% of the 2-yr to the 10-yr Peak Annual**

| Development Scenario | C-Soil | D-Soil |
|---|---|---|
| Residential with Retention & Detention | 92% | 91% |
| Commercial with Detention Only | 9% | 96% |
| Commercial with Retention & Detention | 71% | 96% |

For the lower infiltration D-soil, high flow durations are suppressed to the same degree by detention alone or in combination with retention for both the residential and commercial scenarios.

In contrast, for the Commercial scenario on a C-Soil with no retention, there is a large drop in performance to 9% compared to the same land use-soil combination that includes retention (71%). The relatively poor performance of the detention-only case is caused solely by extremely poor performance at the extreme low end of the range (i.e. -700% at half the 2-yr level). For flows ranging from the 2-yr the 10-yr, performance is consistently above 90%. If the lower limit of the threshold of concern were raise to the 2-yr peak flow, there would be minimal difference between the C-Soil and D-Soil performance under either development scenario.

Results of the commercial simulations and analysis suggest that on-site retention facilities are not necessarily superior to detention facilities in controlling high flow durations on tight (D) soils; however, on C soils the additional infiltration greatly assists in lower durations of flows smaller than the 2-yr peak annual flow.

### Reduction and Treatment of Surface Runoff Volume

Surface runoff entering on-site retention facilities from developed impervious surfaces infiltrates and on occasion overflows and runs off the site during larger storms and wetter seasons. Under the retention standard and sizing approach discussed earlier, model simulations indicate that between 70% and 81% of surface runoff is infiltrated for all cases where retention is applied. Table 10, below, provides a summary of these results for the two different development scenarios and soil types. The relatively consistent performance of retention facilities constructed on high infiltration and low infiltration soils is made possible by the additional storage volume specified for D-soil facilities which compensates for their slower infiltration rate.

| Table 10. Average Percentage of Surface Runoff Infiltrated and Treated by On-site Retention Facilities | | |
|---|---|---|
| Scenario | C-Soil | D-Soil |
| Residential with Bioretention | 81% | 69% |
| Commercial with Porous Pavement and Bioretention | 76% | 70% |

### Base Flows

Under dry, summer conditions exemplified by project outflow hydrographs during July, 2000, base flows are depleted by factors ranging from 2 to 7 if no on-site retention is provided. The depletion factor is directly related to the intensity of development as indicated by the percentage of impervious surface. However, with on-site retention facilities, base flows are actually augmented over the baseline case with 100% pasture condition for both development and soil scenarios. This "over mitigation" may be restorative to varying degrees in stream basins where summer base flows may have been depleted by previous development that did not implement on-site retention.

### References

EPA Office of Water, 2009. Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the Energy Independence and Security Act, EPA 841-B-09-001, (http://www.epa.gov/owow/NPS/lid/section438/), 60 pp.