Chapter 4

HYDRAULICS

Table of Contents

4.1 INTRODUCTION

Hydraulic analysis is an integral component of both site and overall stormwater infrastructure design. Good design must strive to maintain compatibility and minimize interference with existing drainage patterns, control flooding of property, convey design flood events and minimize potential environmental impacts from stormwater runoff. For guidance related to specific hydraulic design and calculations, please refer to the most recent version of North Carolina Department of Transportation (NCDOT) manual "*Guidelines for Drainage Studies and Hydraulic Design"* and the Federal Highway Administration's (FHWA) manual *"Hydraulic Design of Highway Culverts, Hydraulic Design Series No. 5"*. Where discrepancies exist, this manual shall govern.

4.2 CLOSED CONVEYANCE SYSTEM DESIGN CRITERIA

Closed stormwater conveyance systems shall be sized based upon the criteria listed in **Table 4.2.** No pumping will be allowed for any stormwater system on public or private property. ~~Inlets shall be sized based on the corresponding design year storm for which the pipe system is also designed.~~

TABLE 4.2
DRAINAGE CRITERIA FOR CLOSED STORMWATER CONVEYANCE SYSTEMS

Drainage Area	*Design Storm*	*Design Criteria*
≤ 25 acres	10-year	HGL for the entire system is to be at or below the crown of all pipes.
	25-year	HGL shall not exceed the top of structures or gutter elevations.
> 25 acres	25-year	HGL for the entire system is to be at or below the crown of all pipes.
	100-year	Inundation does not exceed the limits of easement or right-of-way (ROW).

Hydraulic grade line (HGL) calculations shall consider all head losses, friction factors and bypass flows. The downstream hydraulic grade line at the outlet end of the stormwater conveyance system shall begin at a known water surface elevation or at the downstream crown of pipe, whichever is greater.

Both 10- and 25-year HGL calculations, as well as 100-year inundation limits, shall be provided with ~~the preliminary or~~ permitting submittal~~, whichever occurs first~~. Include the following data in the report, as well as justification for each:

- Intensity (i)
- Time of concentration (t_c)
- Runoff coefficient (C)
- Drainage area map
- Profiles showing HGLs

If properties proposed for development or redevelopment contain existing through-drainage systems, the systems shall be evaluated based on current design criteria. If the existing systems do not comply with the current drainage criteria, the existing systems shall be replaced or improved to meet the criteria. For 10-year discharges exceeding five cubic feet per seconds (cfs), stormwater conveyance systems are required, if not already existing.

If any existing system is replaced or supplemented, or if any new system is proposed to meet the criteria outlined in **Table 4.2,** a Stormwater Development Analysis (SDA) shall be prepared in accordance with *Chapter 2 – Site Development Requirements*. Any increase in flow or velocity on downstream properties may require on-site mitigation, off-site improvements and/or easements.

Any stormwater conveyance systems shall not be placed under or within 10' of any permanent structure or their associated foundation.

All stormwater conveyance systems shall be designed so that no building or insurable structure, either proposed or existing, floods or has water impounded against it during the 100-year storm event. To prevent structural flooding or impoundment, overland relief is required. The 100-year storm ponding elevations, areas of extent and overland relief zones shall be shown and labeled on the preliminary or permitting submittal, whichever occurs first.

4.3 INLET AND SPREAD DESIGN CRITERIA

Inlets shall be sized based on the corresponding design year storm for which the pipe system is also designed. Reference Table 4.2, above.

Spread calculations, for the design storm frequency specified in **Table 4.2**, shall be provided for all proposed public and private streets with the ~~preliminary or~~ permitting submittal~~, whichever occurs first.~~. Curb inlets in the roadway shall be placed in such a way that the spread of water in the road (associated with the design storm intensity in **Table 4.2**) meets the following criteria:

- Maximum spread of half the width of one travel lane on two- or three-lane streets and one-lane width on wider streets
- When the typical section includes a full shoulder (four feet or greater) or parking lane, no encroachment into the travel lane will be allowed.

In addition to inlets on grade, ~~I~~inlets shall be provided at sags, upgrade of intersections, upgrade of superelevation crossovers and at any location where more than three cfs will be discharged into a street for the 10-year storm.

In sag areas where relief by curb overflow is not provided, the system standard design level (25- or 50-year storm events) is to be used for analysis to ensure traffic flow is not interrupted. Guidance for sag area calculations can be found in the NCDOT *"Guidelines for Drainage Studies and Hydraulic Design"*. In a sag condition where relief by overflow for a typical roadway cross section is not provided, inlet capacity and the stormwater conveyance system must be designed for:

- One dry eight-foot travel lane in the 25-year event on two- or three-lane streets
- Two dry eight-foot travel lanes (one in each direction) in the 50-year event on four-lane

or more streets

Verify spread is not exceeded upstream of sags ~~(at the 0.5% slope point)~~. Additional flanking inlets upstream may need to be added to keep spread criteria from being exceeded at these locations.

Regarding site development, inlets shall be provided to capture runoff and carry flow into the drainage system before it reaches the ROW. Ponding at yard inlets outside the roadway shall be limited to a maximum of one foot above a grated inlet for the 10-year storm if no structures are flooded as a result. No increase in 100-year ponding levels on adjacent property shall be allowed without an easement.

Gutter spread calculations shall include the following, along with **Table 4.3**:

- All flow rates in cfs to the nearest hundredth
- Inlets shall be designed assuming 50% blockage on grade and in sag locations where combination inlets are required
- Double catch basins shall be provided at all sag locations
- Methodology, assumptions and equations used to determine the spread

TABLE 4.3

EXAMPLE TABLE OF CHECKS FOR SPREAD CALCULATIONS

Inlet #	*Bypass Inlet*	*Spread (ft)*	*Allowable Gutter Spread (ft)*	*Bypass (cfs)*	*Check*
CB1	CB2	4.0	6.0	0.00	Pass
CB2	Offsite	5.5	6.0	0.25	Pass

4.3.1 Drainage Structures

NCDOT standard inlets shall be used for all streets unless an alternative is specifically requested from and approved by Stormwater Development Review staff. The City of Raleigh has approved green stormwater infrastructure (GSI) standard details as alternatives to NCDOT standard inlets. Approved GSI alternative inlet designs do not need additional approval if proposed on any non-NCDOT street. Approval from NCDOT would be required for their use on NCDOT maintained streets.

All structures shall allow for access to the stormwater conveyance system with a grate, manhole ring and cover or a lid capable of being removed. Minimum invert drop at structures is 0.1 feet for horizontal and vertical alignment changes. Minimum invert drop at structures for pipe size increases is based on matching crown elevations. For proposed pipe size decreases, a detailed study will need to be performed and approved by Stormwater Development Review staff with special provisions for maintenance. Details shall be provided on the plans for all such structures and shall conform to the appropriate City standard detail.

Drainage structures with access shall be provided as follows:

- For pipe systems with an equivalent size of a 48-inch pipe or larger, there should be a maximum spacing of 400 feet

- For pipe systems with an equivalent size of less than a 48-inch pipe, there should be a maximum spacing of 300 feet
- Where the public and private drainage systems connect to delineate the separation of publicly and privately maintained infrastructure
- Wherever there is a change in pipe size, grade or direction within a stormwater conveyance network

4.4 PIPE MATERIAL AND COVER CRITERIA

Stormwater conveyance pipes in the City ROW or outside of City ROW that connect to the City stormwater infrastructure shall be reinforced-concrete pipe (RCP), Class III or higher, with a minimum diameter of 15 inches and a minimum cover of 2.4 feet. RCP slopes shall be a maximum of 10% and a minimum of 0.5%, with a minimum flow velocity of 2.5 feet per second. Other scenarios may be discussed on a case-by-case basis with the Stormwater Development Review staff. As newer materials are accepted by the City, the City's website will post these materials and associated design specifications.

High-density polyethylene (HDPE) may be used in minor residential streets, as defined in the City of Raleigh *"Street Design Manual"*, provided it is installed according to the following requirements:

- Corrugated exterior/smooth interior pipe (Type S) shall conform to American Association State Highway and Transportation Officials (AASHTO) M294.
- Certification shall be provided by Plastic Pipe Institute (PPI).
- Bell and spigot joints with O-ring gasket (on spigot end) shall be installed on all pipe within ROW. Bells shall cover two full corrugations on each section of pipe. Gaskets shall conform to American Society for Testing and Materials (ASTM) F477.
- Installation trench width shall be a minimum of the outside diameter of the pipe plus four feet.
- HDPE shall be backfilled with six inches of #57 stone bedding under the pipe and to the top of pipe. Remaining backfill shall be installed in accordance with current City standards.
- Third-party certification shall be provided by a North Carolina licensed professional engineer. Certification shall be based upon periodic observations of installation procedures.
- Diameter shall be a minimum diameter of 15 inches and a maximum diameter of 48 inches.
- Cover for HDPE shall be a minimum of 2.4 feet from the outside wall of pipe to finished grade.
- ~~Cover for HDPE exposed to heavy traffic during construction shall be a minimum of 48 inches.~~

- Pipe velocity shall be a minimum of 2.5 feet per second.
- Maximum slope shall be 10% and minimum slope of 0.5%. Greater slopes may be approved by the Director of Engineering Services upon submittal of appropriate detailed structural designs and other supporting documentation.
- No HDPE end treatments shall be allowed. Reinforced-concrete pipe/headwalls shall be used for all end treatments. Transition of HDPE to RCP shall have a dissimilar materials adapter incorporating a geotextile coupler with mastic coating and stainless-steel straps, and a full concrete encasement around the connection.
- Bury depths greater than 12 feet shall have prior approval by the Director of Engineering Services.

4.5 OPEN CHANNEL DESIGN CRITERIA

For purposes of this manual, open channel conveyance systems refer to ditches, swales and man-made channels commonly used as part of the overall stormwater conveyance system. Design storm events, minimum longitudinal slopes and maximum side slopes specified herein are limited to these applications. Larger natural streams and rivers that may require stabilization or natural channel design techniques as part of the development will incorporate applicable design considerations and be reviewed by the City on a case-by-case basis for approval.

TABLE 4.5

DRAINAGE CRITERIA OPEN CHANNEL CONVEYANCE SYSTEMS

Drainage Area	*Design Storm*	*Design Criteria*
< 25 acres	10-year	HGL for the entire system is at or below top of banks
	100-year	Inundation does not exceed the limits of easement/ROW
≥ 25 acres	25-year	HGL for the entire system is at or below top of banks
	100-year	Inundation does not exceed the limits of easement/ROW

A yard swale will require an easement when it drains one or more upstream properties. Easement requirements can be found in *Chapter 2 – Site Development Requirements*.

Open channel conveyance systems shall be sized based upon the criteria listed in **Table 4.5**

10-, 25- and 100-year design calculations and inundation limits shall be provided with the preliminary or permitting submittal, whichever occurs first. A table with channel segment, slope, drainage area, proposed velocity, proposed discharge, channel lining and maximum channel lining velocity shall be provided on the plans. Include the following data in the report, as well as justification for each:

- Intensity (i)
- Time of concentration (t_c)
- Runoff coefficient (C)
- Drainage area map
- Profiles with HGLs

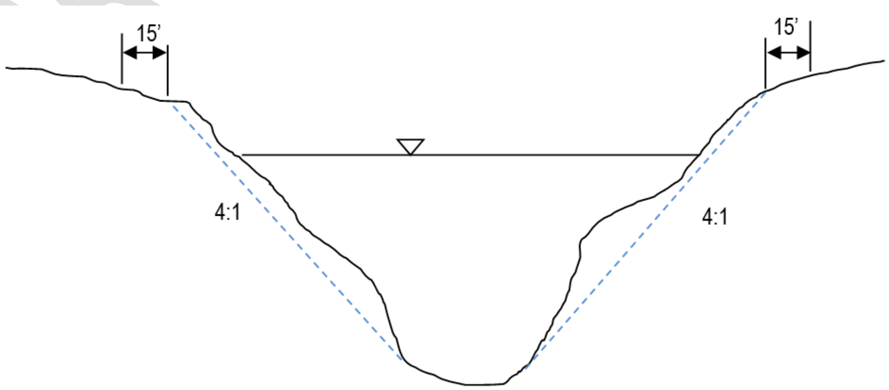
4.5.1 Erosion Hazard Setback

Open channel conveyance systems shall be designed such that non-erosive velocities are maintained per the City's Unified Development Ordinance (UDO) under UDO Section 9.4.4.G.2. Maximum allowable side slopes for vegetated conveyance shall be 3H:1V with a minimum longitudinal slope of 1%. Vegetated conveyance shall be sodded, not seeded. Where open channel conveyance systems discharge into other water courses, discharge should be accomplished through diffuse flow techniques, such as level spreaders or preformed scour holes, to the maximum extent practical.

An erosion hazard setback shall be contained within the easement (as specified in *Chapter 2 – Site Development Requirements*) for all existing and proposed earthen channels. Erosion hazard setbacks are not required for swales, as discussed in Chapter 2, Section 2.4 – Lot Grading Plan (LGP). The purpose of this set back is to reduce the potential for any damage to public or private infrastructure from erosion of the channel bank. The erosion hazard setback shall be determined as follows:

- Project a 4H:1V line sloping away from the toe of channel until it intercepts finished grade on each side. From these intersections add an additional 15 feet (see **Figure 4.5.1**).
- Any encroachments ~~or reduced erosion hazard setback proposed~~into this setback that changes the existing topography will require a geotechnical and geomorphological stability analysis and approval by the City. Minor encroachments that do not change existing topography including fences, playground equipment, HVAC systems, generators, light poles and signs will not require this stability analysis.

Figure 4.5.1. Schematic of the Erosion Hazard Setback



4.6 BRIDGE AND CULVERT DESIGN CRITERIA

For guidance related to specific hydraulic design and calculations, please refer to the most recent version of NCDOT manual "*Guidelines for Drainage Studies and Hydraulic Design*" and the FHWA manual "*Hydraulic Design of Safe Bridges*." Where discrepancies exist, this manual will govern.

4.6.1 Culverts

Inlet and outlet control calculations for all proposed culverts shall be provided with the preliminary or permitting submittal, whichever occurs first. The downstream hydraulic gradient at the outlet end of the culvert shall begin at a known water surface elevation or at the downstream crown of the culvert, whichever is greater. In addition to calculations for the design storm event, calculations for the 100-year storm event and inundation mapping shall be provided and used to verify the proposed culvert is not impacting insurable structures.

4.6.2 Bridges

To minimize the risk of failure, the hydraulic requirements of a stream crossing must be recognized and considered during the development, construction and maintenance phases of bridge design. Calculations related to existing or proposed bridges shall be provided with the preliminary or permitting submittal, whichever occurs first. Flow velocities through bridge openings should not cause scour within the bridge opening or in the stream reaches adjacent to the bridge.

4.6.3 Design Criteria

Bridges and culverts shall be sized based upon the criteria listed in **Table 4.6.3.** All bridges and culverts shall be designed so that no building or insurable structure [unless the structure(s) is a properly floodproofed, non-residential structure(s)], either proposed or existing, floods or has water impounded against it during the 100-year storm event. Greater freeboard and other special considerations may be needed for unique issues, such as heavy debris, extreme weather and navigational clearance.

TABLE 4.6.3
FREEBOARD CRITERIA FOR CULVERTS AND BRIDGES

System	*Design Storm*	*Design Criteria*
Road Crossings with Drainage Area ≤ 25 ac	25-yr	12 in to top of road[1] with HW/D ≤ 1.2 or 12 in from the low chord[2]
	100-yr	No increased inundation shall exceed the limits of easement/ROW

Road Crossings with Drainage Area > 25 ac	50-yr 100-yr	24 in to top of road[1] with HW/D ≤ 1.2 or 12 in from the low chord[2] No increased inundation shall exceed the limits of easement/ROW
Road Crossings over Regulated Floodways	100-yr	24 in to top of road[1] with HW/D ≤ 1.2 or 24 in from the low chord[2] No increased inundation without approved floodplain map revisions
[1]Culvert freeboard is measured from the top of the road and is defined as the lowest adjacent point where roadway overtopping would occur. [2]Bridge freeboard is measured from the low chord, which is the bottom of the bridge structure that defines the waterway opening.		

All culvert crossings shall use cast-in-place or precast-concrete boxes or RCP. For road crossings serving 10 acres or more, the maximum depth of the water impounded during the 100-year storm event should not exceed 15 feet, as measured from the upstream invert of the culvert to the water surface elevation. Should the maximum depth be exceeded, appropriate engineering calculations shall be submitted to verify the stability of the embankment against slope failure and seepage effects.

4.6.4 Headwalls and Endwalls

Cast-in-place and pre-cast concrete headwalls and endwalls shall be required for all pipe system outfalls. All headwalls and endwalls shall be designed in accordance with NCDOT standards. No flared end sections shall be allowed without prior approval from the City.

Energy dissipation calculations shall be provided with the preliminary or permitting submittal, whichever occurs first. The following outlet protection and energy dissipators are allowable:

- Plunge pools
- Riprap apron
- Baffled outlets

Calculations shall be in accordance with the North Carolina Department of Environmental Quality (NC DEQ) *"Erosion and Sediment Control Planning and Design Manual"* and the FHWA manual *"Hydraulic Engineering Circular No. 14 HEC-14: Hydraulic Design of Energy Dissipators For Culverts and Channels"*.

4.7 OUTLET DESIGN

Primary outlets regulate outflow for stormwater control measures (SCMs) and may be incorporated into the development of the site. There are several different types of outlets that may consist of a single-stage outlet structure or several outlet structures combined to provide multi-stage outlet control. Descriptions and equations are provided for the following outlet types for use in stormwater infrastructure, including but not limited to, orifices, perforated risers, pipes and weirs.

Non-corrosive material and mounting hardware should be implemented to extend device longevity, ease operation and reduce the cost of maintenance. Special attention must also be paid to not placing dissimilar metal materials together where a cathodic reaction will cause deterioration of metal parts.

4.7.1 Orifices

An orifice is a circular or rectangular opening of a prescribed shape and size. The flow rate depends on the height of the water above the opening and the size and edge treatment of the orifice.

For a single orifice, the orifice discharge can be determined using the standard orifice equation below. The orifice equation is only appropriate when the headwater depth is above the top of the orifice (HW>D).

[EQ 4.7.1.a]

$$\boldsymbol{Q = C \times A \times \sqrt{(2 \times g \times h)}}$$

$\boldsymbol{Where,}$

$$Q = the\ orifice\ flow\ discharge\ (cfs)$$

$$C = discharge\ coefficient\ (see\ \boldsymbol{Table\ 4.7.1})$$

$$A = cross\text{-}sectional\ area\ of\ orifice\ or\ pipe\ (ft^2)$$

$$g = acceleration\ due\ to\ gravity\ (32.2\ ft/s^2)$$

$$h = effective\ head\ on\ the\ orifice,\ from\ the\ center\ of\ orifice\ to\ the\ water\ surface\ (ft)$$

TABLE 4.7.1 ORIFICE DISCHARGE COEFFICIENTS	
Condition	*Coefficient*
Sharp Edge (material thickness < orifice diameter)	0.6
Sharp Edge (material thickness > orifice diameter)	0.8
Rounded Edge	0.92

For square-edged entrance conditions the generic orifice equation can be simplified:

[EQ 4.7.1.b]

$$\boldsymbol{Q = 0.6 \times A \times \sqrt{2 \times g \times h} = 3.78 \times D^2 \times \sqrt{h}}$$

$\boldsymbol{Where,}$

$$\boldsymbol{D = diameter\ of\ orifice\ or\ pipe\ (ft)}$$

4.7.2 Perforated Risers

A perforated riser is a special kind of orifice flow. It is important that the perforations in the riser convey more flow than the orifice plate so as not to become the control. A shortcut formula has been developed to estimate the total flow capacity of the perforated section of a riser (McEnroe, 1988):

[EQ 4.7.2] $$\boldsymbol{Q = C_p \times \frac{2A_p}{3H_s} \times \sqrt{2g} \times H^{3/2}}$$

Where,

$Q = discharge\ (cfs)$

$C_p = discharge\ coefficient\ for\ perforations\ (normally\ 0.61)$

$A_p = cross\text{-}sectional\ area\ of\ all\ the\ holes\ (ft^2)$

$H_s = distance\ from\ \frac{S}{2}\ below\ the\ lowest\ row\ of\ holes$
$to\ \frac{S}{2}\ above\ the\ top\ row\ (ft)$

$S = centerline\ spacing\ between\ holes$

4.7.3 Pipes as Outlet Structures

Discharge pipes are often used as outlet structures for SCMs. The design of these pipes can be for either single- or multi-stage discharges. Pipes smaller than 12 inches in diameter may be analyzed as a submerged orifice, as long as H/D is greater than 1.5. For low-flow conditions when the flow reaches and begins to overflow the pipe, weir flow controls. As the stage increases, the flow will transition to orifice flow. Pipes greater than 12 inches in diameter should be analyzed as a discharge pipe with headwater and tailwater effects considered. The outlet hydraulics for pipe flow can be found in the NCDOT manual *"Guidelines for Drainage Studies and Hydraulic Design"*.

The following equation is a general pipe flow equation derived through the use of the Bernoulli and continuity principles:

[EQ 4.7.3] $$\boldsymbol{Q = a \times \left[\frac{(2gH)}{(1 + k_m + k_p L)}\right] \times 0.5}$$

Where,

$Q = discharge\ (cfs)$

$a = pipe\ cross\ sectional\ area\ (ft2)$

$g = acceleration\ of\ gravity\ (ft/s2)$

$H = elevation\ head\ differential\ (ft)$

$k_m = coefficient\ of\ minor\ losses\ (use\ 1.0)$

$k_p = pipe\ friction\ coefficient = 5087n^2/D^{4/3}$

$n = Manning's\ roughness\ coefficient$

$D = diameter\ of\ orifice\ or\ pipe\ (ft)$

$L = pipe\ length\ (ft)$

4.7.4 Weirs

If the overflow portion of a weir has a sharp, thin leading edge, such that the water springs clear as it overflows, the overflow is termed a sharp-crested weir. If the sides of the weir also cause the through flow to contract, it is termed an end-contracted sharp-crested weir. Sharp-crested weirs have stable-stage discharge relations and are often used as a measurement device. The discharge equation for this configuration can also be used for circular pipe risers (Chow, 1959):

[EQ 4.7.4.a] $$Q = C_w L H^{1.5}$$

Where,

$Q = Discharge\ (cfs)$

$C_w = Weir\ coefficient$

$L = Length\ (ft)$

$H = Height\ of\ water\ above\ the\ crest\ of\ the\ weir$

For sharp-crested weirs, 3.33 is typically used for C_w, while 3.0 is typically used for broad-crested weirs. C_w is not a true a constant, but rather a function of flow depth and geometry.

The discharge calculation of compound weirs can usually be estimated by superposition. For example, the total discharge of the compound weir (Q_{tot}) shown below is the sum of the two partial discharges (Q_a and Q_b):

[EQ 4.7.4.b] $$Q_{tot} = Q_a + Q_b \quad or \quad Q_{tot} = C_w L_a H_a{}^{1.5} + C_w L_b H_b{}^{1.5}$$

4.8 CERTIFICATIONS AND AS-BUILTS

Upon project completion, the City shall require certifications and as-built information to verify compliance with all applicable stormwater regulations. Stormwater Development Review staff acceptance of the as-built certifications are required prior to final approval of a Stormwater Control Permit and the Certificate of Occupancy(s) and/or Certificate of Compliance on a building.

4.8.1 Stormwater Infrastructure Inventory Data

Stormwater infrastructure- as-built and video documentation shall be submitted in accordance with the requirements as outlined in *Stormwater Conveyance As-Built Submittal Checklist*. For stormwater conveyance system installation within the City's jurisdiction, certified surveyed as-built plans and profiles, sealed by a North Carolina professional land surveyor, shall be furnished to the Engineering Services Department upon completion of all installed stormwater infrastructure, both inside and outside of the public ROW. In addition, for stormwater conveyance systems, video documentation shall be completed by a Pipeline Assessment Certification Program (PACP) Certified Professional.

Acceptance of the stormwater conveyance system within the public ROW for maintenance purposes shall be made by City Development Services – Engineering, not the Stormwater Management Division. Privately maintained infrastructure is the responsibility of the property owner and/or property owner's association and acceptance of as-built surveyed inventory data does not constitute acceptance of the private system for maintenance by the City.