Regional Detention Feasibility Study for City of College Station

January 4, 2013

Prepared by:

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Home of Texas A&M University®

Watearth™
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January 4, 2013

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Job No. 2010-CS-01

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Re: Regional Detention Feasibility Study

Dear Carol:

I've enjoyed collaborating with you and the City on this project. It represents an important direction in 21st century stormwater management within the City's jurisdiction. The following document is a letter report outlining the results of this study. The highlights of the executive summary are:

- Capital regional detention projects offer multiple benefits for the City that are outlined in this report (in many cases flood control is not the primary benefit);
- Private regional detention projects are feasible in portions of watersheds outlined in this report;
- Incorporation of water quality features into stormwater management facilities is key to meet future permit requirements;
- Green infrastructure and Low Impact Development (LID) helps the City meet multiple stormwater management objectives.

While results of this feasibility study indicate that regional detention offers benefits for the City of College Station, the greatest impact for Capital projects may be achieved from multi-functional facilities that also offer amenities, such as parks, recreational features, trails, water quality components, wetlands mitigation banking, and other items. Even though structural flooding occurred during recent intense rainfall in February, 2012, structural flooding has not historically been a significant issue. As such, the use of multi-functional facilities provides a range of additional opportunities while improving flood control within City watersheds.

Maintenance of detention facilities is a critical element and associated erosion and sedimentation may contribute to water quality issues in receiving streams, which is especially problematic as the City is subjected to stronger stormwater quality requirements as part of future National Pollutant Elimination Discharge System (NPDES) permit revisions. Centralizing detention into regional or sub-regional facilities, where appropriate, may reduce the overall maintenance burden and improve the efficiency of operations and water quality performance.

While consolidation of detention maintenance operations is a key component of regional detention facilities, regional stormwater management sites also offer the City potential for wetlands mitigation banking; future water quality credits; developer credits with an associated development impact fee for flood control, water quality, and wetlands mitigation; and other recreational amenities. Although centralized detention facilities may increase the efficiency and effectiveness of flood control system, adequate conveyance paths and/or on-site controls for smaller rainfall events are also important complementary stormwater management components.

Even though Capital regional detention projects may enhance development or redevelopment within specific portions of the City, potential also exists for regional or sub-regional detention facilities constructed by developer partnerships to provide effective mitigation for several adjacent developments.

Results of this study indicate several of the potential sites investigated are feasible for providing effective regional stormwater detention. The table below lists potential site locations and priorities along with additional information on suggested multi-functional and stormwater quality components at each site. This table also includes sites with potential that were not analyzed, which are indicated by gray shading within the applicable table row. A full listing of sites evaluated for this study is listed in Appendix D.

The primary distinction between private and Capital projects with regards to the regional detention facilities is that private facilities mitigate new development projects, whereas Capital projects may address flood control, wetlands banking, water quality, or recreational goals. Additionally, if a project is appropriate on City land it could be developed as a Capital project and capacity sold to developers to off-site development nearby in the watershed.

Note that capacity sold to developers applies primarily to flood control benefits rather than water quality, unless water quality features are constructed within the regional detention facility. Development may also require on-site BMPs due to future MS4 permit regulations. Unless on-site LID features are constructed, the storm sewer infrastructure would not typically be reduced. Additionally, off-site facilities may also be required to convey flows to the regional detention facility depending on location.

Site	Watershed	Implementation Priority	Project Type	Primary Site Benefits	Secondary Site Benefits
A-1/2	Alum Creek	Medium	Private	Flood control	Parks
B-5	Bee Creek	High	Private	Flood control	Parks and Trails
BTC-1/2	Burton Creek Trib. 1	Low	Capital	Flood control for redevelopment	Parks and Trails
C-8/9	Carters Creek	Medium	Capital	Wetlands mitigation banking and water quality	Parks
L-4	Lick Creek	High	Capital	Flood control, Wetlands mitigation banking, water quality, parks, trails	Regional detention capacity to market to private development
---	Peach Creek	Low	Private	Flood control	Parks
S-6	Spring Creek	Medium	Private	Flood control	Parks and Trails
WP-Parks	Wolf Pen Creek	High	Capital	Water Quality (Rain Garden) Retro-fits at Parks	Parks

The following projects represent a potential starting point for a regional stormwater management program for the City:

1. From a combination of wetlands/flood control, the Lick Creek site (L-4) is multi-functional and provides significant benefits. This project may be constructed as a City project or as a regional facility for private projects. Given the wetlands component, it may be beneficial for the City from a wetlands-banking perspective.

2. Wolf Pen Creek rain garden/water quality retro-fits as a demonstration of water quality and start towards MS4 permit compliance at a relatively low cost. This project primarily serves as a retro-fit rather than mitigation of new City or private projects.

3. Site B-5 in the Bee Creek watershed performs well for peak flow reduction; however, additional land could enhance the performance to achieve desired water surface elevation reductions. This project may be constructed as a City project or as a regional facility for private projects.

The following sites rank highly for wetlands mitigation and wetlands banking potential:

- Carters Creek – C-8/9
- Lick Creek – L-4
- Lick Creek – Regional Park
- Bee Creek - B-4
- Spring Creek – S-1

In planning for regional wetlands, the Harris County Flood Control District's *Water Quality Planning Tool* document identifies regional wetlands as being ideally suited for the following areas of watersheds:

1. undeveloped or low density areas (due to large area requirements);
2. areas with longer time of concentrations (typically undeveloped or low density areas/watersheds);
3. upper third of the watershed top priority, middle third is middle priority, and lower third is lowest priority (similar to locating regional detention facilities).

In addition to these regional detention projects, additional stormwater management improvements are beneficial to reduce sediment and bacteria loads to streams and improve water quality as well as to reducing stream erosion. The following enhance stormwater quality, improve aesthetics, increase habitat, and reduce maintenance requirements:

1. Retro-fit detention basins with additional outfall restrictors to reduce peak flows in smaller rainfall events and reduce in-stream erosion.

2. Retro-fit existing detention basins with water quality improvements, such as: native grasses/vegetation, conversion to wet bottom facilities, and construction of rain gardens and/or bioretention in shallow facilities. Detention basins of particular concern are those with heavy sediment and/or bacteria loads from the contributing area or with grazing livestock and/or dog parks located within the facility.

3. Incorporate water quality elements into new regional and on-site detention basins.

4. Develop demonstration or pilot projects within City parks or regional detention facilities that include Low Impact Development (LID) facilities, such as: bioretention, vegetated buffers, and vegetated filter strips to provide water quality treatment for mitigation of total suspended solids (TSS), bacteria, and other pollutants of concern.

5. Include green streets in conjunction with planned Capital projects. Green streets typically utilize bioretention, vegetated swales, or other techniques to manage stormwater runoff within the landscape elements and improve water quality. These techniques may also result in cost savings due to reduced infrastructure (pavement/storm sewer) costs.

This document includes the following segments:

- **OVERVIEW**
- **DATA REVIEW**
- **REGIONAL DETENTION FEASIBILITY**
- **STORMWATER QUALITY AND MULTI-USE FACILITIES**
- **RECOMMENDATIONS**

APPENDICES

Appendix A – Watersheds Considered for Regional Detention
Appendix B – Potential Regional Detention Sites
Appendix C – Figures of Potential Regional Detention Sites
Appendix D – Regional Detention Site Ranking Table
Appendix E – Routed Hydrographs for Analyzed Sites
Appendix F – HEC-HMS Models




INTRODUCTION

This letter report documents the results of the regional detention feasibility study performed for the City of College Station. While detention is required to mitigate peak flow impacts associated with development, most developments provide on-site detention without addressing the watershed impacts of development. This regional detention feasibility study was initiated by the City to assess the feasibility of implementing a regional approach to detention that emphasizes multi-functional benefits and improves the overall system performance and efficiency.

Regional detention facilities typically provide storage mitigation for multiple projects and/or developments and are the focus of this study. Other types of shared detention include sub-regional detention that may be utilized by multiple phases of a single development. For this study, the focus is on regional detention facilities to mitigate existing stormwater issues within City watersheds and provide storage for multiple projects.

The purpose of this phase of work is to determine the feasibility of regional detention for the City of College Station and identify targeted sites for moving forward into a regional detention program. The following watersheds within City limits were evaluated as part of this assessment:

- Alum Creek
- Bee Creek
- Burton Creek Tributary C (Burton Creek main stem and other significant tributaries are outside City limits)
- Carters Creek
- Lick Creek
- Spring Creek
- Whites Creek (outside of Texas A&M University lands)
- Wolf Pen Creek

Because models were not available on Peach Creek, recommendations for this watershed were based on typical watershed performance and land use patterns within the watershed. Foxfire Creek was not included based on direction from City staff. For other streams or stream segments where hydrologic models were not available, recommendations were also based on typical watershed performance and land use within the watershed.

Based on the results of this study, regional detention is feasible at various locations within the City's watersheds, with a focus on multi-functional facilities for improved benefit to the City's taxpayers and residents. This document identifies several potential regional stormwater management sites. Several recommendations are provided to guide the future direction and growth of the City's stormwater management program to solve existing challenges, create multi-functional stormwater facilities, and meet anticipated regulatory requirements.

Future efforts are recommended as new and updated hydrologic models become available for City watersheds. Due to the feasibility nature of this phase of work, detailed modeling and analysis will be performed in a future phase of work for those recommended potential regional detention sites that the City elects to pursue.

DATA REVIEW

Existing Drainage Criteria

Existing drainage criteria used within the City of College Station primarily consists of the October, 2012 version of the *Unified Stormwater Design Guidelines*, which were developed and implemented jointly with the City of Bryan. Note that the 2009 version was in effect for the technical portion of this project. Based on this set of criteria, detention may be required for projects within the City watersheds for the following purposes:

- Type 1 Detention (Flood Control)
- Type 2 Detention (Conveyance Management)
- Type 3 Detention (Dual Purpose)

Type 1 (Flood Control Detention) is intended to mitigate runoff from a project that is likely to increase peak flows and flooding potential within the receiving stream and may not be required depending on the development location. Type 2 (Conveyance Management Detention) is intended to manage runoff that must drain through adjacent properties prior to discharging into the receiving stream. Type 3 (Dual Purpose Detention) refers to detention facilities required for both flood control and conveyance management perspective.

In locations where detention is required, peak flow rates must be maintained at or below pre-development conditions for the following design storm events: two-year (50%), ten-year (10%), twenty-five-year (4%), and 100-year (1%). To maintain consistency with these requirements criteria, future detailed regional detention analyses will include all of these design storm events. For this study, the 1% event was used solely to assess potential mitigation associated with various locations within City watersheds.

In addition, Chapter 13 of City code related to Flood Hazard Protection was recently updated to incorporate a No Adverse Impacts policy for flood plain management. As such, adverse impacts due to encroachment and development within the regulatory 1% flood plain or Special Flood Hazard Area must be avoided or mitigated. Chapter 13 defines adverse impacts as any of the following upstream, within, near, adjacent to, or downstream of such encroachment: increases in base flood elevations (BFEs), loss of conveyance, loss of flood plain storage, creating additional flood plain areas, and increased velocities during the Base Flood.

This study is not intended to revise the City's No Adverse Impacts policy related to flood plain management and implementation of a regional detention program does not eliminate the need to mitigate conveyance and flood plain storage losses due to fill in the flood plain. In general regional detention facilities are not the best choice for flood plain fill mitigation due to the relative distance from the project under development. Typically, loss of conveyance requires mitigation along the site being filled whereas loss of storage requires mitigation within the site or nearby in the stream routing reach.

The regional detention approach investigated in this feasibility study maintains consistency with Chapter 13 requirements for No Adverse Impacts. Future phases of work must address the overall service area of each regional detention facility, potential for impacts and mitigation between the discharge location and the regional detention facility, and appropriateness of mitigating flood plain fill impacts within the regional detention facility.

GIS Data

The following geographical information systems (GIS) hydrologic and hydraulic data provided by City staff was evaluated for this assessment:

- Topography
- Aerials
- Flood Plains
- Watershed Boundaries
- Soils
- Public Park Lands
- City-Owned Land
- Existing and Future Land Use Data
- Areas of Known Future Development
- Areas with Issues and Potential Regional Detention Locations Identified by City Staff

Existing and future land use data and watershed boundaries were reviewed to identify areas of watersheds with large, consolidated areas available to be developed or likely to have a change in land use. These items are addressed under the Regional Detention Feasibility section below.

Hydrologic and Hydraulic Models

Effective hydrologic and hydraulic models for major streams and tributaries within the City were acquired from the Federal Emergency Management Agency (FEMA) by the City and provided for this project. The hydrologic models included both HEC-HMS and HEC-1 programs, while the hydraulic models included HEC-2 and HEC-RAS.

Because of the conceptual nature of this study, overall effective models were used even in locations where updated models are available for a small stream segment. However, consideration of the most recent models is an important component of future detailed analysis and design projects.

Details on hydrologic and hydraulic characteristics of various watersheds within the City identified from evaluation of these models as well as the actual models used are included in the *Watershed Timing Assessment* report prepared by Watearth, Inc. Key hydrographs, hydrologic data, and hydraulic data are summarized in that report as well.

REGIONAL DETENTION FEASIBILITY

Goal of Regional Detention

Based on input from City staff, there is not currently a significant need to provide flood damage reduction as structural flooding has not historically been a major issue. Therefore, the primary goal of regional detention is to consolidate detention operations and provide multiple cost-effective benefits within regional flood control facilities. As such, the City is interested in the following multi-functional benefits, which are listed roughly in order of priority:

a. Stormwater quality benefits (TMDL limits for bacteria anticipated for Burton Creek and Carters Creek)
b. Detention mitigation for City projects
c. Detention mitigation for private development projects
d. Consolidating and reducing operation and maintenance requirements
e. Preservation of green/open space
f. Wetlands mitigation facilities and banking
g. Recreational benefits
h. Infiltration within regional detention facilities to address additional runoff volume associated with development

While selling excess storage capacity to mitigate private projects may be beneficial for the community, using regional detention capacity solely to mitigate City projects is also an acceptable approach.

Another important consideration is retro-fits to existing detention basins to reduce maintenance, improve stormwater quality performance, and to modify outlet structures to more effectively mitigate a range of rainfall events. These types of hydromodifications address frequent rainfall events (i.e., 50% event or two-year event and more frequent events) and associated stream erosion when discharge is not limited.

Targeted Watersheds for Regional Detention

Eight watersheds were initially selected to consider for regional detention based on critical hydraulic issues, potential for efficient mitigation within available sites, the goal of regional detention as a multi-functional tool, available City land or other targeted sites in mid-to upper portions of the watershed, available hydrologic and hydraulic models for the watershed, and input from City staff. In addition, existing and future land use data and watershed boundaries were reviewed to identify areas of watersheds with large, consolidated areas available to be developed or likely to have a change in land use as the region develops.

The eight watersheds for consideration include those listed below and additional notes are provided in Appendix A:

- Alum Creek*
- Bee Creek*
- Burton Creek Trib. C
- Carters Creek*
- Lick Creek*
- Peach Creek
- Spring Creek*
- Wolf Pen Creek*

Watersheds with an asterisk were considered for conceptual modeling in this feasibility assessment based on the availability of existing hydrologic models.

Potential Regional Detention Sites

From the seven watersheds under consideration, potential regional detention sites were identified based on the following:

- potential for effective detention and flood control mitigation
- location of existing City-owned property or park land
- input from City staff on areas with issues, etc.
- potential changes in land use in the watershed

- potential for multi-functional use
- non-developable flood plain land
- potential available storage volume

Potential regional detention sites are listed in tabular format in Appendix B and illustrated graphically in Appendix C. Potential sites were not identified for Peach Creek because neither hydraulic nor hydrologic models were available for the watershed.

Site reconnaissance was performed for the potential regional detention sites identified above as well as other portions of the targeted watersheds. The land use of the site and surrounding vicinity was observed as well as general hydrologic and hydraulic characteristics of the vicinity surrounding each site. The hydraulic characteristics of the proposed diverting/receiving stream were also assessed in the vicinity of the site.

After site reconnaissance, the initial group of potential regional detention sites was reduced to five for further evaluation from a flood control perspective (Table 1). Appendix D includes a site ranking matrix developed in collaboration with City Engineering and other departmental staff. To support site selection, weighting was assigned to various parameters included in the site ranking table. While the potential regional detention sites selected for conceptual analysis were not selected solely based on the highest weights, all analyzed sites had weighted values of 40 or higher. City staff provided final input on the sites for analysis based on land availability or potential for land acquisition in the vicinity.

TABLE 1: REGIONAL DETENTION SITES IDENTIFIED FOR CONCEPTUAL TESTING IN HYDROLOGIC MODEL

Site	Watershed	Primary Site Benefits
A-1/2	Alum Creek	flood control for private projects
B-5	Bee Creek	flood control for private projects, parks, trails
C-8/9	Carters Creek	wetlands mitigation banking, water quality, parks
L-4	Lick Creek	flood control, wetlands mitigation, water quality, parks, trails
S-6	Spring Creek	flood control for private projects, parks, trails

The following sites rank highly (3) for wetlands mitigation and wetlands banking potential:

- Carters Creek – C-8/9 (40 total ranking score)
- Lick Creek – L-4 (47.5 total ranking score)
- Lick Creek – Regional Park (42 total ranking score)
- Bee Creek - B-4 (29 total ranking score)
- Spring Creek – S-1 (29 total ranking score)

Evaluation of Selected Sites

Because this phase of work is performed as a feasibility study, evaluation of the five selected sites for further investigation was performed at the planning-level. Each of these five facilities was evaluated in a similar manner to yield consistency of results. Should the City elect to move forward with detailed analysis and design, then individual sites may require differing detailed analyses.

The following assumptions were used in the conceptual detention evaluations:

- Existing hydrologic models provided by City used as a base condition;
- Hydrologic detention routing for 1% event performed in HEC-HMS v. 3.5;
- Detention basins modeled with side-weir diversions into the basin (side weir configurations varied to optimize peak flow reductions);
- No tailwater conditions for this conceptual, volume-based approach;
- Surface areas of 11 acres (ac) and bottom areas of 10.2 ac used for all sites for consistency, based on potential land area available for Site B-5;
- Average depth of approximately four feet from basin bottoms to top of bank used for all sites for consistency in evaluation.

Routed outflow hydrographs for the five sites are included in Appendix E and Table 2 lists potential peak flow reductions downstream of each site. Appendix E also contains prints of HEC-HMS model layout to tie locations in graphs to locations in the watershed. While similar 1% peak flow reductions were found in B-5 and C-8/9, the percent reduction varied considerably due to the differences in overall watershed size of Bee Creek and Carters Creek, respectively.

Results generally indicate that site B-5 functions well for potential of mitigation of private development projects. Site A-1/2 yields positive results on downstream peak flows within Alum Creek. Although benefits from A-1/2 diminish downstream on Lick Creek, this site has potential for mitigation private development projects. Site C-8/9 may work especially well for wetlands mitigation and/or water quality features with parks amenities, whereas to achieve a flood control benefit, significant volume and land area would be required. While site L-4 may have significant flood control benefit, this site is also exceptionally well-suited for wetlands mitigation, water quality features, and recreational (trails and parks) amenities. Even though site S-6 is not yielding significant reductions in peak flows in Spring Creek, it may yield positive results for surrounding development discharging through a centralized regional detention facility that also includes parks and trails amenities.

Note that sites in a similar location within each watershed are anticipated to produce similar results and benefits to those analyzed in this study. For example, L-5 (not analyzed) or other adjacent sites may function similarly to the L-4 site located in the Lick Creek watershed and evaluated in this feasibility study. Note that increased performance is expected if additional land is available and used for these regional detention sites.

TABLE 2: 1% PEAK FLOW REDUCTIONS FOR REGIONAL DETENTION SITES

Site	Watershed	HEC-HMS Node Identifier		Existing 1% Peak Flows (cfs)		Proposed 1% Peak Flows (cfs)		Change in 1% Peak Flows (cfs)		% Change in 1% Peak Flows (cfs)	
		Near Outfall	Downstream	Near Outfall	Downstream	Near Outfall	Downstream	Near Outfall	Downstream	Near Outfall	Downstream
A-1/2	Alum Creek	+ALUM	+LM5	3,720	13,073	3,399	12,836	-321	-237	-8.6%	-1.8%
B-5	Bee Creek	Split	Outlet	1,482	1,791	1,255	1,547	-227	-244	-15.3%	-13.6%
C-8/9	Carters Creek	420D	470/OUT	21,622	22,288	21,371	22,219	-251	-69	-1.2%	-0.3%
L-4	Lick Creek	+N@CONF	+LM5	2,319	13,073	1,356	12,186	-963	-887	-41.5%	-6.8%
S-6	Spring Creek	J2	J8	2,229	2,711	2,126	2,626	-103	-85	-4.6%	-3.1%

While the results of this conceptual analysis provide useful information in moving forward with potential regional sites, additional detailed analysis is needed in a future phase of work and results are subject to change. For example, the effectiveness of those sites located within the flood plain or floodway may be less than shown in this planning-level analysis. The models used for these conceptual analyses are included in the CD attached as Appendix F. Note that Alum Creek falls within the Lick Creek watershed.

Detailed Analysis of Regional Detention Sites

The goal of this regional detention feasibility study was to select regional detention sites for further consideration in the next phase of this project. Because the current phase was conceptual in nature, a more detailed and comprehensive analysis is needed prior to constructing selected regional detention facilities. We recommend that the detailed analysis be performed within HEC-RAS unsteady flow for those watersheds with available hydraulic models to accurately account for detailed diversions through side-weir structures into and out of regional detention facilities. Where hydraulic models are not available, the regional detention analyses may be performed in HEC-HMS.

While only the 1% event was considered in this feasibility study, the next phase of work is anticipated to analyze effects and customize the outfall structure configuration for a range of events specified in the *Unified Design Criteria*, including the 50%, 10%, 4%, 2%, and 1% events. The detailed analysis will also include detailed grading of the regional detention facilities and consideration of sedimentation and freeboard requirements specified in the *Unified Design Criteria*. For wetland-bottom facilities, micro-grading of the wetlands portions will also be performed. In addition, the next phase of work will determine the level of effect for flood control for City and/or private projects.

In addition, a downstream impacts assessment is recommended to assess the watershed impacts on the stream(s) served by the regional detention facility. The downstream impacts assessment should be carried to the mouth of the stream(s) being served by the regional detention facility. This analysis should be performed in the existing hydrologic model for the watershed (i.e., HEC-HMS) unless special conditions warrant a more detailed approach within a dynamic hydraulic model. The Simplified Downstream Impacts Analysis described in the *Watershed Timing Assessment* report prepared by Watearth, Inc. is not adequate for regional detention facilities.

We recommend that items such as funding of facilities, phasing of construction, impact fees for private developments, and maintenance considerations be included as important components of the detailed analysis. Prior to construction or land acquisition (if any), environmental assessments, wetlands delineations, geotechnical investigations, and topographic survey data is needed. We also recommend that consideration of water quality benefits or stormwater wetlands be evaluated for use as general improvement of water quality within the watershed or as mitigation banks for upcoming City or private developments.

Additional continuous simulation or water balance modeling may be needed for wetland-bottom or stormwater wetlands facilities to determine functionality during a historical period of record on average, wet (75%) and dry (25%) rainfall years. This type of modeling may be performed within HEC-HMS or within a continuous simulation dynamic hydraulic routing program, such as XP-SWMM or PC-SWMM.

STORMWATER QUALITY AND MULTI-USE FACILITIES

Based on local hydrologic/hydraulic conditions and anticipated bacteria and/or Total Suspended Solids (TSS) Total Maximum Daily Load (TMDL) requirements, stormwater quality and multi-use features were identified for possible use within regional detention facilities in the City of College Station and are listed below. Specific recommendations on feasible stormwater quality or multi-functional use for each potential regional detention site are included in the recommendations section.

Water Quality and Stormwater Features

- Wet ponds (i.e., retention water quality features), see Figures 1 and 2;
- Wetland-bottom ponds (i.e., wetlands combined with wet ponds), see Figure 3;
- Wetlands (i.e., stormwater treatment wetlands, wetlands mitigation facilities, and possibly wetlands banking), see Figure 4;
- Stormwater Treatment Train (i.e., multiple interconnected wet ponds, wetland areas in series, or other stormwater BMPs in series);
- Native vegetation/grasses to improve stormwater quality and reduce maintenance requirements (Figure 5) ;
- Infiltration enhancements to address additional runoff volume associated with development;

- Low Impact Development (LID) features within regional detention sites (i.e., bioretention, rain gardens, vegetated filter strips, vegetated swales, etc.) to enhance stormwater quality and reduce runoff volume (Figure 6 illustrates a commercial example of bioretention);
- Vegetated buffers (stream buffers) to meet anticipated riparian regulations and improve stormwater quality (i.e., reduced erosion and sedimentation), see Figure 7.

Figure 1 illustrates a wet pond in Mason Park that drains through two treatment wetlands using the stormwater treatment train approach concept before discharging into Brays Bayou just upstream of the Houston Ship Channel. Wet ponds tend to perform significantly better than dry detention basins, especially with regards to sedimentation which is sometimes exacerbated with poorly constructed and/or maintained dry detention basins.

Figure 1: Wet Pond
Mason Park Near Brays Bayou, Houston

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The wet pond shown in Figure 2 is the downstream stormwater facility for a redeveloped residential community prior to discharge into the receiving stream. The development also utilizes many LID features, such as porous concrete, bioretention, and disconnected downspouts. The City of Seattle Public Utilities Department is a leader in LID and green infrastructure and has pioneered many programs to implement these features throughout the City's watersheds.

Figure 2: Wet Pond
High Point Development, Seattle

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The Harris County Flood Control District's (HCFCD's) training center includes many sustainable stormwater management features, including the wetland bottom pond illustrated in Figure 3. This technique combines elements of wet ponds with stormwater wetlands to receive additional water polishing benefits.

Figure 3: Wetland Bottom Pond
Harris County Flood Control District, Houston

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The stormwater wetlands in a St. Louis public park shown in Figure 4 are an example of an open-space amenity that provides excellent stormwater quality benefits as well as peak flow and volume reductions in smaller design storm events. Due to the amount of land typically required, stormwater wetlands are generally best-suited for non-urbanized areas and work well in climates with high annual rainfall amounts similar to College Station. They are especially well-suited for public parks and for developments with adequate space to construct the wetlands.

Figure 4: Stormwater Wetlands
St. Louis Public Park

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The native grasses planted in the residential detention basin shown below in Lenexa, Kansas (Kansas City metropolitan area) are ideal for reducing on-going mowing maintenance, improving stormwater quality, and providing more aesthetic features than dry detention basins.

Figure 5: Native Grasses in Detention Basin
Lenexa, Kansas (Home of Rain to Recreation Program)

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Bioretention is one of many LID techniques and is a frequently used tool to reduce drainage infrastructure and associated costs and improve stormwater quality from parking lots. The feature shown below is located at the redeveloped Northgate Mall shopping area in Seattle and is an outstanding example.

Figure 6: Commercial Parking Lot Application of Bioretention
Northgate Mall, Seattle

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Stream buffers are easy-to-implement in areas with undeveloped stream riparian areas to prevent erosion and sedimentation and improve water quality as well as reduce peak flows into receiving streams. The stream buffer in Figure 7 is adjacent to a drinking water reservoir in Washington State that serves the City of Seattle.

Figure 7: Vegetated Stream Buffer
Seattle, Washington

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Recreational Features

- Walking/jogging trails alongside detention facilities and possibly connected to other greenway trails (see Figure 8 for local example)
- Soccer or baseball fields in dry basin bottoms (see Figure 9 for local example)

The local example shown in Figure 8 illustrates a multi-functional stormwater management facility. It includes walking trails alongside a detention basin with trees as an amenity for shade and is planted with native vegetation and trees to reduce maintenance and improve stormwater quality.

Figure 8: Walking Trail Along Detention Basin Planted with Native Vegetation and Trees
Edelweiss Gardens, College Station

Figure 9 illustrates typical multi-use of a detention basin as a recreational feature (soccer field) during dry-weather conditions.

Figure 9: Soccer Field in Detention Basin
Edelweiss Gardens, College Station

RECOMMENDATIONS

We recommend the City implement the following items:

1. **Updated Watershed Studies:** Recommendations for updating watershed studies are included in the *Watershed Timing Assessment* report. Because of the conceptual nature of this study, further detailed analysis may be warranted as updated models become available.

2. **Regional Detention:** Implement regional detention to consolidate detention and maintenance operations and increase efficiency and effectiveness of flood control system. Regional detention facilities also offer opportunities for multi-functional facilities to provide recreational amenities and water quality features. These facilities can be used to mitigate developments requiring detention. Operation and maintenance costs may also be off-set with impact fees from developments not requiring detention that do not fully incorporate LID facilities. Major benefits of regional detention basins are improved effectiveness, reduced risk of downstream impacts, and consolidated maintenance operations that may result in cost savings.

3. **Recommended Regional Detention Sites:** Results of this study indicate several of the potential sites investigated are feasible for providing effective regional stormwater detention. Table 3 lists recommended site locations along with additional information on suggested multi-functional and stormwater quality components at each site. This table also includes sites with potential that were not selected for analysis. Those sites indicated by gray shading were not analyzed in models; however, ranked highly in the table included in Appendix D.

TABLE 3: RECOMMENDED REGIONAL DETENTION SITES

Site	Watershed	Implementation Priority	Project Type	Primary Site Benefits	Secondary Site Benefits
A-1/2	Alum Creek	Medium	Private	Flood control	Parks
B-5	Bee Creek	High	Private	Flood control	Parks and Trails
BTC-1/2	Burton Creek Trib. 1	Low	Capital	Flood control for redevelopment	Parks and Trails
C-8/9	Carters Creek	Medium	Capital	Wetlands mitigation banking and water quality	Parks

Site	Watershed	Implementation Priority	Project Type	Primary Site Benefits	Secondary Site Benefits
L-4	Lick Creek	High	Capital	Flood control, Wetlands mitigation banking, water quality, parks, trails	Regional detention capacity to market to private development
---	Peach Creek	Low	Private	Flood control	Parks
S-6	Spring Creek	Medium	Private	Flood control	Parks and Trails
WP-Parks	Wolf Pen Creek	High	Capital	Water Quality (Rain Garden) Retro-fits at Parks	Parks

The primary distinction between private and Capital projects with regards to the regional detention facilities is that private facilities mitigate new development projects, whereas Capital projects may address flood control, wetlands banking, water quality, or recreational goals. Additionally, if a project is appropriate on City land it could be developed as a Capital project and capacity sold to developers to off-site development nearby in the watershed.

Note that capacity sold to developers applies primarily to flood control benefits rather than water quality, unless water quality features are constructed within the regional detention facility. Development may also require on-site BMPs due to future MS4 permit regulations. Unless on-site LID features are constructed, the storm sewer infrastructure would not typically be reduced. Additionally, off-site facilities may also be required to convey flows to the regional detention facility depending on location.

The following projects represent a potential starting point for a regional stormwater management program for the City:

1. From a combination of wetlands/flood control, the Lick Creek site (L-4) is multi-functional and provides significant benefits. This project may be constructed as a City project or as a regional facility for private projects. Given the wetlands component, it may be beneficial for the City from a wetlands-banking perspective.

2. Wolf Pen Creek rain garden/water quality retro-fits as a demonstration of water quality and start towards MS4 permit compliance at a relatively low cost. This project primarily serves as a retro-fit rather than mitigation of new City or private projects.

3. Site B-5 in the Bee Creek watershed performs well for peak flow reduction; however, additional land could enhance the performance to achieve desired water surface elevation reductions. This project may be constructed as a City project or as a regional facility for private projects.

The following sites rank highly for wetlands mitigation and wetlands banking potential:

- Carters Creek – C-8/9
- Lick Creek – L-4
- Lick Creek – Regional Park
- Bee Creek - B-4
- Spring Creek – S-1

In planning for regional wetlands, the Harris County Flood Control District's *Water Quality Planning Tool* document identifies regional wetlands as being ideally suited for the following areas of watersheds:

1. undeveloped or low density areas (due to large area requirements);
2. areas with longer time of concentrations (typically undeveloped or low density areas/watersheds);
3. upper third of the watershed top priority, middle third is middle priority, and lower third is lowest priority (similar to locating regional detention facilities).

4. **Regional Detention Impact Fee:** In portions of watersheds served by regional detention facilities, we recommend implementation of an impact fee based on area of development or impervious area in lieu of on-site detention. We further recommend that items such as funding of facilities, land acquisition, phasing of construction, and maintenance considerations be included as important components of the detailed analysis. We also recommend that consideration of water quality benefits or stormwater wetlands for mitigation banking be considered in establishing impact fees. In general regional detention capacity should not be used to offset flood plain fill, unless approved by City staff.

5. **Detention Basin Retro-Fit and Hydromodification Program:** Because the outfall structures on the majority of the detention basins within the City that were built before the smaller design storm requirements went into effect may not have been adequately designed or constructed for smaller rainfall events, they are typically not effective during frequent rainfall events. In addition, dry detention basins typically perform poorly with regards to stormwater quality. In fact, many of the facilities within the City contribute sediment loads to receiving streams due to erosion within the basins. As such, we recommend the City consider a hydromodification plan to retro-fit outfall structures to mitigate smaller design storm events, such as the two-year event.

   In addition, it may be beneficial to perform a detailed analysis of a few existing detention facilities to determine the operation and mitigation during a range of design storm events using stage hydrographs where appropriate rather than fixed tailwater, which was likely

used for the original design of the facilities. Of further benefit is a watershed study of the combined operation of existing detention basins within the watershed, which may be performed in HEC-HMS or HEC-RAS unsteady flow. The results of such a study may warrant updates to the City's detention criteria to ensure future detention facilities operate effectively to mitigate impacts over range of events.

Watersheds, such as Bee Creek or Wolf Pen Creek are ideal candidates as HEC-HMS models are available for the watershed and there are currently a significant number of detention basins in operation due to the level of development within these watersheds. Carters Creek may also be an option; however, the level of effort may be greater as it is a larger watershed. Although Lick Creek and Spring Creek have a great deal of undeveloped areas, if multiple detention basins are currently in operation in these watersheds, they may also be possible candidates as comprehensive HEC-HMS models are available.

While analysis of specific basins with appropriate tailwater, unit hydrograph, and rainfall conditions is needed to accurately determine the effects of outlet modification, it is likely that modifications to the outlet structures will enhance mitigation during a range of rainfall events as well as public perception of the efficacy of the facilities.

6. **Retrofitting Existing Basins for Water Quality Improvements:** It may be beneficial for the City to retro-fit existing detention basins to enhance stormwater quality, improve aesthetics, increase habitat, and reduce maintenance requirements. Such retro-fits may include the following: native grasses/vegetation, conversion to wet bottom facilities, and construction of rain gardens and/or bioretention. Future efforts by the City may be warranted to develop a step-by-step guideline for use by City Maintenance staff, Homeowner's Associations, scouting groups, or volunteer groups.

7. **Low Impact Development (LID):** LID facilities, including bioretention, vegetated buffers, and vegetated filter strips provide water quality treatment for mitigation of TSS, bacteria, and other pollutants of concern. These facilities also reduce runoff volume, especially in frequent rainfall events that significantly impact water quality, erosion, and stream sedimentation. To enhance water quality performance of regional detention facilities and to promote these techniques, demonstration or pilot projects within regional detention sites, City land, and/or City parks is recommended.

8. **Green Streets:** To promote the use of green infrastructure and LID techniques for stormwater management and water quality, the City may consider constructing green streets in conjunction with planned Capital Improvements Project (CIP) projects. Green streets typically utilize bioretention (Figure 10), vegetated swales (Figure 11), or other LID techniques to manage stormwater runoff and may result in cost savings due to reduced infrastructure (pavement and storm sewer) costs.

Figure 10: Bioretention Along an Urban Roadway
(Near Portland State University, Portland, Oregon)

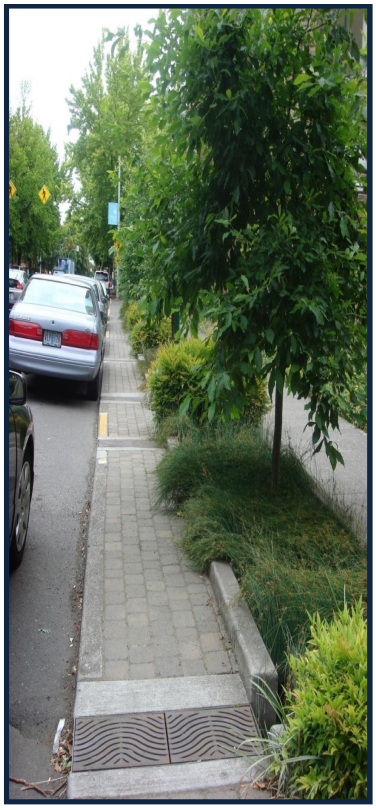


Figure 11: Vegetated Swale During Winter Months
(Seattle Green Streets)

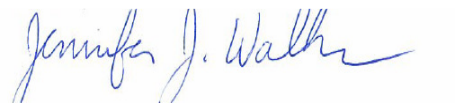
9. **Stormwater Quality Enhancements:** Incorporating native grasses and vegetation, wet bottom ponds, or wetlands vegetation may significantly improve the stormwater quality performance while reducing regular operation and maintenance of the facilities associated with on-going mowing programs. Such improvements also enhance aesthetics, recreational, and environmental benefits and convert single-purpose stormwater management facilities into multi-functional features for the community. Detention basins of particular concern are those with grazing livestock and dog park facilities, which may benefit from incorporated bioretention and/or wetlands to reduce bacteria loads into receiving streams.

10. **Detention Basin O&M:** Maintenance of detention facilities is often neglected and erosion and sedimentation may contribute to water quality issues in receiving streams. Operations and Maintenance (O&M) for dry detention basins is typically recommended to include regular mowing, inspection, and removal of trash and debris from outlet structures as well as periodic sediment removal. We recommend the City include an O&M plan and budget for life-cycle and O&M costs as part of future detailed regional detention analyses. The O&M plan and life-cycle costs should also address associated stormwater quality or green infrastructure features.

    Sediment removal is typically required in the first five to seven years for newly constructed detention facilities, especially if the contributing area has not been fully stabilized and in 20-year increments thereafter. This may be highly variable based on the actual sediment load and regular inspections by maintenance staff are recommended. While detention basin sediments are not typically classified as hazardous wastes, stormwater hotspots may require testing of sediments prior to landfill disposal. Sediment loads can be reduced through proper design and construction of detention facilities.

Please do not hesitate to call me at 832.444.0663 with any questions. We appreciate the opportunity to assist with this project to position the City to implement regional stormwater management solutions to solve current issues and meet future regulatory requirements.

Sincerely,



Jennifer J. Walker, PE, D.WRE, CFM
President
Watearth, Inc.

APPENDIX A – WATERSHEDS CONSIDERED FOR REGIONAL DETENTION

Appendix A: Watersheds Targeted for Regional Detention

TABLE A-1: WATERSHEDS CONSIDERED FOR REGIONAL DETENTION

Watershed	Consider?	Comments
Alum Creek*	Yes	Detailed model not available, but included in Lick Creek model, Significant areas undeveloped planned for development in future land use
Bee Creek*	Yes	Some undeveloped area adjacent to Bee Creek and tributary in middle portion of stream planned for development in future land use conditions, City-owned sites that might work well for regional mitigation
Burton Creek*	No	Mainly outside of City limits and significantly developed
Burton Creek Trib. C	Yes	No significant development planned, but City-owned site located in good proximity to planned redevelopment
Carters Creek*	Yes	Mostly developed within City limits, significant areas undeveloped planned for development in future land use outside City limits to east, one large City-owned site(s) identified in upper portion watershed that may provide excellent stormwater benefits even though sites draining directly to Carters Creek will not require detention per *Watershed Timing Assessment*
Foxfire Creek	No	No per City input and no models available
Lick Creek*	Yes	Significant areas undeveloped planned for development in future land use, multiple City-owned sites identified
Peach Creek	Yes	No models available, but recommend consider acquiring large tract in upper portion to mitigate future development
Spring Creek*	Yes	Significant areas undeveloped planned for development in future land use, City-owned sites identified in lower portions of watershed may not be as effective for detention
Whites Creek*	No	Primarily located in TAMU limits and no sites identified by City or as City-owned land
Wolf Pen Creek*	Yes	Minimal areas in downstream end currently undeveloped and planned for development in future land use, City-owned sites identified

Note: * indicates available hydrologic model.

APPENDIX B – POTENTIAL REGIONAL DETENTION SITES

APPENDIX B: POTENTIAL REGIONAL DETENTION SITES

TABLE B-1: POTENTIAL REGIONAL DETENTION SITES

Watershed	Location
Alum Creek	A-1 or A-2
Bee Creek	B-1/2 City-owned land, good location to mitigate future mid-watershed development
	B-3 City-owned land just d/s of TAMU, may work for downstream mitigation
	Just u/s of B-4 (no designation) – encourage private partnership?
	B-4 City-owned land (dog park in detention basin) in upper portion Trib. B-3/B.3.1 (may not have hydrology model for Trib. B or B-3). Current flooding in watershed near B-4 and upstream of TxDOT/railroad crossing – culvert may be undersized
	B-5 Cain Road area. Land just upstream of site B4. Ranch/non-ag.
	B-6/7 Ranch/non-ag. Land just upstream of SH 6 and near confluence with Trib. A (B7 was excavated to provide fill dirt for City Center project)
Burton Creek Trib. C	BTC-1 Hensel Park (Leased from Texas A&M) Between College & Texas Ave.
	BTC-2 Park Owned Near Northgate Redevelopment Area, which is zoned for dense urban land use, also ditch available, areas where existing apartments flooded
Carters Creek	C-8/9 (79.35 ac) South of Harvey, East of Earl Rudder, site is in flood plain, good location for trails and connectivity
Lick Creek	L-1 or L-2 City-owned land, upstream of Spring Creek confluence, between SH 6 & Rock Prairie Rd
	L-3 City-owned land at Graham Rd, near u/s end of Lick Creek
	L-4 City-owned land (Spring Creek Corporate Campus, Master Plan and Greenway Reserve), between Lick Creek and Spring Creek, d/s of SH 6, good location for cluster development or preservation of open space

APPENDIX B: POTENTIAL REGIONAL DETENTION SITES

Watershed	Location
	L-5 City-owned land (landfill, not available), between SH 6, Rock Prairie Rd, and William D. Fitch Pkwy.
	L-6 Non-ag land, d/s of William D. Fitch, between Rock Prairie Rd, Spring Creek, and Alum Creek
	L-7 Ranch/ag, adjacent to William D Fitch and Rock Prairie Rd
	L-8 Ranch/ag, just d/s SH 6
	L-9 Non-ag land, Trib. 13, u/s SH 6
	Regional park for wetlands and water quality
Spring Creek	S-1 (Existing Dry Detention Basin) TRY WATER QUALITY RETRO-FITS or S-2 (Part of Spring Creek Corporate Campus Master Plan); City-Owned south of SH 6
	S-3 Undeveloped between William D. Fitch, SC, and Trib 5, not City-Owned (Platted)
	S-4 Privately owned, ranch/non-ag land on Spring Creek (Preliminary Plat Submitted), no frontage
	S-5/6 Privately owned, ranch/non-ag land on Spring Creek, frontage William D. Fitch Pkwy (USACE permit for mitigation on S-6)
Wolf Pen Creek	WP-1/2 City-owned land (Existing park/sedimentation issues with stream/pond), downstream of confluence of Wolf Pen and Trib. A and u/s SH 6
	WP-3/4 City-owned land, near confluence of Wolf Pen and Trib. A, this area and many parks throughout watershed may work for rain garden or pocket wetland retro-fits
	WP-5 Upstream end of Trib. B, City-owned land

APPENDIX C – FIGURES OF POTENTIAL REGIONAL DETENTION SITES

The City of College Station

Potential Regional Detention Sites

Planning & Development Services

BTC-1
BTC-2
WP-5
WP-5
WP-3/4
WP-3/4
WP-1/2
C-8/9
B-1/2
B-7
B-7
B-1/2
B-3
B-6
B-4
B-5
L-1
L-5
L-7
L-8
L-4
L-6
L-3
L-9
L-9
S-1
S-4
S-6
S-6
S-5
S-3
A-1
A-2

W VILLA AV
UNIVERSITY DR E
WELLBORN RD
COLLEGE AV
COLLEGE MAIN ST
UNIVERSITY DR
LINCOLN AV
FRANCIS DR
MUNSON AV
DOMINIK DR
TEXAS AV
HARVEY RD
EARL RUDDER FWY S
APPOMATTOX DR
SH 30
F & B RD
RAYMOND STOTZER PW
GEORGE BUSH DR
DEXTER DR
ANDERSON ST
SOUTHWEST PW
GLADE ST
FAIRVIEW AV
HOLLEMAN DR
MARION PUGH DR
EMERALD PW
HARVEY MITCHELL PW S
LUTHER ST W
WEI SH AV
WESTRIDGE DR
RIO GRANDE BL
BROTHERS BL
PONDEROSA DR
LONGMIRE DR
WOODCREEK DR
SH 6 S
ROCK PRAIRIE RD
FM 2154
GRAHAM RD
VICTORIA AV
ALEXANDRIA AV
EAGLE AV
BARRON RD
CAPSTONE DR
GREENS PRAIRIE RD W
WILLIAM D FITCH PW
LAKEWAY DR
ROCK PRAIRIE RD
HOLLEMAN DR S
STASNEY ST
ORAN CR
GAYTHA CR
SPRUCE ST
CHERRY ST
TAUBER ST
NATALIE ST
BOYETT ST
COLLEGE MAIN ST
CROSS ST
FIRST ST
SECOND ST
LOUISE AV
WELLBORN RD

0 2,550 5,100 10,200 Feet

APPENDIX D – REGIONAL DETENTION SITE RANKING TABLE

APPENDIX D - REGIONAL DETENTION ANALYSIS STORMWATER MANAGENT SITE RANKING TABLE
Watearth, Inc.
6-Sep-11

		Weighted x 1	Weighted x 3			Weighted x 1									Weighted x 3	Not Used in Ranking	Weighted x 1	
Watershed	Site	Targeted Watershed	Flood Control Performance	Flood Control Volume	Water Quality (Wetlands, etc.)	Improved Performance Small Events	Encourage Redevelopment	Anticipated Dvlpt. in Watershed	Fix Exist. Problems	Hydrology Model Available	Trail Connectivity	Park Amenity	City Owned Land		Possible Construction Cost Range	Possible Total Cost Range	Total Score	Comments
	Ranking Criteria																	
	0	No	Poor Location	None/No Addtl.	None	None	No Anticipated Redev.	None	None	No	Poor	No Park Amenity	No		---	---	Sum of	
	1	---	Minimal	Minimal	Small	Small	Small	Minimal	Small	---	Moderate - No H&B Plan	Small/Poor Location	Leased		> $500,000	Highest	All	
	2	---	Moderate	Moderate	Yes - Not Focus	Yes - Not Focus	Moderate	Moderate	Moderate	---	Moderate - H&B Plan	Moderate	---		$100,000 - $500,000	Medium	Categories	
	3	Yes	Good	Large	Significant Focus	Significant Focus	Large	Significant	Significant	Yes	Good - H&B Plan	Large/Good Location	Yes		< $100,000	Lowest		
	Potential Regional Stormwater Management Site																	
Alum Creek	A-1 or A-2	3	3	3	2	2	3	3	0	3	2	2	0		1	0.5	42.5	requires land acquisition
Bee Creek	B-4	3	0	0	3	3	0	2	1	3	2	3	3		3	3	29.0	retro-fit
Bee Creek	B-1/2	3	1	2	2	2	2	2	0	0	3	3	3		2	2.5	32.5	small regional facility
Bee Creek	B-5	3	3	3	2	2	3	2	0	3	1	2	0		1	0.5	40.5	requires land acquisition
Burton Creek Trib. C	BTC-1	3	3	3	2	2	2	1	0	0	2	3	1		2	1.5	38.5	small to large, may require land acquisitior
Burton Creek Trib. C	BTC-2	3	3	1	1	2	3	1	0	0	0	2	3		2	2.5	28.5	small regional facility
Carters Creek	C-8/9	3	1.5	3	3	2	1	1	0	3	2	3	3		2	2.5	40.0	large regional facility
Lick Creek	L-1/2	3	2	2	2	2	1	3	0	3	2	3	3		2	2.5	37.5	small regional facility
Lick Creek	L-4	3	2.5	3	3	2	3	3	0	3	3	3	3		1	2	47.5	large regional facility
Lick Creek	Regional Park	3	1.5	3	3	2	1	3	0	3	2	3	3		2	2.5	42.0	large regional facility
Peach Creek	---	0	3	3	2	2	3	3	0	0	0	3	0		1	0.5	35.5	requires land acquisition
Spring Creek	S-6	3	3	3	2	2	3	3	0	3	3	3	0		1	0.5	44.5	requires land acquisition
Spring Creek	S-2	3	2.5	2	2	2	2	3	0	3	2	2	3		2	2.5	39.0	small regional facility
Spring Creek	S-1	3	0	0	3	3	0	3	1	3	1	3	3		3	3	29.0	retro-fit
Wolf Pen Creek*	WP-1/2	3	3	3	3	2	2	1	3	3	2	3	3		2	2.5	48.5	small regional facility
Wolf Pen Creek	WP-Parks	3	1	1	2	3	0	1	1	3	2	3	3		3	3	31.0	retro-fit

Notes:

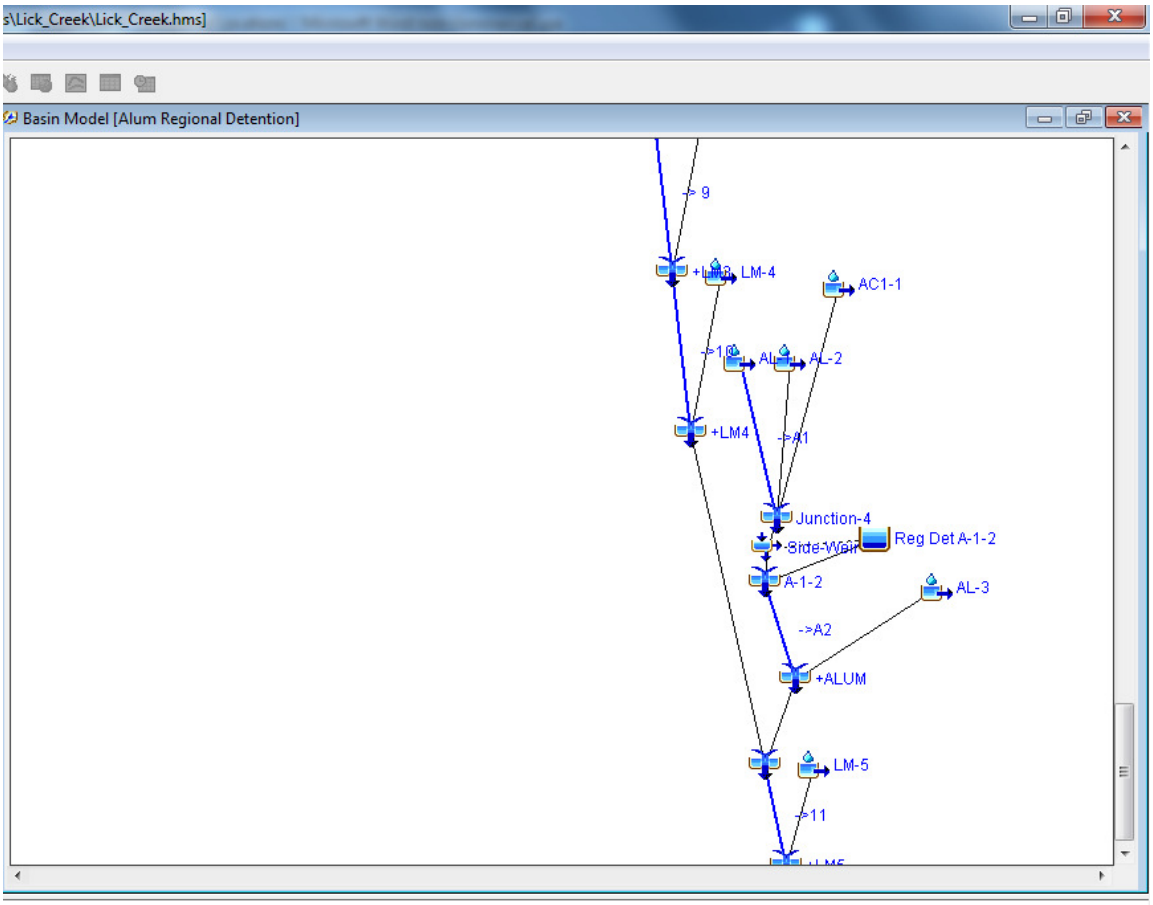
1. Ranking on the Fix Existing Problems category based on input from City staff.
2. Ranking on Trail Connectivity and Park Amenity based on input from City staf
3. Ranking on Flood Control Volume based on potential volume within identified tracts of land.flood control iten
4. Ranking on Flood Control Performance based on location in watershed and flood plain (i.e., sites located where detention is not required in lower portions of watershed less likely to be effectiv
5. Ranking on Water Quality based on adequate space for stormwater wetlands and/or possibility for inclusion of other water quality features, such as bioretention or rain gardens as well as potential for effect on watersh
6. Ranking on Anticipated Development in Watershed based on current and future land use plans and input from City staf
7. Ranking on Improved Performance in Smaller Events based on intent of facility (i.e., flood control vs. retro-fit of existing basin for smaller event and water quality performanc

* While WP-1/2 achieves a relatively high ranking, we understand that a previous project has been attempted in the area and it is not likely that another project will be undertaken in the forseeable futu

APPENDIX E – ROUTED HYDROGRAPHS FOR ANALYZED SITES

Watearth™
Water Resources + Green Infrastructure

ALUM CREEK – A/1-2



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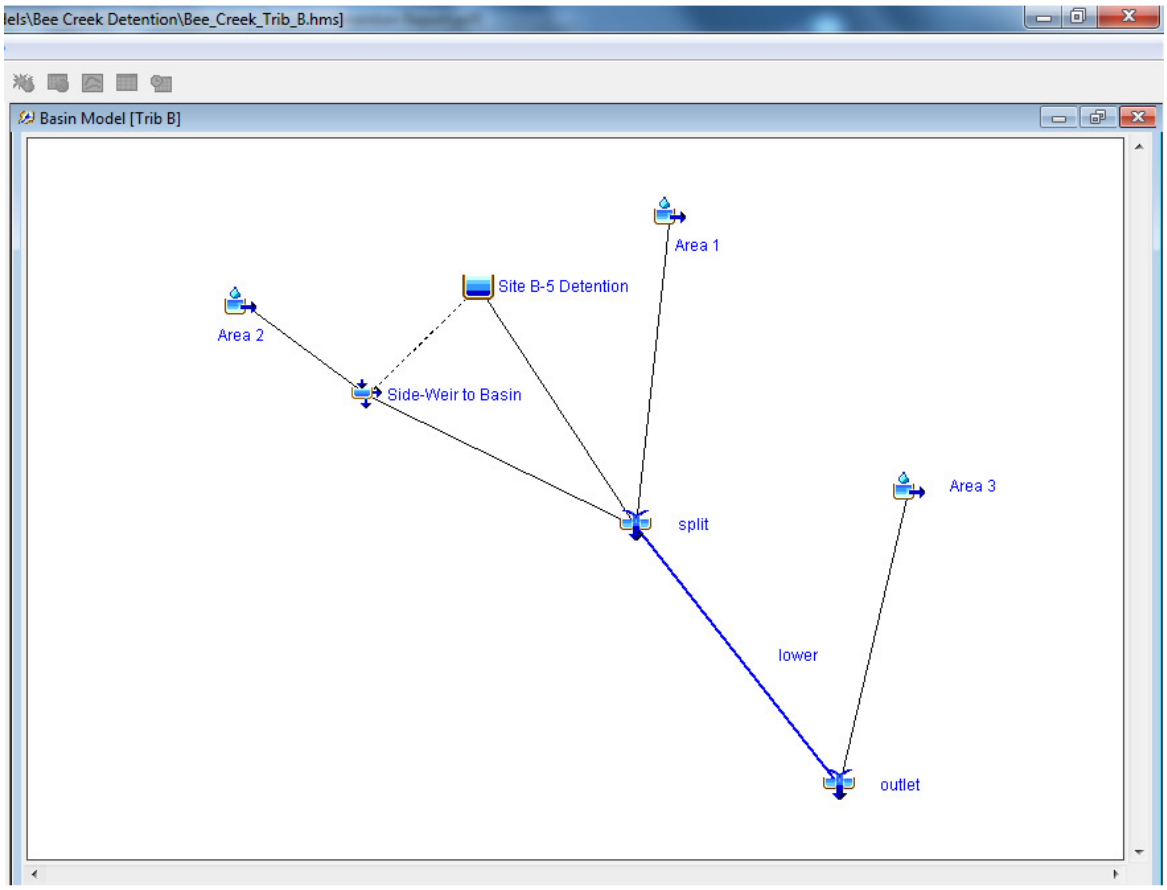
Water Resources + Green Infrastructure

BEE CREEK – B/5



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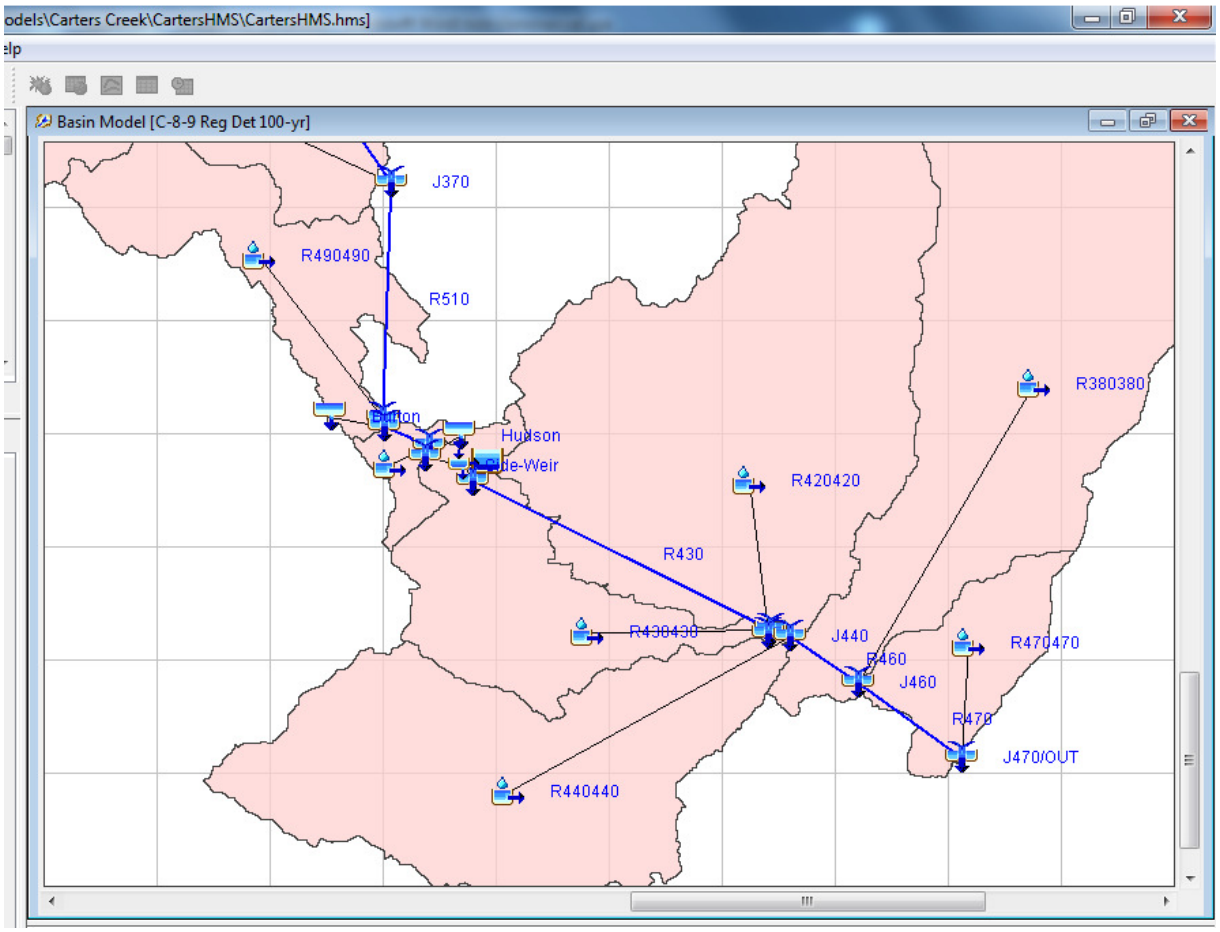
CARTERS CREEK – C-8/9



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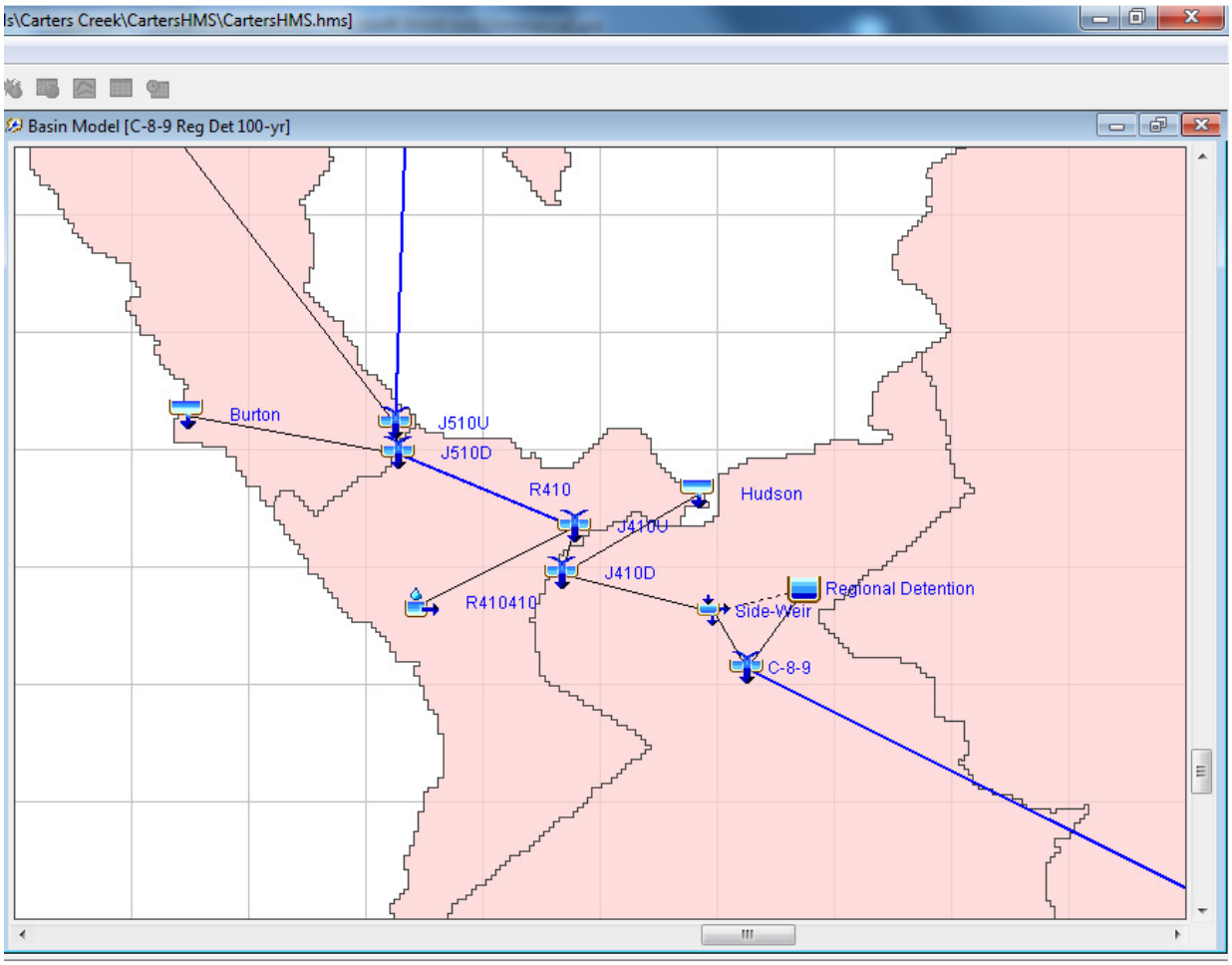
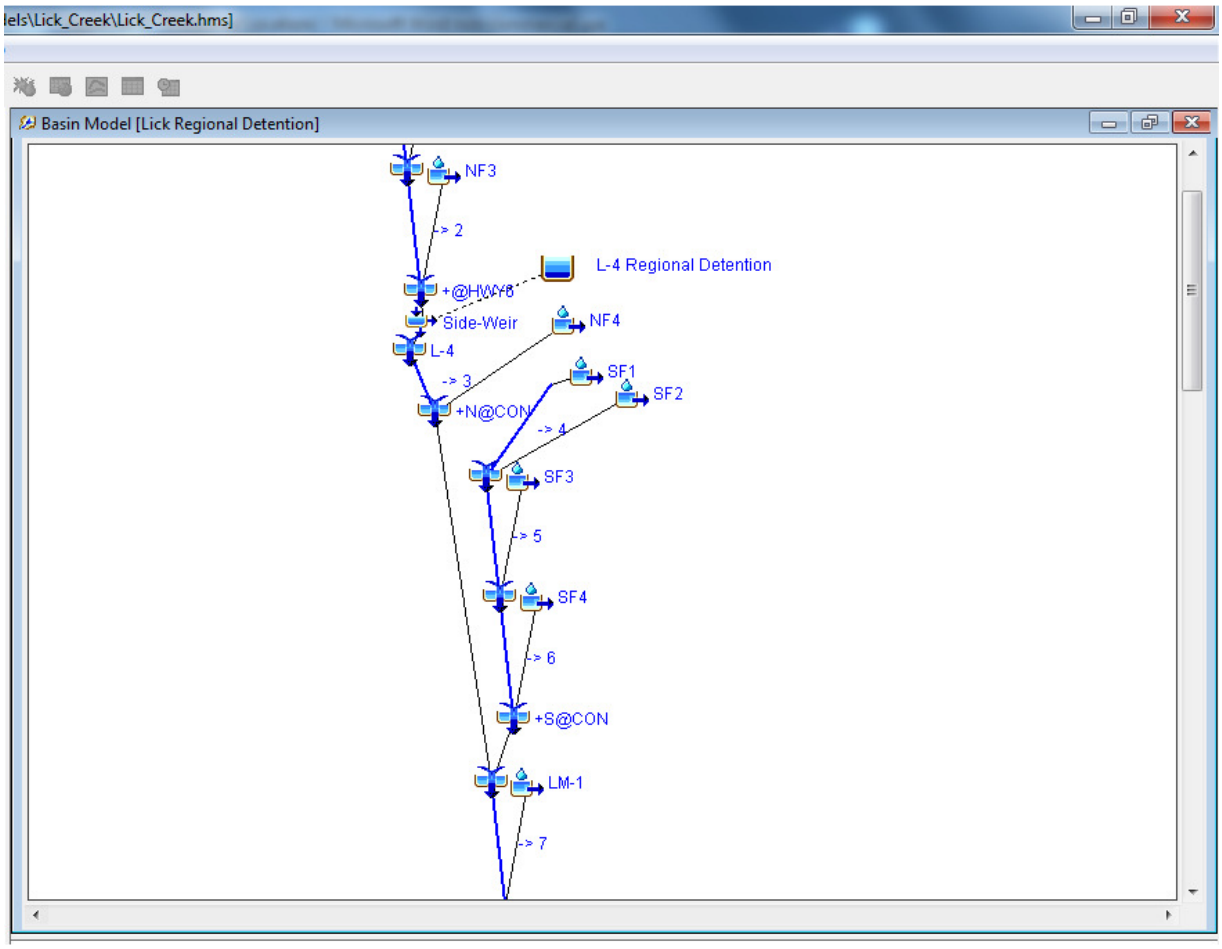
Water Resources + Green Infrastructure

CARTERS CREEK – C-8/9



LICK CREEK – L4



SPRING CREEK – S6

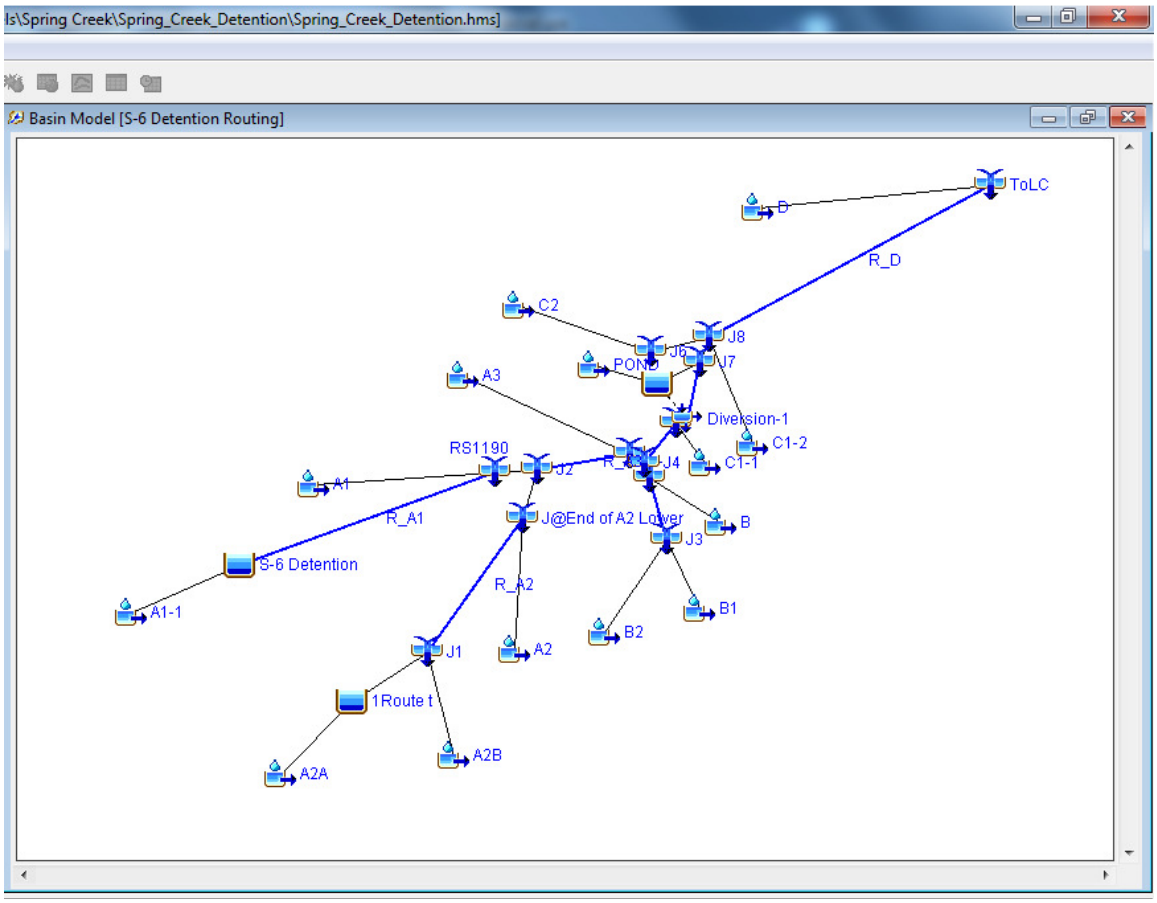


Figure E-1: Effect of Detention at A-1/2 on Downstream Hydrographs in Alum/Lick Creek

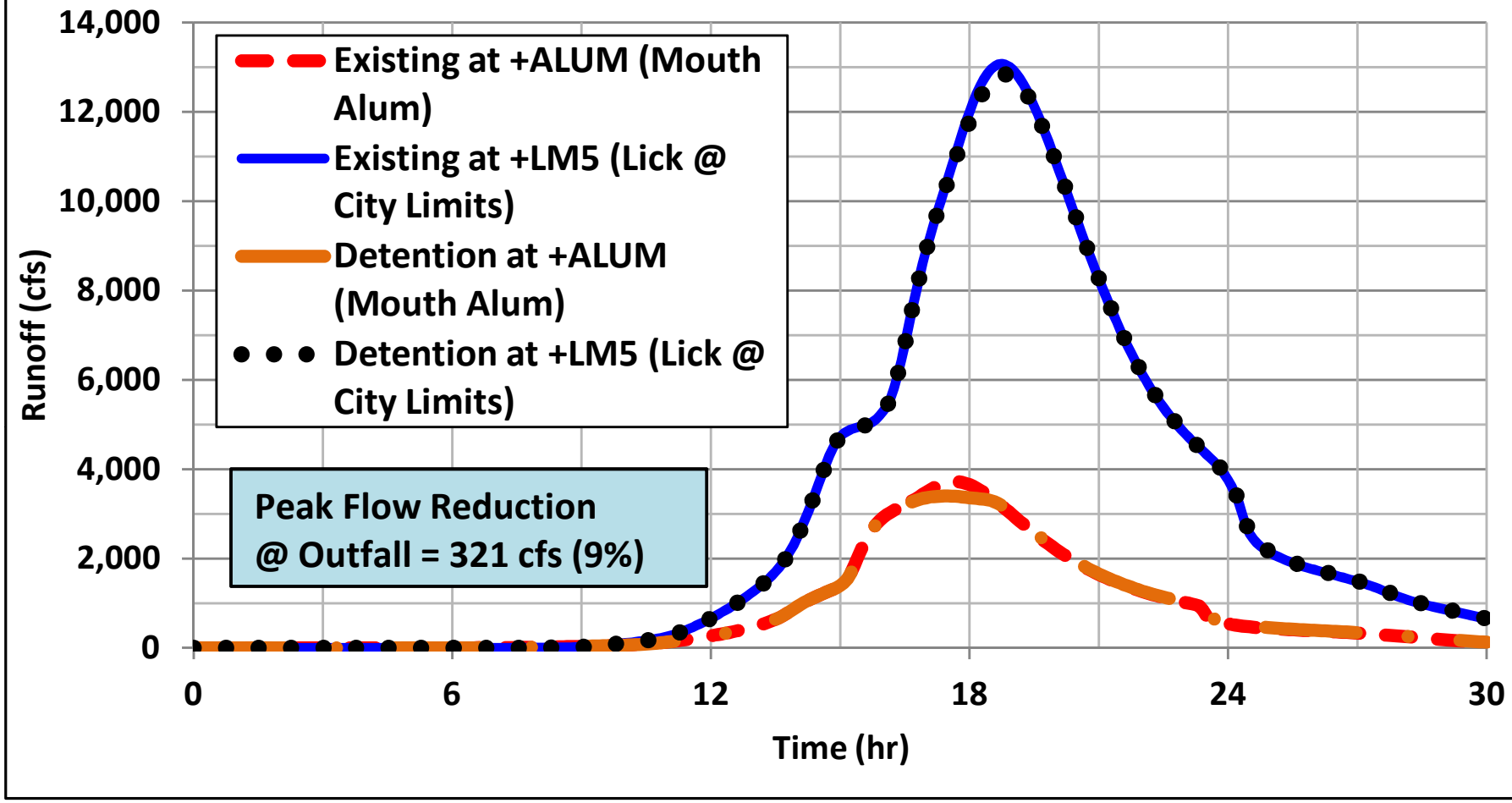


Figure E-2: Effect of Detention at Site B-5 on Downstream Hydrographs in Bee Creek Trib. B

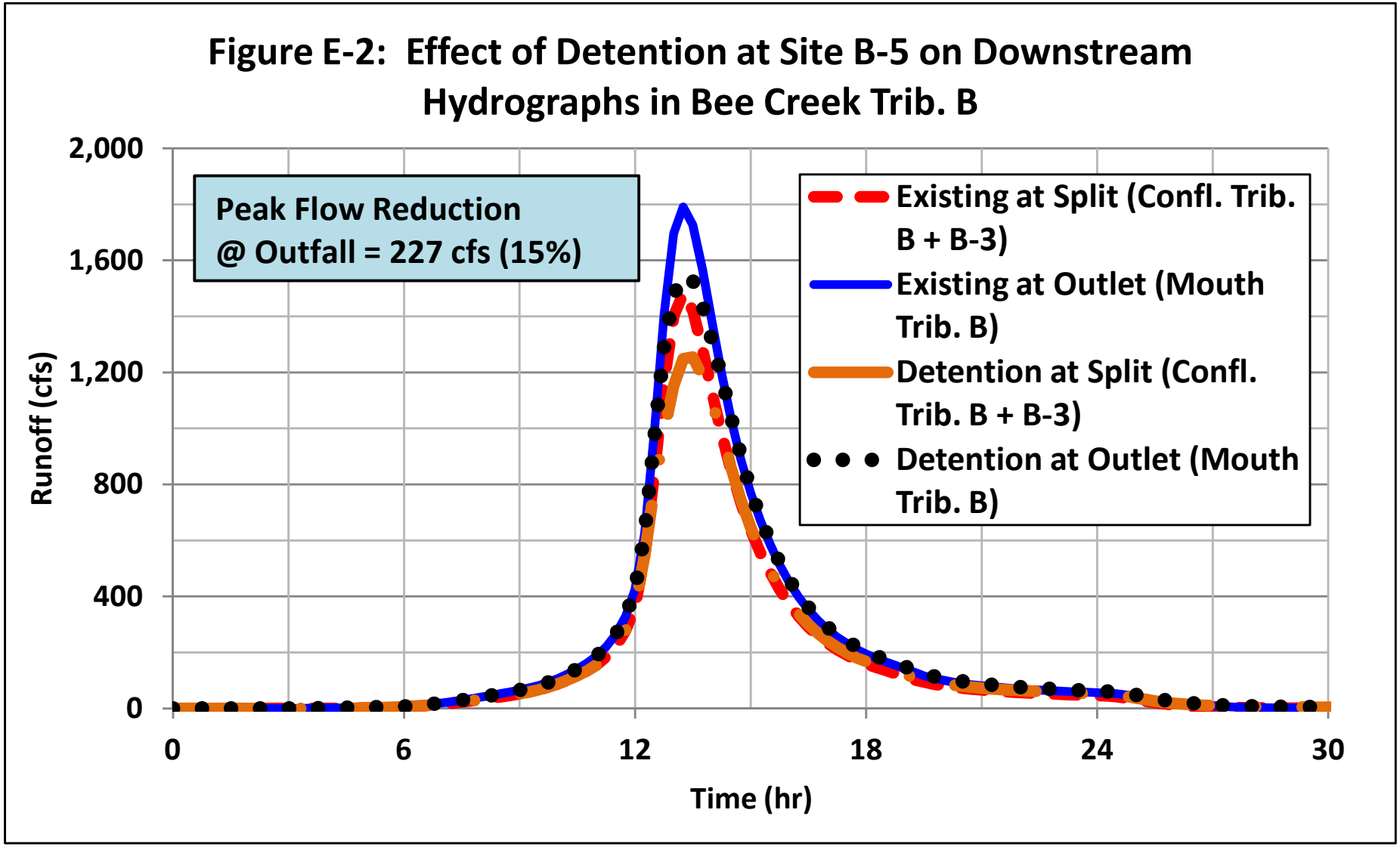


Figure E-3: Effect of Detention at Site C-8/9 on Downstream Hydrographs in Carters Creek

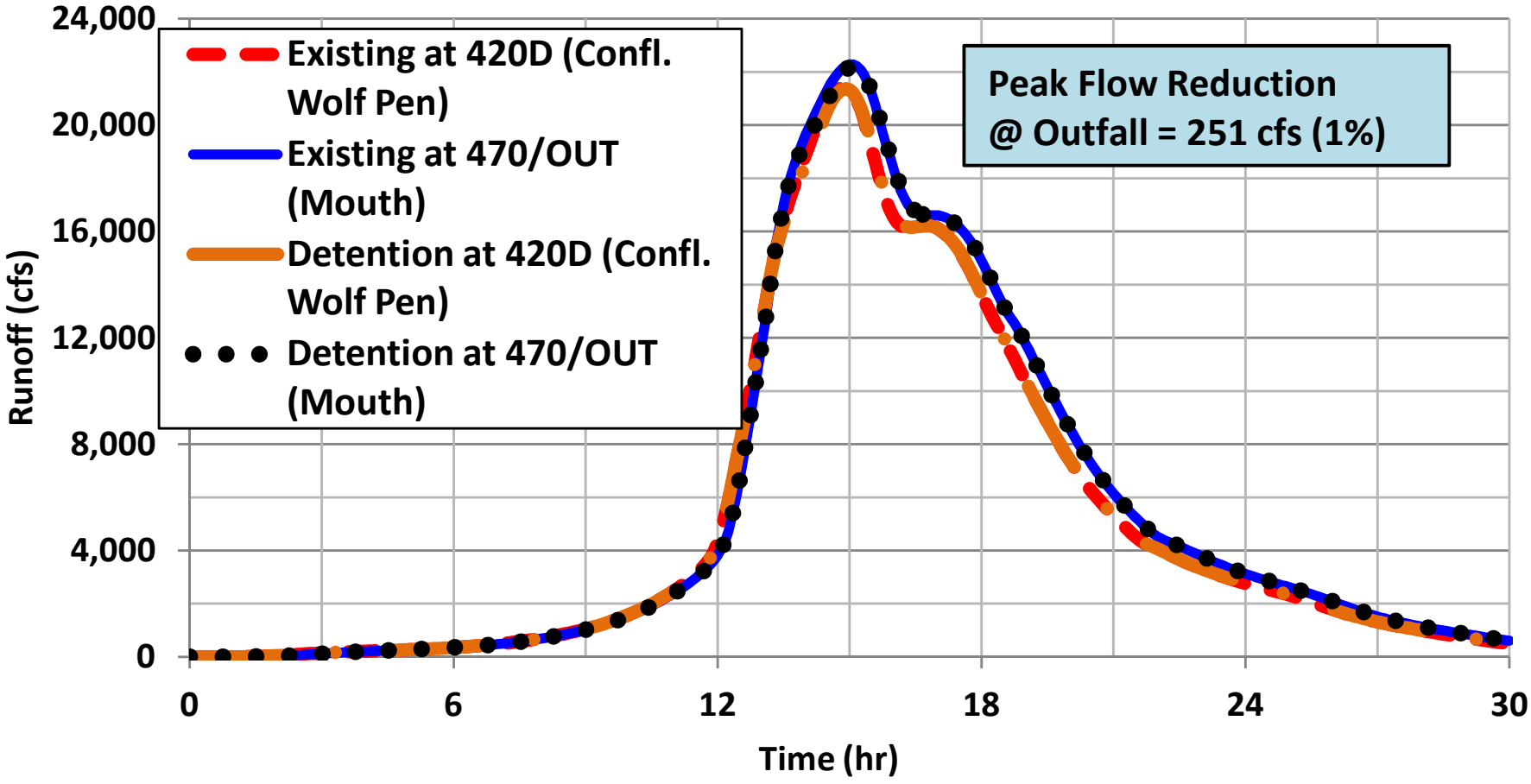


Figure E-4: Effect of Detention at Site L-4 on Downstream Hydrographs in Lick Creek

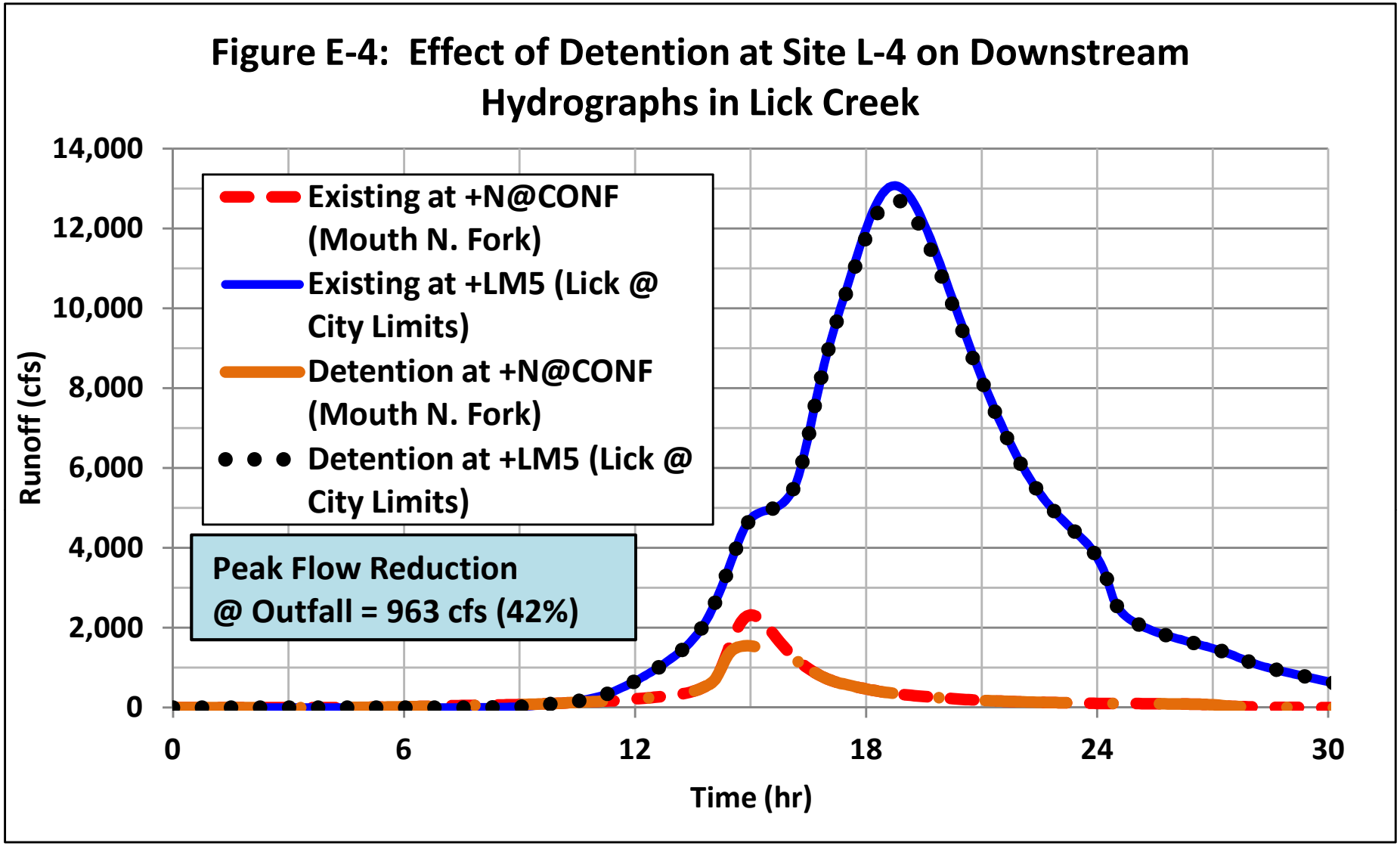
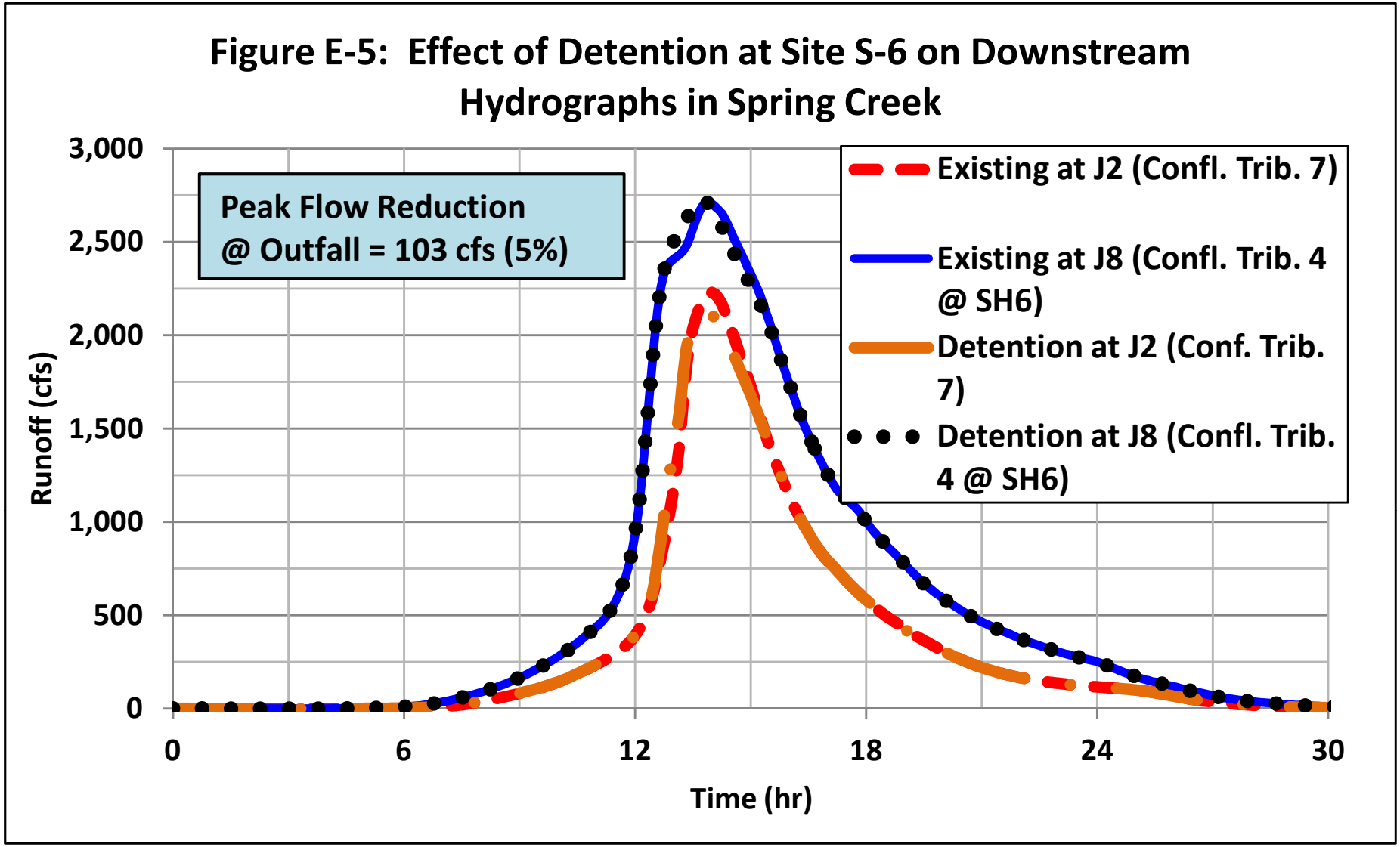


Figure E-5: Effect of Detention at Site S-6 on Downstream Hydrographs in Spring Creek



APPENDIX F – HEC-HMS MODELS (PROVIDED SEPARATELY)