DOWNTOWN SHALL NOT FLOOD AGAIN

*Greeley and Hansen LLC
2116 W Laburnum Avenue, Suite 100
Richmond, Virginia 23227

** Department of Public Utilities, City of Richmond, Virginia

ABSTRACT

The City of Richmond, Virginia conducted a study to evaluate local drainage system in its downtown business district to remedy conditions that cause flooding more than once in a two-year period. The main goals of this study are to evaluate the capacity of the storm water collection system in the downtown area to handle the 2-year storm event, identify system constraints and provide recommendations for improvement. The study area, Shockoe Bottom watershed, is a 65-acre sub-basin located within the City’s largest combined sewer watershed, Shockoe Creek watershed, which has an existing land area of approximately 8,000 acres.

Extensive hydrologic and hydraulic modeling and analyses on the existing Shockoe Bottom drainage system, including the Dock Street Pumping Station, the Northeast Interceptor, and the stormwater inlets in the Shockoe Bottom watershed and in adjacent watersheds, were conducted. Field investigations included an inventory of the number and size of the existing stormwater inlets, and connectivity of roof rain leaders. The study showed that the storm water ponding in the downtown low-lying areas may be caused by: (1) Flows discharging into the Shockoe Box Sewer exceed the capacity of Dock Street Pumping Station. This is caused by: a) Excess flows transferred into the Shockoe Box Sewer from the Northeast Interceptor watershed and, b) Flow transferred from the Shockoe Arch Sewer into the Shockoe Box Sewer through existing gates between the Northeast Interceptor and the Shockoe Arch Sewer. (2) Excess overland runoff flow, which exceeds the capture capacity of the existing storm water catchments. This excess overland flow is from the downtown watershed itself and from the adjacent watershed to the east.

Based on these findings, a series of capital improvement projects were identified and evaluated to minimize the nuisance flooding in the downtown area. Benefit-to-cost analyses showed that the Northeast Interceptor improvements, installation of more stormwater inlets near the low points susceptible to flooding, as well as modification of Dock Street pumping station operation are the most cost effective measures.

KEYWORDS

Flood, CSO, drainage
INTRODUCTION

The City of Richmond is located at the falls of the James River. The older portion of the City is served by a combined sewer system (CSS) that comprises about 12,000 acres or 30% of the City’s total area. There are currently 29 CSO outfalls identified in City’s VPDES permit, most of which are located along the James River and its tributary, Gillies Creek. The largest basin in the system is the Shockoe Creek combined sewer area, which is approximately 8,000 acres or about 2/3 of the CSO system. The downtown Shockoe Bottom area is a 65-acre watershed tributary to the Shockoe Box sewer, as shown on Figure 1.

Figure 1 - CSO Areas at Richmond, Virginia

Being the lowest point on the north side of James River, the Shockoe Bottom area is subject to flood from both the James River and interior rainfall event. In 1994, the City completed the flood wall project which protects Shockoe Bottom from the river flooding. Since then, business and development have quickly thrived in the bottom area. However, it has been observed that the low-lying areas in Shockoe Bottom, such as Pine Alley, Walnut Alley and the Farmers Market, have experienced local flooding more than once in a two-year period (see Figure 2). The purpose of this study was to evaluate the capacity of the storm water collection system in the
Shockoe Bottom to handle the 2-yr storm event, identify system constraints and provide recommendations for improvement.

Figure 2 – Local Flooding in Shockoe Bottom Area

DRAINAGE SYSTEM EVALUATION

Shockoe Watershed History

The original combined sewer system in the Shockoe watershed, initially built in late 1800’s, carried the sanitary sewage and runoff from storms to the James River through three natural creeks – Bacon’s Quarter Branch, Cannon’s Branch and Shockoe Creek. During mid-1920’s through early 1930’s, the City completed a series of flood control projects for the Shockoe watershed. The major components of the project, as shown on Figure 3, include: (1) the Shockoe Arch pressure conduit that conveys runoff from the upper portions of the Shockoe watershed to the river; (2) a 17- by 12-foot concrete box (Shockoe Box) sewer with a pumping station (Byrd Street Pumping Station) and upper and lower gate houses, which removed storm water runoff and sanitary wastewater from the low-lying areas (Shockoe Bottom) not drained by the pressure conduit; (3) a 63-inch sewer along 19th Street and a flow regulator at 19th Street and Main Street diverting the majority of the wet weather flow in CSO 034 and CSO 035 to the City Dock, which reduced the drainage area of Shockoe Bottom; (4) Cannon Branch and
Bacon’s Quarter Branch combined sewers, which collected the combined sewage from upper portion of Shockoe Creek Watershed areas to Shockoe Arch Sewer.

**Figure 3 - Shockoe Watershed Improvements in Mid-1920’s and Early 1930’s**

In mid-1950s, the City began the construction of the Wastewater Treatment Plant (WWTP) to provide primary treatment and to treat sludge collected in the primary facilities. Beginning the late 1950s through the early 1960s, the City constructed the interceptor system to convey the sanitary sewage and portion of the combined sewage to the WWTP. The 96-inch Shockoe Creek Interceptor and the twin 66-inch City Dock River Crossing were constructed during this period, as shown on **Figure 4**.

In late-1970 to early-1980’s the City’s Shockoe Retention Facilities were installed to capture the first flush from the Shockoe Creek combined sewer system. These facilities included the diversion structures, the retention basin, and flap gate connections to the Shockoe Box installed on storm drains located in Pine Alley, Creek Alley and Walnut Alley. (See **Figure 4**).

Flooding from the James River continued to be a threat for the City until the U.S. Army Corps of Engineers (Corps) built the floodwall, which was designed in the 1980’s and completed in the fall of 1994. The floodwall project relocated storm sewers from the Shockoe Arch sewer to the Shockoe Box sewer to limit the discharge and prevent over pressurizing the Arch sewer during river floods.
East gravity outlet (EGO) was constructed just east of the East Diversion Structure to convey all storm water runoff which is not carried by the other conduits through the floodwall. The EGO was designed to reduce ponding up to the 100-year storm.

West Interceptor was constructed to collect storm water runoff from the existing railroad yard north of Marshall Street, from a large inlet in the Main Street Station parking lot, and from new and existing separated storm drains west of Arch Sewer and convey it through the floodwall to the James River.

Northeast Interceptor was constructed to collect existing combined sewers which are east of the Arch Sewer and which flow to the Arch Sewer and convey them to the existing Box Sewer at just downstream of the Upper Gate House. This was designed to isolate them from the existing Arch Sewer during high river stages, to prevent flooding within the pressurization areas, and to prevent damage to the existing combined sewers from the internal pressure. The large combined sewers retain a gated connection to the Arch Sewer, which allows most flows to continue to flow to the Arch Sewer and allows the design of Northeast Interceptor to be based on a design storm during high river stages, yielding a much lower design flow and hence smaller pipe size.

Other improvements associated with the floodwall project included, upgrading the Upper and Lower Gate Houses, the demolition of the Byrd Street Pumping Station, and construction of the new Dock Street Pumping Station. Figure 4 shows the existing Shockoe Watershed flood control and interior drainage system.

**Figure 4 - Shockoe Watershed Flood Control and Interior Drainage System (Present)**
Operation of Shockoe Retention Facilities

Shockoe Retention Facilities is the most critical component in the Shockoe Watershed drainage system. It can be operated in two modes: pollution prevention mode which is the normal operational mode, or flood protection mode which is exercised during less frequent interior rain event (25-year or higher). In this paper, we only address the normal operation mode. Figure 5 shows the normal operation during dry and wet weather conditions.

Figure 5 – Normal Operation of Shockoe Retention Facilities
Normal dry weather flow from Shockoe Creek CSO area will flow through the Shockoe Arch Sewer and the Shockoe Diversion Structures (SDS) to the 96” Shockoe Creek Interceptor, and ultimately to the WWTP for treatment. During wet weather events, the combined sewer flows coming down through the Shockoe Arch and Box sewers will build up in the SDS. At the same time, the WWTP will pump the water out of the system up to its wet weather treatment capacity (75 MGD). When the water level in the SDS approaches the crest elevation of the Bascule Gates (El +16.0), the roller gates will open and allow the flow into the SRB through three Diversion Conduits. Once the basin is filled, the roller gates close and excessive flow will spill over the Bascule Gates, then over the Overflow Weir and discharge into the James River. After the storm event, the WWTP will keep pumping at 75 MGD until the SDS and SRB are emptied.
In the normal operation mode, both the upper and lower gates are closed to isolate Shockoe Box from the pressure conduit Shockoe Arch, and the combined wastewater in the Shockoe Box sewer is pumped around the lower gate house to the Diversion Structure by Dock Street Pumping Station, which has a firm capacity of 134 cubic feet per second (cfs).

**Operation of Shockoe Box Sewer**

Figure 6 shows the drainage system in the 65-acre Shockoe Bottom area. The Shockoe Box receives flow from combined trunk sewers as well as street curb inlets connected directly to it. The low-lying spots such as Pine Alley and Walnut Alley have flap gate connections to the Shockoe Box to prevent the combined sewage in the Box sewer from backing up to these areas.

**Figure 6 – Shockoe Bottom Drainage System**

Figure 7 shows the hydraulic profile of the Box Sewer from the East Diversion Structure’s crest gate through the drop inlet in Pine Alley. The drop inlet has a flap gate to prevent the water from exiting the Box Sewer and discharging into the alley. The top of the grating at Pine Alley drop inlet is about elevation 14.0 ft, which is below the normal crest gate elevation of 16.0 ft. To the north of the drop inlet, there is an underground parking garage. The low point of the ramp to this parking garage is about elevation 14.3 ft. If the water elevation in the Box Sewer is greater than the water elevation in Pine Alley, the flap gate will close. Thus the only way to remove the storm water in Pine Alley is to operate the Dock Street Pumping Station. As shown in Figure 7, during low intensity rainfall event, the Dock Street Pumping Station is able to control the water level in Box Sewer at set point of 12.5 ft, so the storm water runoff in Pine Alley will drain into the Box Sewer. However, during higher intensity rainfall (greater than 3 inch per hour for 10 to 15 minutes), the Dock Street Pumping Station has not been able to control the level in the Box Sewer, and the excess flow may be relieved through the six flap gates located in the Combination Flood Control Roller Gate at the Lower Gate House (Figure 8). Once the water elevation in the
Box Sewer exceeds about 14.0 ft, the flap gate will close, and the storm water runoff from the parking lot west of Pine Alley plus the roof drains will discharge to the alley and eventually flow into the underground parking garage.

Figure 7 – Operation of Shockoe Box Sewer During Low Intensity Rainfall

Figure 8 – Operation of Shockoe Box Sewer During Higher Intensity Rainfall
SHOCKOE BOTTOM WATERSHED HYDRAULICS

Based on the understanding of the existing Shockoe system, the storm water ponding in the low-lying areas in Shockoe Bottom may be caused by the following:

- Excess overland runoff flow, which exceeds the capture capacity of the existing storm water catchments. This excess overland flow is from the Shockoe Bottom watershed itself and from the adjacent watershed to the east.

- Flows discharging into the Box Sewer exceed the capacity of Dock Street Pumping Station. This is caused by:
  - Excess flows transferred into the Box Sewer from the Northeast Interceptor watershed, and,
  - Flow transferred from the Arch Sewer through existing gates between the Northeast Interceptor and the Arch Sewer.

Hydraulic Analyses of Existing Storm Water Inlets

A field investigation was conducted on the stormwater inlets in both Shockoe Bottom drainage area and adjacent areas that may contribute overland flow to the bottom, as shown on Figure 9. There are a total of 84 stormwater inlets identified within the 65-acre Shockoe Box Sewer watershed, of which 58 are within the watershed tributary to Farmer’s Market and Walnut Alley. Thirty (30) curb inlets were identified in the 32-acre adjacent watershed east of Shockoe Bottom. There are about 74 curb inlets identified outside of the Shockoe Bottom and the 32-acre adjacent watersheds. Over 95% of these inlets are curb-opening inlets, and the rest are grate inlets and grate-curb opening combination inlets. It was found that more than 50% of the curb inlets in the bottom and adjacent area are smaller than 4-ft. Given the steep topography and high imperviousness, the number and size of existing curb inlets in the Shockoe Bottom and adjacent watersheds may not be adequate to capture a 2-year stormwater runoff.
Figure 9 – Existing Storm Water Inlets in Shockoe Bottom and Adjacent Watersheds

Figure 10 and Figure 11 show simplified hydrographs for Shockoe Bottom watershed and adjacent watershed for various storm events.
Figure 10 – Hydrograph for Existing Shockoe Bottom Watershed

Figure 11 – Hydrograph for Existing Watershed Adjacent to Shockoe Bottom

Note: (1) Assumes all catchments are clean
Hydraulic Analyses of Northeast Interceptor

**Figure 12** shows the delineation of Northeast Interceptor watersheds. There are seven sub-basins tributary to the Northeast Interceptor. Three combined trunk sewers (Marshall Street, Washington Street, and Williams Street) are also connected to the Arch Sewer through gated structures (Gate 11, Gate 14 and Gate 15, respectively). As described above, the NE Interceptor and gated structures were designed to isolate the combined trunk sewers from the Arch Sewer during high river stages (when the bascule gates at Shockoe Diversion Structures are lowered, and the Upper and Lower Gates on the Box Sewer are open). Under normal conditions, these gates are open to allow most of the flow from these sub-basins to drain into the Arch Sewer.

**Figure 12 – Northeast Interceptor Watersheds**

Extensive hydraulic analyses were conducted for the Northeast Interceptor and its sub-basins. **Figure 13** shows the 2-yr storm hydraulic profile of Northeast Interceptor at low water level in Arch Sewer (shown as dashed lines). The majority of the runoffs from Williams Street,
Washington Street and Marshall Street will flow into the Arch with free discharge. When the Arch level is low, the flow into the Box Sewer through the Northeast Interceptor is approximately 60-70 cfs.

**Figure 13 – Hydraulic Profile of Northeast Interceptor at Low Water Level in Arch Sewer**

When the Arch Sewer is surcharged and the gates are open, flow may be transferred from the Arch Sewer to the Northeast Interceptor, and discharged into the Box Sewer. **Figure 14** shows the hydraulic profile in the Arch Sewer at various flow rates, and **Figure 15** shows the hydraulic profiles of Northeast Interceptor given an Arch flow of 7000 cfs under low water level (blue line) and surcharged water level (green line) in the Box Sewer.
Figure 14 – Hydraulic Profile of Arch Sewer at Various Flow Rates

Figure 15 – Hydraulic Profile of Northeast Interceptor at Arch Flow of 7,000 cfs

Figure 16 shows the flow transferred from Arch to Box through Northeast Interceptor as a function of Arch flow rate over the bascule gate (at elevation 16.0). The invert of Northeast Interceptor at the Marshall Street gate is only 17.72, which allows flow to transfer even during low intensity rainfall event.
Figure 16 – Flow Transfer from Arch Sewer to Box Sewer

![Flow Transfer from Arch to Box](image)

Box WSEL at 19.5 feet
Free Discharge Into Box Sewer
NE Interceptor Invert at 17.72

Figure 17 shows the hydrograph of flow transfer from Arch to Northeast Interceptor derived from once per summer hydrograph for Arch Sewer.

Figure 17 – Hydrograph of Flow Transferred from Arch Sewer to Box Sewer

![Hydrograph of Flow Transfer](image)

A composite hydrograph was developed for Shockoe Bottom using the individual hydrographs for Shockoe Bottom watershed itself, flow from the CSO 034 dry weather regulator at 19th and
Main Streets, runoff transferred from adjacent watershed, and transfer flow from Arch to Box via Northeast Interceptor, as illustrated on Figure 18 for 1-year storm event.

**Figure 18 – Composite Shockoe Bottom Hydrograph for 1-Year Storm Event**

*Figure 19* shows how the existing system would perform under a 1-year storm event with hydrograph shown on *Figure 18*. This example assumes that the rainfall starts in the Shockoe Bottom at about the same time as the rainfall starts in the entire Shockoe watershed. Flow from the Northeast Interceptor and CSO 034 may surcharge the Box Sewer, discharge through the combination roller/flap gates in Lower Gate House, and into Farmers Market.
FLOOD CONTROL ALTERNATIVES EVALUATIONS

Potential improvement projects for flood controls in the Shockoe Bottom area were evaluated for three design conditions:

- Normal condition – interior rainfall only
- River flooding
- River flooding with interior rainfall

In this paper, only the alternatives under normal operational conditions will be discussed.

Adjacent Watershed Improvements

The adjacent watershed improvements would minimize excess overland flow from this area to the Shockoe Bottom low-lying areas such as Farmers Market and Walnut Alley. The improvement projects may be implemented in 2 phases. Phase 1 project will add new large curb inlets near 19th Street at the boundary of adjacent watershed and Shockoe Bottom watershed, along 15th Street, and on Main Street between 14th Street and 15 Street. These new curb inlets would intercept as much bypass flow from upstream as possible, but may still pass some excess flow to the bottom area under the 2-year storm event. Phase 2 would address the entire adjacent watershed and install new curb inlets throughout the watershed to capture the 2-year runoff. The existing curb inlets will be rehabilitated during the implementation of the improvement projects. Figure 20 shows the project area, and summarizes the design features, preliminary cost, advantages and disadvantages of this alternative. Figure 21 shows the design criteria for the curb inlets in the adjacent watershed.
Figure 20 – Adjacent Watershed Improvements

Features:
- Rehab existing inlets
- Part 1: New curb inlets in adjacent watershed along 19th Street, 15th Street, and Main Street between 14th and 15th St.
- Part 2: Remainder of New curb inlets in adjacent watershed to capture 2-yr storm

Preliminary Estimated Costs:
- Capital Cost
  - Part 1 = $550,000
  - Part 2 = $1,180,000
- O&M Cost
  - Part 1 = $5,000/yr
  - Part 2 = $9,000/yr
- Annual Cost
  - Part 1 = $53,000/yr
  - Part 2 = $112,000/yr

Advantage:
- Potential to Implement in Phases
- Reduce excess overland flow from adjacent watershed to Shockoe Bottom

Disadvantages:
- Increased number of catchments to maintain

Figure 21 – Curb Inlets Design in the Adjacent Watershed

Excess Runoff Transferred to Shockoe Bottom
Design Catchments in Adjacent Watershed to Capture 2-yr Event
Shockoe Bottom Watershed Drainage Improvements

The goal of these improvements is to keep the water off the street and minimize excess runoff to Farmers Market and Pine Alley. The potential projects may be implemented in 3 phases. Phase 1 focuses on drainage improvements in Farmers Market and Pine Alley. New large curb inlets may be installed near and in Farmers Market and Walnut Alley to capture flows greater than 2-year event. In Pine Alley and Walnut Alley, new drop inlets with flap gate connection to the Box may be installed or the existing drop inlets may be enlarged. The rain leaders from the buildings in Pine Alley will be hard piped to the Box Sewer to reduce surface runoff. Phase 2 will install new large curb inlets in Shockoe Bottom along elevation 22.0. Phase 3 would address the remainder area of Shockoe Bottom with new curb inlets installed to capture 100% of 2-year runoff. Figure 22 and Figure 23 summarize the improvement projects and storm water inlet design criteria.

Figure 22 – Shockoe Bottom Watershed Improvements
Northeast Interceptor Improvements

As discussed above, the majority of excess flow into the Box Sewer under normal condition (interior rainfall only) appears to be from the Northeast Interceptor watershed and the flow transferred from the Arch Sewer. It is proposed that gate structures be installed on the Northeast Interceptor to control the flow transfer between the Arch Sewer and the Northeast Interceptor, as shown on Figure 24. The improvements include three new gate structures: 1) on the Washington Street combined sewer near the existing Gate G14 – two new sluice gates (G14b and G14c) may be installed and are normally closed so that the flow from Washington Street watershed is directed to the Arch Sewer; 2) on the Marshall Street combined sewer near the existing gate G11; and 3) just upstream of the new gate structure on Marshall Street to control the flow from Clay and Venable Street watershed. The existing manhole covers on the new gate structure influent sewers would be bolted down. Gate G15 would need to be raised to handle surcharged Arch Sewer hydraulic grade line. During normal conditions, all gates on the Northeast Interceptor would be closed and all gates connecting to the Arch Sewer would be open, which allows the Dock Street Pumping Station to pump only the runoff tributary to the Shockoe Bottom watershed plus small amount of runoff from the Broad Street watershed and CSO 034. During high river stage, all gates on Northeast Interceptor would be open, and the gates connecting to Arch Sewer would be closed. Figure 24 also shows the flood trigger elevation for the operation of the gates.
Figure 24 – Northeast Interceptor Improvements

Features:
• Three New Gate Structures
• Five New Sluice Gates
• One Connection to Arch Sewer
• One Manhole
• Bolt Down MH Covers
• Raise Gate 15 Structure

Preliminary Estimated Costs:
• Capital Cost: $902,000
• O&M Cost: $18,000/yr
• Annual Cost: $97,000/yr

Advantage:
• Potential to Implement in Phases
• Prevents transfer of water from Arch Sewer to Box Sewer
• Allows Dock St PS to pump runoff tributary only to Shockoe Bottom

Disadvantages:
• More sluice gates to maintain & operate during flood events

Modification of Operation of Dock Street Pumping Station

Figure 25 shows the composite Shockoe Bottom watershed hydrograph after the improvements to the Northeast Interceptor and adjacent watershed. Figure 26 shows that approximately 1.8 MG of storage would be needed to capture 10-yr to 25-yr event peak flow after the improvements to the Northeast Interceptor and adjacent watershed. Currently the set point of the Dock Street Pumping Station is at elevation 12.5, which would allow Pine Alley to drain into the Box Sewer. Figure 27 shows that by dropping the pumping set point to elevation 5.3, there will be additional 1.8 MG storage available in the Box Sewer, which can be used to capture the 10-yr to 25-yr storm event peak without causing flooding in Pine Alley.
Figure 25 – Shockoe Bottom Watershed Hydrograph after Improvements to Northeast Interceptor and Adjacent Watershed

Figure 26 – Storage Needed in Box Sewer to Capture 10-yr to 25-yr Event
New Pumping Station Near Lower Gate House

New pumping station with firm capacity of 120 cfs can be constructed around the Lower Gate House to compensate the inadequate capacity at Dock Street Pumping Station, as shown on Figure 28. This pumping station can provide additional CSO storage volume in the Box Sewer, and the diesel-powered pumps can serve as back-up for Dock Street Pumping Station.
Figure 28 – Potential New Pumping Station Near Lower Gate House Site Plan

Features:
- Six Stand-by Pumps
- Wet Well
- Suction & Discharge Piping with Valves
- Sluice Gated Connections to Box Sewer
- Operated Primarily During River Floods Greater than 25-year event

Preliminary Estimated Cost:
- Capital Cost = $5.0 M
- O&M Cost = $151,000/yr
- Annual Cost: $582,000/yr

Advantage:
- Provides additional CSO Storage Volume
- Provides backup for Dock Street Pumping Station

Disadvantages:
- More complex operation & maintenance than other alternatives

Stand-by Alley Pumping Station

A stand-by pumping station may also be installed to collect and pump the ponding water in Pine, Creek and Walnut Alleys to the Arch Sewer, as shown on Figure 29. This alternative does not solve the main watershed issues and may not be needed if other improvements are implemented. In addition, it will not prevent flooding in Farmers Market if the Box Sewer is surcharged (water can not enter the Box Sewer and will flow overland to the low-lying Farmers Market area).
FINDINGS AND RECOMMENDATIONS

The potential improvement components evaluated above are grouped into 7 projects and planned to be implemented in the next 5 years. The project descriptions, the results of the benefit-to-cost analysis, as well as corresponding project rankings are summarized in Table 1. The benefits of the projects are estimated based on real estate value, business revenue and city revenue, and damage prevented in the Shockoe Bottom area. Projects SBD-1 through SBD-6 address the sources of flooding in the Shockoe Bottom and thus are recommended for “phased” implementation in the Fiscal Years shown in Table 1. Projects SBD-4 and SBD-5 (stormwater inlet improvements) contribute to a higher level of flood protection and could be further divided into smaller projects, to match the funding availability, as needed. Project SBD-7 was considered and exhibits the lowest cost-to-benefit ratio. This project may be implemented as a partial solution for Pine Alley and Walnut Alley. However, it may not be needed after projects SBD-1 through SBD-6 are implemented. Thus Project SBD-7 is not recommended as an integral element of the overall solution for the Shockoe Bottom at this time. The most cost effective projects are the Northeast Interceptor improvements, modification of Dock Street Pumping Station operation, and storm water catchment improvements near the low-lying areas (Pine Alley, Walnut Alley and Farmers Market).

Other recommendations include updating the flood wall O&M manual to change the operation of the Shockoe Box and the gates on the Northeast Interceptor, developing educational
information to help the public better understand the system, and developing emergency plans for interior rainfall greater than 50-yr event, floodwall overtopping, and combination of James River flood with interior rainfall, such as early warning system, public notification and evacuation plan, and operational protocols of the emergency management, police, fire, public works and public utilities departments.

Table 1 – Project Description, Benefit-to-Cost Ratio and Project Ranking

<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>Project ID</th>
<th>Project Description</th>
<th>Normal: Flood Protection Range</th>
<th>Preliminary Estimate of Capital Cost</th>
<th>Estimated Cumulative Annualized Cost</th>
<th>Total Estimated Annual Benefit(1)</th>
<th>Total Benefit to Cumul Cost Ratio</th>
<th>Project Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>05-06</td>
<td>SBD-1</td>
<td>NE Interceptor Improvements: - Washington St, Marshall St &amp; Venable St Gate Structures Shockoe Bottom Watershed Part 1: - Connect Pine Alley Rain Leaders to Box Sewer - Add Stormwater Inlets in Farmer’s Market &amp; Walnut Alley - Modify Operation of Dock Street Pumping Station</td>
<td>1-yr to 2-yr</td>
<td>$1,246,000</td>
<td>$140,000</td>
<td>$733,000</td>
<td>5.2</td>
<td>1</td>
</tr>
<tr>
<td>06-07</td>
<td>SBD-2</td>
<td>Adjacent Watershed Improvements Part 1: - Add Stormwater Inlets Along 19th Street, 15th Street, and Main Street Between 14th Street and 15th Street</td>
<td>2-yr to 5-yr</td>
<td>$550,000</td>
<td>$193,000</td>
<td>$733,000</td>
<td>3.8</td>
<td>2</td>
</tr>
<tr>
<td>06-07</td>
<td>SBD-3</td>
<td>Shockoe Bottom Watershed Improvements Part 2: Add Stormwater Inlets Along El 22 Contour</td>
<td>2-yr to 5-yr</td>
<td>$220,000</td>
<td>$215,000</td>
<td>$733,000</td>
<td>3.4</td>
<td>3</td>
</tr>
<tr>
<td>07-08</td>
<td>SBD-4</td>
<td>Adjacent Watershed Improvements Part 2: Add Remainder of Stormwater Inlets to Capture 2-yr Event</td>
<td>5-yr to 10-yr</td>
<td>$1,180,000</td>
<td>$327,000</td>
<td>$733,000</td>
<td>2.2</td>
<td>4</td>
</tr>
<tr>
<td>08-09</td>
<td>SBD-5</td>
<td>Shockoe Bottom Watershed Improvements Part 3: Add Remainder of Stormwater Inlets to Capture 2-yr Event</td>
<td>10-yr to 25-yr</td>
<td>$680,000</td>
<td>$391,000</td>
<td>$733,000</td>
<td>1.9</td>
<td>5</td>
</tr>
<tr>
<td>09-10</td>
<td>SBD-6</td>
<td>Lower Gate House Pumping Station</td>
<td>10-yr to 25-yr</td>
<td>$4,939,000</td>
<td>$973,000</td>
<td>$733,000</td>
<td>0.8</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>SBD-7</td>
<td>Alley Pumping Station</td>
<td>10-yr to 25-yr</td>
<td>$4,198,000</td>
<td>$1,424,000</td>
<td>$733,000</td>
<td>0.5</td>
<td>7</td>
</tr>
</tbody>
</table>

Note: (1) Total Annual Benefit includes estimated annual damages plus 50% of the City’s annual revenue. Assumes that 50% of businesses would leave Shockoe Bottom if flooding was not controlled to at least two year event.