Considerations In Estimating Tailwater Elevations

by

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This course addresses typical considerations in determining design tailwater elevations in predominantly outlet controlled conditions, which reflects typical design conditions in large parts of Florida (central, southern and coastal).

COURSE OBJECTIVES

This course discusses:

-Typical tailwater conditions encountered during actual practice
-Typical agency tailwater design requirements
-Common pitfalls in estimating tailwater elevations
-Impacts of over or underestimated tailwater elevations
-Identifies things to consider when determining design tailwater elevations

INTRODUCTION

Engineers, particularly those that are not involved with drainage designs like to joke that "water flows downhill." While with assistance of a pump, water may indeed sometimes flow uphill, it is important for the drainage engineer to remember that in order for a designed system to work properly, water needs to flow down gradient (i.e. from a higher gradient elevation to a lower gradient elevation). In order for this to happen, the designer needs to have an idea of not only what kind of flow rates he/she is dealing with; but what the downstream conditions are as well.

In the design of a project, the Stormwater Management Engineer typically has three areas to address with regards to the project drainage and hydraulics. These areas are: the drainage of the project site, impact of the project on adjacent upstream properties, and the impact of the project on adjacent downstream properties. The internal project site drainage is the major component of the project and is usually where most of the design emphasis is placed. Residential and commercial sites may have requirements that finished floor elevations of buildings are a specified distance above a certain flood elevation. Storm drains and culverts for roads and other facilities are designed to specified recurrence intervals. Roadway drainage has to meet certain standards with regards to inlet capacities, allowable pavement spread, hydraulic gradient elevations, etc. A project cannot adversely impact the existing drainage of adjacent parcels. Adverse impacts to upstream adjacent parcels usually result from project site improvements that reduce or block the existing conveyance of stormwater runoff from the upstream properties, alter the timing of the runoff leaving the upstream properties, or increase tailwater elevations at the outfalls of these parcels. These adverse impacts are identified by increased water stages on the adjacent upstream properties.

Downstream properties are adversely impacted when a project site produces or allows more runoff to flow onto the adjacent property than occurred during the pre-improvement conditions. Increased runoff is due to site improvements such as improved conveyance, loss of existing storage volume, increased paved area, and corresponding decrease in pervious surface, or a change in the timing of runoff, etc. The additional runoff in turn, can cause an increase in water surface elevations on the downstream properties. Post-developed project site discharges should be attenuated to meet pre-developed discharge rates using stormwater management facilities constructed as part of the project's internal site drainage. A project's internal site drainage will also include conveyance of offsite flows from upstream properties, through or around the project site, to the adjacent downstream properties.

All three areas are usually addressed during the project design and the evaluation of impacts to adjacent properties (upstream and downstream) is usually part of the stormwater permitting process. The hydraulic calculations performed for these three areas are all dependent on downstream water surface elevations or tailwater.

The determination of the tailwater elevation is one of the least emphasized components of the hydraulic design. However, in areas with flat, low-lying terrain, there can be significant consequences when tailwater elevations are either overestimated or underestimated in the design of hydraulic structures. Overestimated tailwater elevations can result in over-designed hydraulic structures which can increase the costs of the project. Overestimated tailwater elevations can also result in actual project discharges that are greater than predicted, resulting in downstream flooding problems. Underestimated tailwater elevations can result in inadequately sized hydraulic structures and undersized stormwater management facilities, which increases the potential for upstream flooding.

BACKGROUND

"Tailwater refers to waters located immediately downstream from a hydraulic structure, such as a dam, bridge or culvert" (http://en.wikipedia.org/wiki/tailwater

Typically, the engineer's first encounter with tailwater is when learning how to perform hydraulic calculations for culverts in accordance with the Federal Highway Administration's (FHWA) Hydraulic Design Series 5 (HDS-5).

For many areas of the country with significant topographic relief, culverts are "Inlet" controlled – meaning that only the discharge, culvert size, and entrance configuration factor into how high the water gets on the upstream side of the culvert. Correspondingly, the downstream water surface elevation is not critical to the calculations when inlet control conditions exist.

For "Outlet" controlled conditions, all of the factors in inlet control, plus the culvert barrel characteristics (roughness, area, shape, length, and slope) and the tailwater elevation factors into the determination of how high the water gets on the upstream side of the culvert. With outlet control, the culvert headwater (HW) is determined by the equation:

$$HW = H + h_o - LS_o$$

Where H is the sum of all losses including entrance, exit, friction, and other losses such as bend losses, junction losses and losses at bar grates. HW is the total available upstream energy to push water though the culvert and is the upstream depth of water measured above the outlet invert/flowline plus the velocity head. The reader is directed to HDS-5 for a more in-depth explanation of culvert design.

In the above equation h_o is defined as the greater of the actual TW (tailwater depth) or $(d_c + D)/2$ where d_c = critical depth at the culvert outlet and D = either the culvert diameter, or height if an elliptical pipe or box culvert. This typically applies when the water surface elevation downstream of the pipe is low, allowing the outlet end to flow freely. When learning culvert design, the emphasis is on the hydraulic calculations for the culvert performance and not on how the tailwater elevation/depths are determined.

Culverts in low-lying, flat terrain areas may be under inlet control for low flow conditions but will typically be under outlet control for design flows and high discharge conditions. This emphasis of this course is primarily outlet controlled, sub-critical flow conditions.

In actual design situations, the design engineer often has plenty of information on her/his project site, but very little information in the form of survey data and existing hydraulic data downstream of the proposed site's discharge point.

The ideal design scenario is to have a project site located immediately adjacent to a large body of water whose stage is not dependent on how much or when runoff from the watershed gets to the water body (See Figure 1).

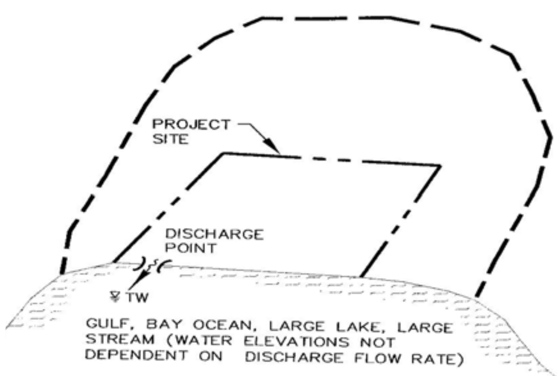


Figure 1

If the elevations in the water body are known (i.e. normal water level if a lake, or the tidal range of elevations if a tidal water body), the design of the site drainage system including tailwater considerations is fairly straight-forward.

Most project sites however, are situated as schematically shown in Figure 2. The project discharge point is upstream of additional hydraulic conveyances and there is usually additional contributing drainage area downstream as well.

The preferred design approach is to model far enough downstream to a point where the water surface elevation is known and does not vary with discharge or time; accounting for the downstream contributing drainage areas and conveyances, and letting the hydrology and hydraulics determine the tailwater stages at the project's discharge point.

Unless there is an existing approved and accepted watershed model that an engineer can input his or her project into, the preferred design approach is frequently not practical. Normal project budgets do not include obtaining survey information far enough downstream to a known water surface elevation that is independent of discharge rates. There may or may not be additional data available for the design engineer to use. Even if there is available data, the designer's fee negotiated with the client usually will not include the modeling effort necessary to model all the way downstream to the watershed outlet.

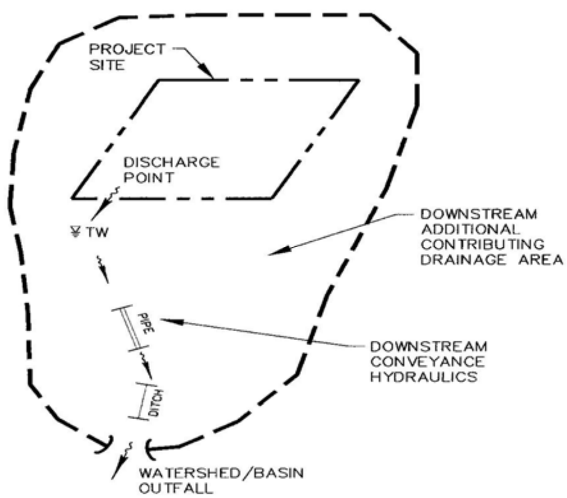


Figure 2

That being said, it is still critical that appropriate tailwater elevations be used in the hydraulic analyses. The first step involves identifying the type of hydraulic facility that is being designed.

TYPICAL TAILWATER DEPENDENT HYDRAULIC STRUCTURES ENCOUNTERED DURING ACTUAL PRACTICE

The type of hydraulic facility being designed is a factor in the determination of the appropriate tailwater elevation or range of elevations. This is because hydraulic systems are designed to meet various flood frequency (recurrence interval) requirements. For instance, the tailwater elevation for a storm drain system on a FDOT arterial roadway (3-year frequency for design) would not necessarily be the same for a cross drain on the same roadway (50-year frequency for design) even if they both discharged at the same lateral ditch. Types of hydraulic conveyance systems affected by tailwater are:

1. **Culverts** are conduit drains that pass under roads, railroads, berms, footpaths, trails, through embankments, etc., and generally drain runoff from the upstream side to the downstream side. Culvert designs are typically associated with a discrete discharge, and corresponding tailwater and headwater elevations. In areas of flat, low-lying terrain, some culverts may serve to hydraulically equalize the water surface elevations at each end. Culverts which are influenced by the tailwater elevation are said to be flowing under "Outlet Control" as previously described.

   Culverts are designed for anywhere from a 10-year flood frequency for a typical side drain pipe to a 50-year event for a cross drain on a major arterial or interstate highway. In addition to the design storm event, cross drains may also be evaluated for more severe events. Federal Highway Administration requirements include evaluating cross drains for the 100-year and 500-year (Greatest Flood) events as well.

2. **Stormwater Pond Control/Discharge Structures** are used to regulate and control discharge from stormwater ponds. A wide variety of structures can serve in this capacity including culverts, weirs, orifices, inlets, etc. that may function as individual elements; or as most commonly used, in combination with each other (i.e. a weir, orifice, and pipe may be combined into one hydraulic structure in which the weir and orifice work in parallel with each other; and in series with the culvert pipe). Stormwater ponds and their control structures are most frequently modeled in hydrodynamic pond routing programs. Tailwater elevations can be constant or vary with regards to discharge or time, depending on the existing conditions at the structure outlet. Discharge rates and upstream stages are determined using a combination of weir flow, orifice flow, and culvert hydraulic

calculations. Within these calculations, there may be submerged weir and/or orifice calculations etc. The “Handbook of Hydraulics,” by Ernest F. Brater and Horace Williams King is an excellent information source for hydraulic design of these individual components.

Stormwater ponds in Florida typically are designed for a 25-year storm event to meet Water Management District criteria. FDOT requires that stormwater management facilities attenuate post-developed discharge rates to meet pre-developed discharge rates for all storms up through and including the 100-year/72-hour event for facilities in open drainage basins; and up through and including the 100-year/240-hour event for closed drainage basins. In addition to these requirements, lesser storm events may have to be evaluated depending on the requirements of the conveyance systems that drain to the ponds.

3. **Storm Drains** are a series of culverts connected by inlets and/or manholes that collect runoff from a series of drainage subareas, and drain the collected stormwater runoff to one or more discharge locations. These locations can be stormwater retention/detention ponds, conveyance ditches, other storm drain systems, open bodies of water, culverts, or overland flow outfalls.

   Storm drain systems are typically designed for recurrence intervals ranging from 3 to 10 years. These systems are often evaluated for more severe storm events that occur less frequently.

4. **Roadside Ditches** drain longitudinally along roadways, footpaths, trails, etc. These ditches collect and drain runoff from the project site as well as runoff from offsite areas. These ditches can discharge into other longitudinal ditches, lateral or outfall ditches, stormwater retention/detention ponds, culverts, or other hydraulic structures.

   Roadside ditches are generally designed for a 10-year flood frequency. However, if the ditch is used as an outfall or for stormwater management, it may have to be evaluated for larger, less frequent storm events.

5. **Lateral or Outfall Ditches** drain away from roadways, footpaths, trails, etc. The bulk of runoff in outfall ditches is usually from offsite areas. Outfall ditches are usually downstream of culverts. These ditches discharge to other ditches,

culverts, downstream hydraulic controls, open water bodies, or may even discharge to storm drain systems.

Lateral or outfall ditches are typically designed for a 25-year frequency. However, larger, less frequent storm events may have to be evaluated as well depending on site conditions or project specific requirements.

6. **Underdrain Systems** are used to lower groundwater elevations. An example of this is lowering the groundwater table elevation to provide adequate clearance for a roadway base. Under drains with sand and filter media are also used in stormwater detention ponds to provide recovery of the water quality treatment volume. Underdrain systems typically discharge to roadside and/or lateral ditches, storm drain systems, culverts, and stormwater retention/detention ponds.

   Recurrence intervals are typically not a major issue in the design of underdrain systems. These systems are typically looked at in terms of water removal and minimum hydraulic capacity. However, a tailwater that is too high may prevent the underdrain from functioning properly.

7. **Bridges** over flowing water bodies are also affected by downstream water surface elevations or tailwater. Flowing streams are governed by open channel flow parameters although the calculations can be complex at times. *This course does not address determination of tailwater (or starting water surface) elevations for bridge hydraulic calculations.*

TYPICAL TAILWATER PHYSICAL CONDITIONS ENCOUNTERED IN ACTUAL PRACTICE

In discussing standard design tailwater conditions for the design of storm drain systems, the Florida Department of Transportation (FDOT) Drainage Manual (Section 3.4) identifies the following typical discharge locations:

1. Lakes
2. Rivers and Streams
3. Stormwater Ponds
4. Tidal Bays
5. Ditches – Free Flowing
6. Ditches – Backwater from downstream controls
7. Existing Storm Drain systems
8. French Drains
9. Closed Basins
10. Regulated Canals

All hydraulic structures typically used for drainage conveyance and stormwater management will outfall into one or more of these typical discharge locations, and it is critical that the proper water surface elevation at these locations (tailwater) be determined.

Conditions found at the outlet end of culverts are typically the tailwater conditions encountered by most hydraulic structures in low-lying, flat terrain. These conditions are identified schematically in Figures 3 through 9. In low-lying, flat terrain, conditions at the outlet end of culverts are sometimes less than desirable. These conditions can include sumps, closed drainage basins, and bubbler structures. Photographs of typical tailwater conditions are shown in Figures 10 through 18.

Typical Tailwater Outlet Conditions

The following figures 3 through 9 illustrate the respective plan and cross section views of typical outlet conditions encountered in actual practice. Figure 10 through 18 are photographs of typical tailwater conditions.

1. Discharging into lateral ditch that drains away from structure

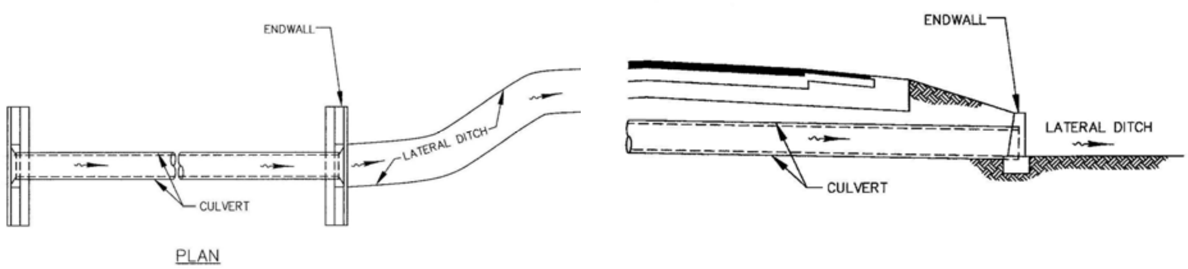


Figure 3

2. Discharging into ditch (i.e. roadway ditch) running parallel to the roadway.

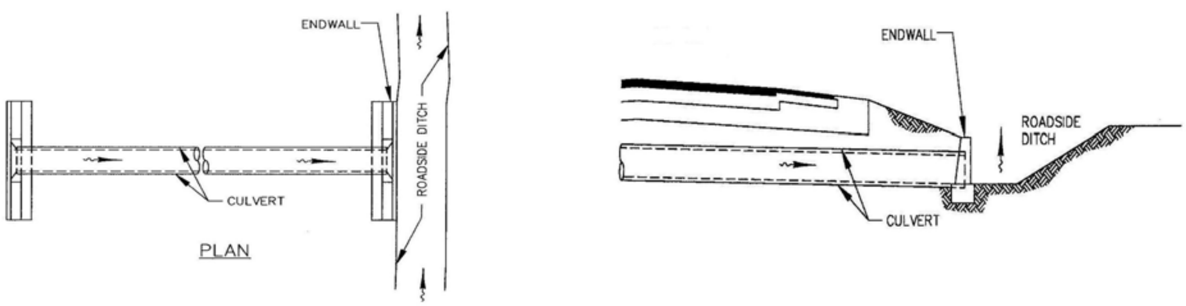


Figure 4

3. Discharging into an open water body

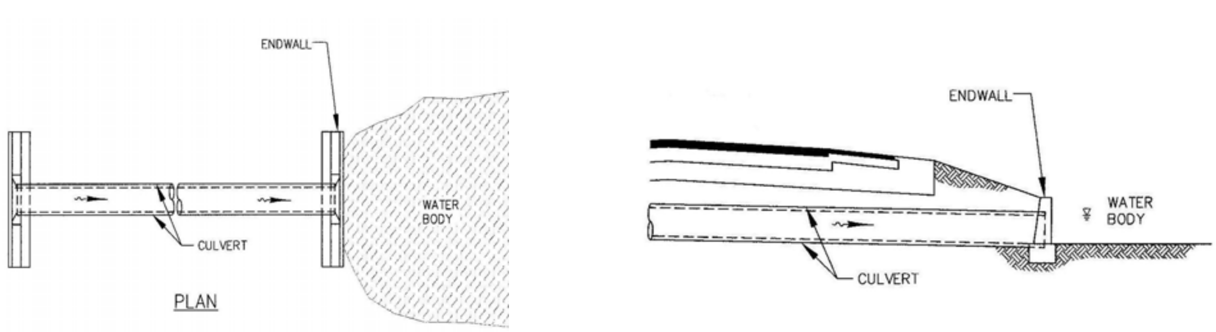


Figure 5

4. Discharging in close proximity to downstream hydraulic structure

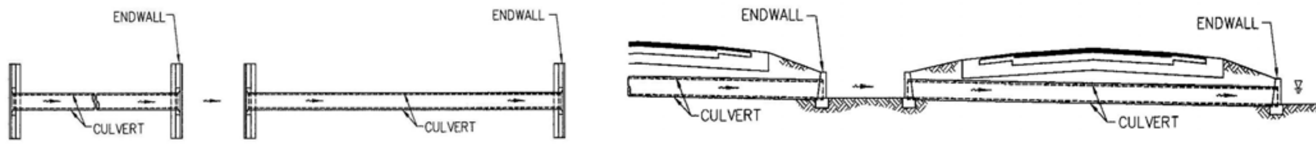


Figure 6

5. Discharging at a location where ground elevations drop rapidly downstream of structure end.

Figure 7

6. Discharging in a sumped outlet condition. The sump could be located such that water exiting the sump can flow overland or the sump could be located within a roadside or lateral ditch.

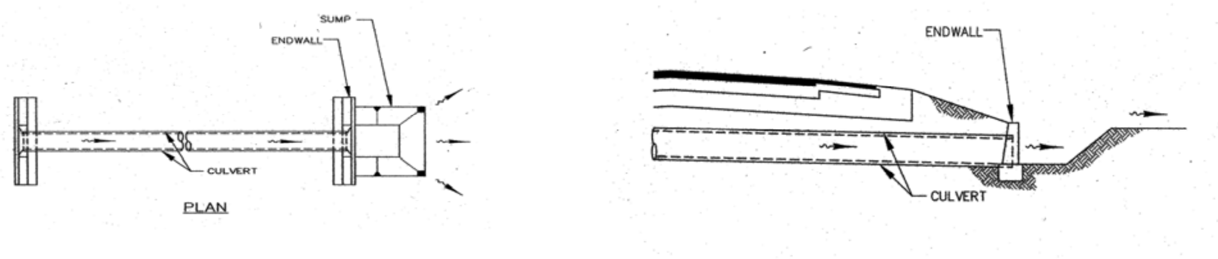


Figure 8

7. Discharging through a "Bubbler Structure." Runoff comes in to a ditch bottom inlet via a storm drain pipe and has to build up to flow out of the inlet through the grated inlet top.

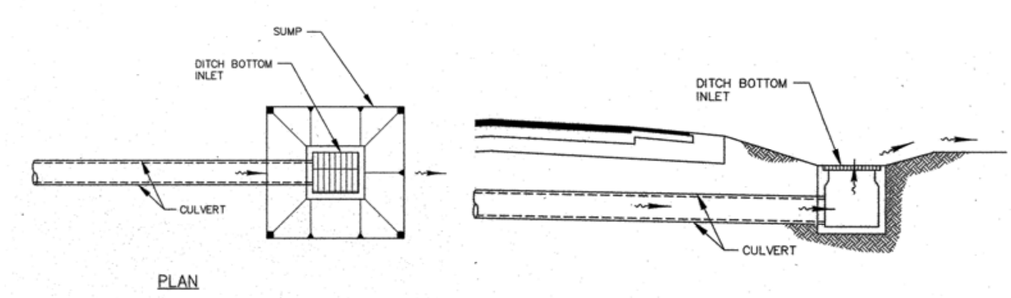


Figure 9

Figure 10: Cross Drain Outlet

Figure 11: Ditch Downstream of Cross Drain Outlet

Figure 12: Detention Pond Dry Conditions

Figure 13: Same Pond Heavy Rainfall

Figure 14: Urban Roadway Dry Conditions

Figure 15: Same Roadway Heavy Rainfall

Figure 16: Pond Outfall into Existing Stream/Lateral Ditch

Figure 17: Ground Drops Away from Culvert Outlet

Figure 18: Discharge into Stormwater Pond

SOURCES OF DATA FOR TAILWATER ESTIMATES

Determination of a suitable tailwater elevation or range of elevations is not a "one size fits all" process. It requires engineering judgment along with hydrologic and hydraulic analyses. Each location will have different physical, hydrologic and hydraulic conditions. Obtaining available data is often only the beginning of the work effort necessary to come up with suitable elevations to be used in design. The data needs to be verified for reasonableness with observed conditions. Sources of data that can be used to estimate design tailwater conditions include but are not limited to:

1. Information from Water Management Districts
2. Local Government Agencies
3. Florida Department of Transportation
4. U.S.G.S.
5. Watershed Studies
6. Recorded High Water Elevations
7. Observed Water Levels
8. Constructed adjacent projects
9. Published data "Best Available Information"
10. Information from adjacent residents, business owners and property owners
11. Federal Emergency Management Agency (FEMA) Flood Insurance Maps and Studies
12. Previous Project Drainage Maps

Field reviews should always be conducted at discharge locations. Field reviews will identify the existence of downstream structures or obstacles which will impact hydraulic elevations. Field reviews can help verify if water is confined to ditches or can overtop the ditch banks. Field reviews are also helpful in identifying the presence of physical or terrain controls which may limit water stages.

TYPICAL AGENCY TAILWATER DESIGN REQUIREMENTS

Standard tailwater design requirements can normally be found in the manuals of local government agencies. These may be client agencies or agencies from which stormwater management permits must be obtained. Agencies may have different requirements. There are times when an engineer may be dealing with multiple agencies and conflicting requirements. This could require the engineer to perform modeling or calculations for multiple tailwater scenarios and storm events.

Tailwater requirements from the Florida Department of Transportation (FDOT) and Hillsborough County are included below.

FDOT Standard Design Tailwater Conditions

The 2009 Florida Department of Transportation Drainage Manual (Section 3.4 for Storm Drain Hydrology and Hydraulics and Section 4.5 for Cross Drains Hydraulics) has identified the following standards for tailwater design.

Storm Drain Systems

For the determination of hydraulic gradient and the sizing of storm drain conduits, a tailwater elevation, which can be reasonably expected to occur coincident with the design storm event, shall be used. Standard design tailwater conditions for the design of storm drain systems are as follows:

Crown of pipe at the outlet, or if higher:

Lakes -----------------------	Normal High Water
Rivers and Streams	Normal High Water
Stormwater Ponds --	Peak stage in the pond during the storm drain design event.
Tidal Bays	Mean High Tide
Ditches:	
Free flowing -------	Normal depth flow in the ditch at the storm drain outlet for the storm drain design storm event. (May differ from ditch design storm event.)
Downstream control ---	The higher of: the stage due to free flow conditions (described above) or, the maximum stage at the storm drain outlet due to backwater from the downstream control using flows from the storm drain design storm event.
Existing Systems ---	Elevation of hydraulic grade line of the system at the connection for the design storm event.

French Drains -----	Design Head over the outlet control structure
Closed Basin -----	Varies, depending on site specific conditions
Regulated Canals ---	Agency control elevation

Cross Drains

Section 4.5 of the 2009 FDOT Drainage Manual says the following in regards to tailwater elevations for cross drains: "For the sizing of cross drains and the determination of headwater and backwater elevations, the highest tailwater elevation which can be reasonably expected to occur coincident with the design storm event shall be used."

Hillsborough County (Florida) Stormwater Technical Manual (July 2008)

The Hillsborough County (Florida) Stormwater Technical Manual (July 2008) gives the following requirements for determining tailwater elevations for storm drain systems and culverts.

Storm Drain Systems

"A design tailwater elevation for each outfall of a storm sewer system must be determined. The design tailwater elevation is the initial downstream elevation for the computed hydraulic grade line. The tailwater elevation must be determined from measured data (if appropriate) or by hydrologic and hydraulic calculation, considering the same design storm frequency used to estimate the design storm sewer flows. In the case where the storm sewer system outfalls to a stormwater pond, if a tailwater elevation cannot be calculated, the hydraulic gradient shall begin at the crown of the discharge pipe at the stormwater pond, or at an elevation equal to the average of the design high water and normal pool elevations of the stormwater pond, whichever elevation is higher. Also, for storm sewers outfalling to Tampa Bay and all adjoining bays, the design tailwater or hydraulic grade elevation shall be assumed to be no lower than elevation 1.6

feet NAVD 88." (Page 9-3 in Section J – DESIGN TAILWATER; 2008 Hillsborough County Stormwater Technical Manual).

Culverts

Page 8-2 in Section I of the Hillsborough County (Florida) Stormwater Technical Manual gives the following requirements for the DESIGN TAILWATER for culverts:

1. All culvert installations shall be designed taking into consideration the tailwater of the receiving facility or body of water (inlet or outlet control). The tailwater elevation must be determined by hydrologic and hydraulic calculations based upon the design criteria and frequencies shown in Table 6-1 (Refer to Page 6-22 of the Hillsborough County Stormwater Technical Manual).

    a. When the tailwater elevation is higher than the proposed culvert crown elevation, the downstream hydraulic grade line elevation shall be at the tailwater elevation.
    b. When the tailwater elevation is below the culvert crown elevation, the downstream hydraulic grade line elevation shall be at or above the crown of the proposed culvert for final design.
    c. Ditch-bottom inlets or "bubbler boxes" designed to discharge as an outfall from ponds are not permitted.

Note: The design criteria cited above are from only two agencies, the Florida Department of Transportation and Hillsborough County. Design Engineers are cautioned to verify the requirements of their applicable client agencies as well as the applicable stormwater permitting agencies.

COMMON PITFALLS IN ESTIMATING TAILWATER ELEVATIONS

Agency design criteria should be used along with engineering judgment in the establishment of tailwater elevations. Available hydrologic and hydraulic data needs to be obtained. Time spent reviewing available data and observing actual conditions in the field will help avoid some of the more common pitfalls in estimating tailwater elevations, which are identified below.

1. Assuming a Constant Tailwater Elevation for a Range of Discharges From Various Storm Events
    a. Downstream conditions can vary depending on discharges and/or water stages (i.e. low flows confined to channel; at high flows there is overbank flow, which reduces the rate that water stages will increase)
        i. The higher conveyance capacity and additional storage area associated with overbank flow areas allows higher discharge rates without significantly increasing water stages.
    b. Lower water surface elevations are usually associated with lower discharge rates
    c. Assumption of a constant tailwater is usually not valid in dynamic routing calculations if a project site is being modeled and the site discharges upstream of additional conveyances and contributing drainage areas.

2. Accepting Watershed Model Results Prepared by Others Without Verification that Model Results are Reasonable
    a. Even adopted, approved, and commonly accepted models may have errors.
    b. The engineer using the data needs to verify for consistency with current physical conditions, observed water levels, etc.
        i. Are the model results reasonable? Can water stages actually get as high as the model says, or will water break over at lower elevations such that it is not possible for water to reach the predicted elevations.
        ii. Conversely, will actual stages get higher than modeled? Is there a downstream control that was not modeled that will prevent or limit discharges and cause higher water stages?
        iii. Are flow rates consistent between model nodes or junctions? Has existing storage been properly accounted for within the model?
    c. Have conditions changed from those that were originally modeled? Has the model been updated to reflect those changes?

3. Making Assumption of Using High Tailwater for "Conservative" Design
    a. Assuming the highest practical tailwater may be conservative for design of a cross drain. However, assuming the same elevation for the outlet of a stormwater pond may result in higher pond stages, translating into a larger pond; more fill for the site; larger drainage structures, etc.

   b. Assuming higher tailwater may result in underestimating the post-developed discharge rate, which can lead to downstream flooding problems.

4. Combining Cross Drain Calculations and Pond Routing Calculations in One Hydrodynamic Model
   a. Engineers have begun doing this to provide comprehensive models that address detention/retention ponds, storm drains, and cross drains.
   b. Tailwater elevations for stormwater pond design discharges may not correlate to the same frequency events as those for designing cross drains.
      i. Using a higher tailwater elevation to satisfy the design criteria for cross drains may result in too high of a tailwater elevation for stormwater pond discharge structures, or storm drain systems, if modeled.
      ii. Similarly, using a tailwater elevation to satisfy storm drain or stormwater pond criteria may result in a too low of a tailwater for the cross drain computations.
   c. This comprehensive modeling approach works best when the entire watershed is modeled and the ultimate discharge point is at a water body where stages are NOT time or discharge dependent. Properly developed models can account for the various peaks in flow rates and water surface elevations for each of the stormwater management system components as well as the timing differentials between them.
   d. If cross drain and pond routing calculations are combined in one model, the engineer may have to run several scenarios. In the case of a project for a FDOT District, the Drainage Department accepted the modeling for the purposes of the stormwater pond designs, but required the engineer to perform separate HY-8 calculations for all of the cross drains on the project, with tailwater elevations in accordance with FDOT criteria.

5. Assuming Seasonal High Water or Culvert Stain Lines as Tailwater Elevations for 50-year, 100-year and 500-year Storm Events for Cross Drain Culvert Design.
   a. Water surface elevations that occur frequently enough, and stay at those levels long enough to support wetland vegetation or cause staining and/or etching of the concrete away from the aggregate of culvert barrels and endwalls, are not appropriate indicators of tailwater elevations for the types of storm events typically evaluated for cross drain design.

b. These elevations typically correlate closer to seasonal high water or normal water (2.33-year design frequency) levels.
c. It should be intuitive to the engineer that higher tailwater and headwater stages should be expected when looking at typical cross drain designs for 25-year and greater storm events.
d. Severe storm events typically will leave debris lines on culvert endwalls that usually only remain present for short periods after the storm event.

6. Not Considering Recorded High Water Elevations in Determining Tailwater
    a. Historical FDOT Drainage Maps often include high water elevations along with present water elevations taken at the time of survey. These elevations can be useful to the Engineer in helping to determine if assumed or calculated tailwater stages appear reasonable. Caution needs to be used with these recorded stages, however, because conditions may have changed over time. Development may have altered terrain or added drainage conveyances such that historical high water elevations are no longer feasible.
    b. Or, changes may have been made that trap water such that current conditions can result in higher stages than those that have occurred historically.
    c. Photographs in Figures 12 and 13 show a stormwater pond in dry conditions and the same pond during heavy rainfall. After reviewing these photographs of the water level overtopping the pond banks, it would be prudent for the designer to consider using a tailwater elevation higher than standard for the storm drain calculations.

7. Ignoring Downstream Contributing Drainage Area Influences on Tailwater
    a. The schematic drawing in Figure 2 shows additional drainage area contributing to the outfall conveyance downstream of the project site's discharge point. This additional drainage area results in higher discharges at the downstream culvert and in the ditch. Depending on the timing of when the runoff from the downstream contributing drainage area gets to the ditch, there could be higher stages in the ditch or upstream of the culvert.
    b. How much of an impact, if any, the additional contributing area will have on conveyance stages depends on the slope of the conveyance, and the time of concentration of the runoff from the downstream contributing

areas. A steeper slope on the ditch will result in less impact, while a shorter time of concentration can result in greater impact.

8. Not Accounting for Downstream Controls or Structures in Ditches Which May Generate Backwater
    a. Most ditches, whether roadside or lateral, will at some point cross under a road, trail, or berm via a culvert, and the headwater elevation on the upstream end of the culvert, may impact the tailwater elevation at the project site's discharge location. The significance of the impact, if any, depends on the channel slope, the distance from the project site's discharge point relative to the downstream culvert, and the flow rate through that culvert.
    b. Other downstream controls may exist in ditches as well, such as weirs, or ditch blocks that may create backwater impacts, such that tailwater depths at the project discharge point are higher than depths determined assuming normal depth flows in the ditch.
    c. More frequently, roadside ditches are being used for stormwater management (treatment and attenuation), particularly for roads that are being widened within existing right-of-way. Because these ditches are retaining/detaining the treatment and attenuation volumes, stormwater management stages in the ditch may be higher than stages based on normal depth calculations.

9. The Seasonal High Water Elevation Downstream at the Discharge point is higher than Seasonal High Water of the Project Site Stormwater Pond
    a. This happens more frequently than one would expect and is not necessarily a problem for a dry retention pond. However for a wet detention pond, the bleed-down orifice/weir will not function properly and the pond will not recover its treatment volume. In the case of wet detention ponds, the pond control elevation should be at or higher than the downstream seasonal high water elevation in order to assure positive drainage at low flow conditions.

10. Tailwater Elevations At Existing Storm Drain Systems
    a. Standard practice for the Florida Department of Transportation with regards to storm drain design has been to design the system so that the

hydraulic gradient is one-foot below the inlet elevation for the design storm event if minor hydraulic losses in the system are not calculated.

b. If minor losses are accounted for in the calculations, the FDOT will allow the hydraulic gradient elevation to reach the inlet elevation.
c. Often, site development engineers do not have any information on the storm drain systems that their site discharges into. Some have used the crown of their discharge pipe as the tailwater elevation; while some have even used the pipe invert. Some engineers have assumed that the gradient is 1-ft. below the inlet elevation at the point where their system ties to the existing storm drain system.
d. Assuming the 1-ft. gradient clearance, while better than the pipe crown and pipe invert assumptions, is no guarantee that the assumed elevation is appropriate, particularly if the minor losses were accounted for and the system's gradient is allowed to rise to the inlet elevation.
e. Storm drain systems are usually designed for more frequent, less severe storm events. This needs to be taken into account by the design engineer, particularly when stormwater ponds (usually designed for less frequent, more severe storm events) discharge into storm drain systems.
f. As with all outfall conditions, observation of the actual system performance is key in determining whether the appropriate tailwater elevation has been assumed. Photograph Figures 14 and 15 show a roadway in dry conditions and when flooded during heavy rainfall. Clearly, if a site development project was to discharge into the roadway's storm drain system with an assumed 1-ft. gradient clearance, the site's stormwater management system would experience significant problems during heavy rainfall events.

11. Not Hydraulically Accounting for Physical Conditions at Discharge Points
    a. Figure 6 shows one culvert discharging upstream of and in close proximity to the downstream culvert. Rather than assuming the tailwater at the pipe crown, if one calculates the headwater elevation on the downstream culvert and it is above the crown of the upstream pipe, a logical approach is to use the calculated headwater elevation of the downstream pipe as the tailwater for the upstream pipe.
    b. Figure 8 shows a culvert discharging into a sump condition. For water to continue to flow away from the culvert, once the sump fills up, water has

to pop over the top-of-bank of the sump in order to continue to flow. The back of the sump acts as a weir and additional head loss should be determined for flow over the weir in order to estimate the tailwater elevation.

c. Figure 9 shows a bubbler structure. Although some agencies do not permit these as discharge structures, several agencies do allow them. Many engineers will set the tailwater at the pipe crown and not hydraulically account for the additional head losses involved with this type of structure. Similar to 11b, the tailwater calculations should include the headloss out of the sump. In addition, the headloss associated with orifice flow through the grate openings of the ditch bottom inlet structure should also be determined. Streamline Technologies, on their website: (http://www.streamnologies.com/modeling_tips/bubbler_systems/icpr_tips_bubbler.htm), gives a suggested modeling approach for these types of systems.

d. Some hydraulic structures discharge into closed basins, where the only outlet is infiltration/percolation into the ground. It may or may not be appropriate to assume a tailwater elevation at the pipe crown, but the engineer needs to know the rate at which water infiltrates into the ground, and probably needs to route the storm runoff through the closed basin area accounting for the storage and infiltration in order to verify the assumed tailwater elevation. Recovery calculations will be volume dependent in closed basins. The design Engineer may be required to estimate tailwater conditions after successive storm events.

12. Using Incorrect Vertical Datum

a. The FDOT has recently adopted the 1988 NAVD as the datum for design. Many local cities and counties used the 1988 NAVD as the design datum for several years now. However, much of the historical available data (plans and calculations) is per the 1929 NGVD. When verifying calculated or assumed tailwater elevations using previous plans and calculations, the engineer needs to be sure she/he is working from the same datum. Using elevations from different datums can result in significant errors in hydraulic results, including errors in tailwater elevations.

13. Not Accounting for Size of Project Area Relative to Watershed Size and Timing of Tailwater Peak Stages
    a. Intuitively, it would be expected that the runoff from a project site, which is small relative to the overall watershed size, and has a shorter time of concentration, would be "in and out" by the time the peak runoff from the watershed gets to this discharge point.
    b. Correspondingly, the tailwater stage of the receiving water at the time runoff from the project site hits; will be lower than the stage at the time the peak runoff from the larger watershed hits. Intuitively, it would be expected that a lower tailwater stage could be used for the project site design.
    c. However, determining the timing of these two events is more difficult unless both the project site and the watershed are included in a comprehensive model as discussed above in Section 4.
    d. If not included in the same model, it may be possible to get the watershed model's stage/time data at the appropriate node/junction and input that into the project site's model. This approach would have to be approved the client agency, if a public project, and the appropriate regulatory permitting agency.

14. Biggest Pitfall – Not Adequately Documenting Assumptions Made in Establishing Tailwater Elevations
    a. FDOT typically requires project drainage documentation to be prepared such that an engineer with experience in drainage and hydraulics, while not necessarily familiar with the project, can understand the design and the assumptions involved in developing the design. This includes how tailwater elevations are determined.
    b. Adequately documenting how the tailwater elevations were determined (including stating the assumptions and providing required calculations as necessary) can reduce the amount of time spent by client and/or permitting agency reviewers. Documentation should include the sources of data used in estimating the tailwater elevations.

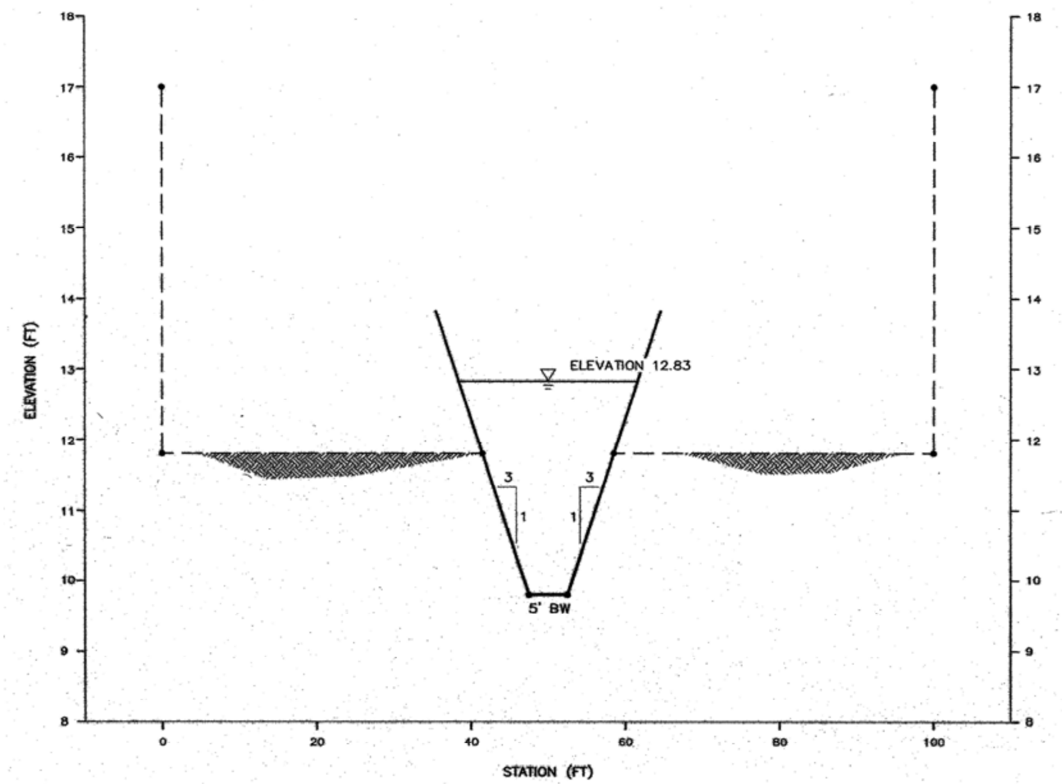
EXAMPLE

One of the pitfalls in determination of tailwater elevations is not accounting for actual physical downstream conditions in the calculations.

The Federal Highway Administration (FHWA) HY-8 culvert design program will calculate normal depth in a ditch downstream of the culvert for the flows under consideration and will develop a tailwater rating curve. In the example which follows, discharges from 50 to 52 cfs were input into the program along with a trapezoidal cross section of a 5' bottom width ditch with 1:3 side slopes on a 0.0005% slope; and a Manning's roughness coefficient of 0.04. The HY-8 Program assumes the channel remains trapezoidal for all water depths, since the program does not require inputting the channel top of bank elevations. The enclosed calculations result in a normal depth tailwater elevation of 12.83 at the outlet end of the pipe and a headwater elevation of 14.61 on the upstream end of the pipe. This is illustrated graphically in Figure 19, which illustrates how HY-8 extends the trapezoidal channel side slopes above the actual top of bank elevation. By assuming the channel remains trapezoidal, water is not able to flow in the overbank sections, resulting in a higher water surface elevation. The associated HY-8 calculations for the trapezoidal ditch assumption are included on the following pages.

Compare this to Figure 20 which shows that the top of bank of the trapezoidal portion of the channel is actually at elevation 11.8, similar to an actual physical condition in which there would actually be overbank flow. Using the irregular channel option for the above main channel characteristics along with the actual overbank conditions in HY-8 serves to lower the normal depth tailwater at the outlet end of the culvert to elevation 12.34 and the corresponding headwater elevation on the upstream end of the pipe is 14.28.

The 0.33' difference in headwater elevations would not be considered significant in areas with topographic relief, but in flat terrain areas such as portions of central and southern Florida, this can make the difference in whether a project gets a permit or not, or whether an upstream property owner can claim damage due to a project improvement.



TRAPEZOIDAL CHANNEL CROSS SECTION

Figure 19

Table 1 - Summary of Culvert Flows at Crossing: Example_Trapezoidal

Headwater Elevation (ft)	Total Discharge (cfs)	Culvert 1 Discharge (cfs)	Roadway Discharge (cfs)	Iterations
14.43	50.00	50.00	0.00	1
14.44	50.20	50.20	0.00	1
14.46	50.40	50.40	0.00	1
14.48	50.60	50.60	0.00	1
14.50	50.80	50.80	0.00	1
14.52	51.00	51.00	0.00	1
14.53	51.20	51.20	0.00	1
14.55	51.40	51.40	0.00	1
14.57	51.60	51.60	0.00	1
14.59	51.80	51.80	0.00	1
14.61	52.00	52.00	0.00	1
17.00	73.59	73.59	0.00	Overtopping

Table 2 - Culvert Summary Table: Culvert 1

Total Discharge (cfs)	Culvert Discharge (cfs)	Headwater Elevation (ft)	Inlet Control Depth (ft)	Outlet Control Depth (ft)	Flow Type	Normal Depth (ft)	Critical Depth (ft)	Outlet Depth (ft)	Tailwater Depth (ft)	Outlet Velocity (ft/s)	Tailwater Velocity (ft/s)
50.00	50.00	14.43	3.998	4.427	7-M2t	3.000	2.293	2.980	2.980	7.080	1.203
50.20	50.20	14.44	4.014	4.444	7-M2t	3.000	2.298	2.986	2.986	7.106	1.205
50.40	50.40	14.46	4.029	4.462	7-M2t	3.000	2.302	2.991	2.991	7.132	1.206
50.60	50.60	14.48	4.045	4.479	7-M2t	3.000	2.307	2.997	2.997	7.159	1.207
50.80	50.80	14.50	4.060	4.497	4-FFf	3.000	2.311	3.000	3.002	7.187	1.208
51.00	51.00	14.52	4.076	4.515	4-FFf	3.000	2.316	3.000	3.007	7.215	1.209
51.20	51.20	14.53	4.092	4.534	4-FFf	3.000	2.320	3.000	3.013	7.243	1.210
51.40	51.40	14.55	4.107	4.553	4-FFf	3.000	2.325	3.000	3.018	7.272	1.212
51.60	51.60	14.57	4.123	4.572	4-FFf	3.000	2.330	3.000	3.024	7.300	1.213
51.80	51.80	14.59	4.139	4.591	4-FFf	3.000	2.334	3.000	3.029	7.328	1.214
52.00	52.00	14.61	4.155	4.610	4-FFf	3.000	2.339	3.000	3.035	7.356	1.215

****

Inlet Elevation (invert): 10.00 ft,   Outlet Elevation (invert): 9.80 ft

Culvert Length: 100.00 ft,   Culvert Slope: 0.0020

Site Data - Culvert 1

Site Data Option: Culvert Invert Data

Inlet Station: 0.00 ft

Inlet Elevation: 10.00 ft

Outlet Station: 100.00 ft

Outlet Elevation: 9.80 ft

Number of Barrels: 1

Culvert Data Summary - Culvert 1

Barrel Shape: Circular

Barrel Diameter: 3.00 ft

Barrel Material: Concrete

Embedment: 0.00 in

Barrel Manning's n: 0.0120

Inlet Type: Conventional

Inlet Edge Condition: Square Edge with Headwall

Inlet Depression: None

Table 3 - Downstream Channel Rating Curve (Crossing: Example_Trapezoidal)

Flow (cfs)	Water Surface Elev (ft)	Depth (ft)	Velocity (ft/s)	Shear (psf)	Froude Number
50.00	12.78	2.98	1.20	0.09	0.16
50.20	12.79	2.99	1.20	0.09	0.16
50.40	12.79	2.99	1.21	0.09	0.16
50.60	12.80	3.00	1.21	0.09	0.16
50.80	12.80	3.00	1.21	0.09	0.16
51.00	12.81	3.01	1.21	0.09	0.16
51.20	12.81	3.01	1.21	0.09	0.16
51.40	12.82	3.02	1.21	0.09	0.16
51.60	12.82	3.02	1.21	0.09	0.16
51.80	12.83	3.03	1.21	0.09	0.16
52.00	12.83	3.03	1.21	0.09	0.16

Tailwater Channel Data - Example_Trapezoidal

Tailwater Channel Option: Trapezoidal Channel

Bottom Width: 5.00 ft

Side Slope (H:V): 3.00 (_:1)

Channel Slope: 0.0005

Channel Manning's n: 0.0400

Channel Invert Elevation: 9.80 ft

Roadway Data for Crossing: Example_Trapezoidal

Roadway Profile Shape: Constant Roadway Elevation

Crest Length: 100.00 ft

Crest Elevation: 17.00 ft

Roadway Surface: Paved

Roadway Top Width: 100.00 ft

IRREGULAR CHANNEL CALCULATIONS

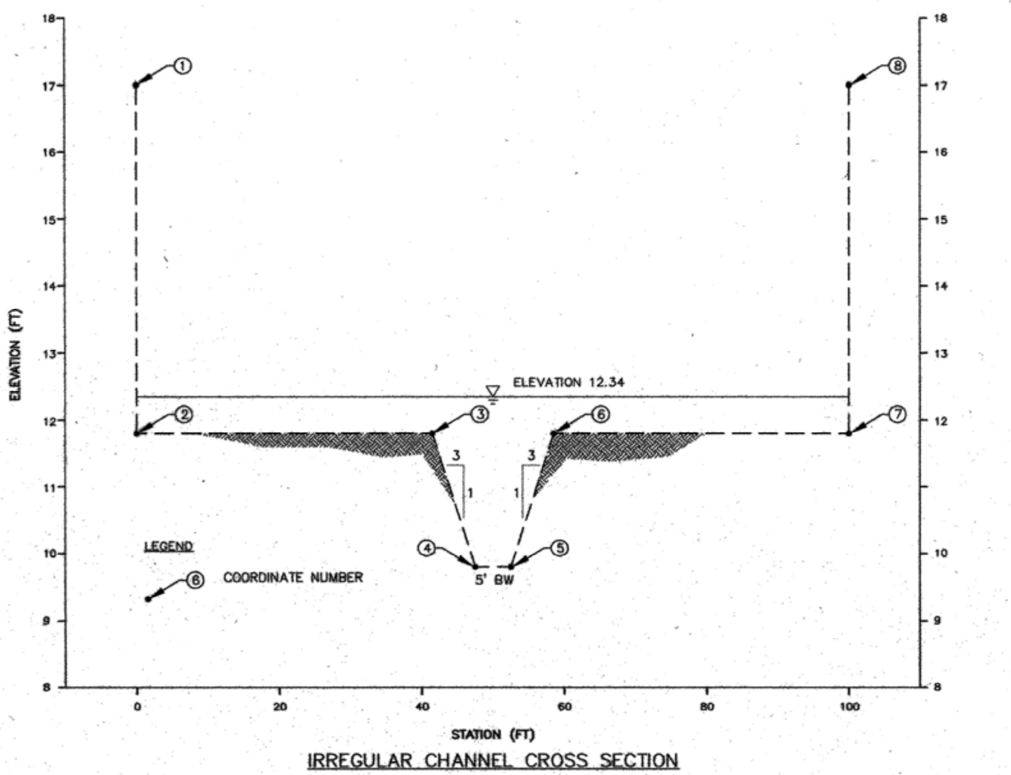


Figure 20

Table 1 - Summary of Culvert Flows at Crossing: Example-_Irregular

Headwater Elevation (ft)	Total Discharge (cfs)	Culvert 1 Discharge (cfs)	Roadway Discharge (cfs)	Iterations
14.13	50.00	50.00	0.00	1
14.14	50.20	50.20	0.00	1
14.15	50.40	50.40	0.00	1
14.17	50.60	50.60	0.00	1
14.18	50.80	50.80	0.00	1
14.20	51.00	51.00	0.00	1
14.21	51.20	51.20	0.00	1
14.23	51.40	51.40	0.00	1
14.25	51.60	51.60	0.00	1
14.26	51.80	51.80	0.00	1
14.28	52.00	52.00	0.00	1
17.00	79.39	79.39	0.00	Overtopping

Table 2 - Culvert Summary Table: Culvert 1

Total Discharge (cfs)	Culvert Discharge (cfs)	Headwater Elevation (ft)	Inlet Control Depth (ft)	Outlet Control Depth (ft)	Flow Type	Normal Depth (ft)	Critical Depth (ft)	Outlet Depth (ft)	Tailwater Depth (ft)	Outlet Velocity (ft/s)	Tailwater Velocity (ft/s)
50.00	50.00	14.13	3.998	4.127	3-M2t	3.000	2.293	2.522	2.522	7.882	0.673
50.20	50.20	14.14	4.014	4.142	3-M2t	3.000	2.298	2.524	2.524	7.908	0.675
50.40	50.40	14.15	4.029	4.153	3-M2t	3.000	2.302	2.526	2.526	7.935	0.676
50.60	50.60	14.17	4.045	4.171	3-M2t	3.000	2.307	2.528	2.528	7.962	0.677
50.80	50.80	14.18	4.060	4.180	3-M2t	3.000	2.311	2.530	2.530	7.988	0.678
51.00	51.00	14.20	4.076	4.196	3-M2t	3.000	2.316	2.531	2.531	8.015	0.679
51.20	51.20	14.21	4.092	4.214	3-M2t	3.000	2.320	2.533	2.533	8.041	0.680
51.40	51.40	14.23	4.107	4.229	3-M2t	3.000	2.325	2.535	2.535	8.068	0.681
51.60	51.60	14.25	4.123	4.247	7-M2t	3.000	2.330	2.537	2.537	8.094	0.682
51.80	51.80	14.26	4.139	4.263	7-M2t	3.000	2.334	2.538	2.538	8.121	0.683
52.00	52.00	14.28	4.155	4.279	7-M2t	3.000	2.339	2.540	2.540	8.147	0.684

****

Inlet Elevation (invert): 10.00 ft,   Outlet Elevation (invert): 9.80 ft

Culvert Length: 100.00 ft,   Culvert Slope: 0.0020

****

Site Data - Culvert 1

Site Data Option: Culvert Invert Data

Inlet Station: 0.00 ft

Inlet Elevation: 10.00 ft

Outlet Station: 100.00 ft

Outlet Elevation: 9.80 ft

Number of Barrels: 1

Culvert Data Summary - Culvert 1

Barrel Shape: Circular

Barrel Diameter: 3.00 ft

Barrel Material: Concrete

Embedment: 0.00 in

Barrel Manning's n: 0.0120

Inlet Type: Conventional

Inlet Edge Condition: Square Edge with Headwall
Inlet Depression: None

Table 3 - Downstream Channel Rating Curve (Crossing: Example-_Irregular)

Flow (cfs)	Water Surface Elev (ft)	Depth (ft)	Velocity (ft/s)	Shear (psf)	Froude Number
50.00	12.32	2.52	0.67	0.08	0.14
50.20	12.32	2.52	0.67	0.08	0.14
50.40	12.33	2.53	0.68	0.08	0.14
50.60	12.33	2.53	0.68	0.08	0.14
50.80	12.33	2.53	0.68	0.08	0.14
51.00	12.33	2.53	0.68	0.08	0.14
51.20	12.33	2.53	0.68	0.08	0.14
51.40	12.33	2.53	0.68	0.08	0.14
51.60	12.34	2.54	0.68	0.08	0.14
51.80	12.34	2.54	0.68	0.08	0.14
52.00	12.34	2.54	0.68	0.08	0.14

Tailwater Channel Data - Example-_Irregular

Tailwater Channel Option: Irregular Channel

Channel Slope: 0.0005

User Defined Channel Cross-Section:

Coord No.	Station (ft)	Elevation (ft)	Manning's n
1	0.00	17.00	0.0400
2	0.00	11.80	0.0400
3	41.50	11.80	0.0400
4	47.50	9.80	0.0400
5	52.50	9.80	0.0400
6	58.50	11.80	0.0400
7	100.00	11.80	0.0400
8	100.00	17.00	0.0400

Roadway Data for Crossing: Example-_Irregular

Roadway Profile Shape: Constant Roadway Elevation

Crest Length: 100.00 ft

Crest Elevation: 17.00 ft

Roadway Surface: Paved
Roadway Top Width: 100.00 ft

CONSEQUENCES OF OVER OR UNDERESTIMATED TAILWATER ELEVATIONS

1. If the estimated tailwater is too high and the actual tailwater is lower than calculated, this translates to lower actual headwater (upstream) stages. Looking at a pond discharge structure, which handles a certain discharge with a weir/orifice and pipe in a typical drop structure configuration, for example. If the tailwater elevation was estimated to be half a foot higher than it actually is; all things (pond size, discharge rates, control structure dimensions and pipe size, etc.) being equal, the actual headwater on the pond discharge structure could be up to a half a foot lower than calculated. That means that instead of providing 1-ft. of freeboard, the pond now provides 1.5' ft of freeboard, which is overdesigned. The pond could have been made smaller or shallower. Perhaps less fill could have been used for the site. Other consequences include:
    a. Larger than necessary stormwater ponds and pipe/culvert systems
    b. More fill for project sites to meet gradient clearance requirements
    c. Higher costs
    d. Potential adverse impacts to downstream property owners due to actual discharges being higher with the lower tailwater, than those discharges that were anticipated with the higher tailwater estimate.

2. If the estimated tailwater is too low and the actual tailwater is higher than estimated, this translates to higher actual headwater stages. For that same example scenario with all things being equal and the actual tailwater is a half a foot higher than predicted, problems opposite of those described above can occur. These include the following:
    a. Increased potential for project site to flood

   b. Stormwater management system does not function as designed
   c. Higher costs with mitigating flood problems; litigation, etc.
   d. Adverse impacts to upstream property owners due to increased water stages

3. If the tailwater for an underdrain system is higher than anticipated, the underdrain may not function as designed. In the case of an underdrain used for treating stormwater, the higher actual tailwater could prevent the pond from recovering. If the underdrain is used to control groundwater for base clearance, the higher than anticipated tailwater would prohibit groundwater from drawing down, which could adversely impact the roadway base and pavement.

CONSIDERATIONS IN ESTIMATING TAILWATER ELEVATIONS

The designer needs to imagine himself/herself as a drop of water traveling through the system. Can the water drop successfully navigate the conveyance? What obstacles would the drop have to overcome in order to get to the ultimate discharge point? Will it have to travel through a bubble-up structure? Will it have to traverse a weir in a ditch? Will it run into a "wall" of ponded water? Will it discharge to a storm drain system that is flowing at capacity? What is the level of the water at each of these locations? What additional energy will the water droplet need in order to get to its destination which is the project discharge point? This additional energy is the hydraulic "head" which shows up as an increase in the water surface elevation of the receiving water. This increase in tailwater is in turn reflected in higher headwater elevations on the upstream end of the hydraulic structure that discharges to the receiving water.

There are several things that the Engineer should consider when determining tailwater elevations. These will help the Engineer avoid some of the common pitfalls that can impact the hydraulic design.

1. Identify the required design frequency for the drainage system under design.
   a. i.e. Storm drain systems are not usually designed to the same frequency as cross drains or stormwater ponds.
   b. Don't always blindly accept a minimum tailwater elevation which corresponds to the design frequency. Consider whether the importance of the facility, risks and impacts associated with flooding, etc. justify a more conservative approach and possibly a higher tailwater?

2. Identify any physical constraints at the project discharge point or at downstream locations that can result in higher than anticipated tailwater elevations.

3. Identify any physical conditions that exist at the project discharge point that would result in lower than anticipated tailwater elevations.

4. Make sure the physical conditions at the discharge point are hydraulically accounted for (i.e. if ground acts as a weir, provide weir calculations) in determining the tailwater elevations.

5. Based on available data and field review determine if the predicted tailwater elevations are reasonable.

6. When comparing data from previous studies, calculations, plans, etc., make sure which datum was used and convert to current datum if necessary.

7. If discharging into an existing storm drain system, obtain the storm drain tabulations for the project in which the existing system was constructed. Old FDOT systems were generally designed to meet a 1-ft hydraulic gradient clearance at inlets. New systems allow the gradient to come up to just below the inlet elevation if minor losses are calculated in storm drain system. This could be a significant impact to your system. Also, verify the design frequency of the existing system and compare it to that of the project site.

8. Clearly document the assumptions made in determining tailwater elevations. Provide photographs at discharge locations which support the assumptions as well as supporting calculations.

The opinions expressed in this course are the opinions of the author and do not constitute direction on the design of any project. Each tailwater location is different. It is the responsibility of the design engineer based on experience and engineering judgment, as well as the requirements of client and regulatory permitting agencies, to determine the best approach to determine tailwater elevations at each location.