Maryland State Highway Administration

Highway Hydraulics Division
Guidelines for Preparing Stormwater Management Concept Reports
April 2003 Draft

1.0 Introduction

Over the past two decades, stormwater management (SWM) has become one of the major design requirements for projects undertaken by the Maryland State Highway Administration (SHA). Early in its implementation, stormwater management design was often an afterthought that was only addressed after most of the highway design decisions had been made. This process resulted in late identification of right-of-way requirements, costs, community impacts, and design conflicts, which in turn led to poor designs and project delays.

Recently in the last decade, progress has been made in identifying stormwater management needs during the early stages of design projects. However, the process and technology for identifying stormwater management needs for major projects in the project planning phase is still in its beginning stages. Often, projects that go through the project planning phase do not have identification of complete environmental impacts associated with stormwater management. Furthermore, the 2001 Stormwater Management Guidelines for State and Federal Projects have introduced a need for much more intense evaluation of stormwater management design. These new requirements, coupled with the new SHA approach to provide context-sensitive products to the stakeholders has led to a new step called conceptual stormwater management design. The SWM regulations are understood by most hydraulics engineers who perform work for SHA. These guidelines are intended for design engineers to address stormwater management for SHA projects in the concept development stages. The guidance provided herein should be used in conjunction with all other applicable design guidelines and regulations. The most important references are:

1) Maryland Department of the Environment (MDE) Stormwater Management Guidelines for State and Federal Projects, 2001.
2) Maryland Stormwater Design Manual (SDM), MDE, 2000.
3) Highway Drainage Manual.
4) SHA's NPDES Permits.
5) Any existing watershed studies in the project area.

SHA major capital projects go through different phases:

1) Regional Planning Phase, where transportation corridors and needs are identified.
2) Project Planning Phase, during which projects follow the public process required under the National Environmental Policy Act (NEPA). This phase ends when the NEPA documents such as the Environmental Impact Statement and Location/Design Approval are completed.

3) Final Design Stage, where the design details are developed and carried through advertisement and bid opening.
4) Construction phase, where bids are opened, the contracts are awarded, and the projects are constructed.
5) Maintenance or Operations phase, where the constructed projects are accepted for maintenance.

The major projects that go through the above phases now reach 30-60 percent plan completion stage by the time Location/Design Approval is received. Although some of the smaller projects may skip the full NEPA process, they are still subject to the environmental regulations (Examples of such projects are system preservation and safety improvement projects). The smaller projects start with design initiation and a concurrent NEPA environmental assessment process. For this reason, there are differences between stormwater management concept processes for projects that go through project planning and projects that do not. These guidelines will address the differences under the different sections below.

2.0 Stormwater Management Concepts in Project Planning

2.1 Purpose

The environmental impact statement (EIS) and Finding of No Significant Impact (FONSI) process require documentation of impacts, their avoidance, minimization, and proposed mitigation. As part of this process, stormwater management should be considered in determining impacts to cultural and natural resources, as well as socioeconomic issues. In some situations, stormwater management can be so difficult to accomplish that it may impact the viability of the highway alternatives being studied. The project planning process is also used by SHA to estimate project costs that will later be used in earmarking funding for projects when their priorities rise. It is, therefore, important to develop stormwater management concepts during the project planning phase and utilize them in impact assessment as well as cost estimating.

2.2 When to Develop Concepts

The stormwater concept studies should start when alternates are selected for detailed study. These studies can start earlier if the range of alternates or solutions available is fairly narrow and the constraints for all alternates are approximately the same.

2.3 How to Develop Concepts

Stormwater management concepts should be developed by hydraulics engineers experienced in stormwater management design for SHA projects, with support from project planners, landscape architects and environmental managers. The study should be completed according to the schedule laid out by SHA, but prior to the Location/Design Hearing. Guidance on specific projects should be sought from SHA's Highway Hydraulics Division.

2.3.1 Regulatory Needs

One of the first steps in developing stormwater management concepts is to identify relevant regulatory requirements. Regulatory requirements for each county or watershed canbe found in the latest version of MDE Stormwater Management Guidelines for State and Federal Projects.

For projects on the Eastern Shore, the required elements to be addressed are Water Quality Volume (WQv) and Overbank Flood Protection Volume (Qp). For projects in the rest of Maryland, stormwater requirements include Water Quality Volume, Channel Protection Volume(Cpv), Recharge Volume (Rev), and Overbank Flood Protection Volume. In interjurisdictional watersheds such as Jones Falls, Gwynns Falls and Carroll Creek, Extreme Flood Protection (Q100) should be addressed as well. **Though waivers and variances may be available, the concept development should start with the assumption that there will be no waivers approved for the project.**

In order to go through a concept development study certain basic information is needed. The information at a minimum should include 1”= 200 ft scale topographic mapping for the entire study area, including at least a 1000 ft strip area on both sides of all the alignments under study for the entire length of the project. Wetlands and other resources should also be identified along the alignments, but only required within the 200 ft area on either side. 1”=100 ft scale mapping or better is required within the 400 ft strip along the alignments in order to locate stormwater management facilities. The topographic mapping should identify approximate property lines, existing developments, and publicly owned land. The proposed highway alignments should be superimposed on the mapping.

2.3.2 Study Point Identification

In order to develop stormwater management concepts, study points should be identified where stormwater runoff leaves SHA right-of-way. This can be accomplished as follows:

1) When projects involve reconstructing or expanding existing highways, the topographic mapping can be used to identify concentrated drainage pathways. The study points will be at the approximate intersection of roadway right-of-way and the concentrated drainage pathways. If the existing drainage pathway indicates sheet flow leaving the right-of-way, an engineering judgment should be made by overlaying proposed highway alignments and determining if the flow will still continue in the same form. For stormwater management purposes, new concentrated outfalls at the expected low points may be needed in such cases.
2) When highway alternates introduce totally new highways in an area, the engineers should use the existing channels to determine study points at intersections with proposed fill lines. In cases of cuts, the vertical profile should be used to determine concentrated outfall points as study points. Recommendations should be made to avoid roadway sumps in cut sections.

All alternates should be studied in this fashion unless directed otherwise by SHA.

2.3.3 Estimating Volume Needs

Once study points are identified, the volumetric storage requirements should be estimated. This process requires delineation of approximate drainage areas reaching the study point including areas well outside the highway alignments, and approximate drainage area within the cut/fill lines of the highway alignments.

Water Quality Volume (WQv) and Recharge Volume (Rev) should be estimated using the drainage areas for the highway alignments, and the guidance provided in the MDE Stormwater Design Manual. 1) Assume 1" of runoff from the entire alignment area in order to estimate WQv, and 2) 30% of this WQv as Rev.

The Stormwater Design Manual outlines methods to compute Channel Protection Volume (CPv). Since the effort to go through such intense analysis is not warranted, approximate Channel Protection Volume (CPv) storage requirement can be estimated by

1) calculating the assumed runoff volume over the drainage area of the alignment for a 1-year storm using 2.2" of runoff multiplied by the drainage area, and
2) assuming that 60% of the runoff will have to be stored in the stormwater facilities and multiplying the above runoff volume by 0.6.

Qp is to be computed for 2-year storm in the Eastern Shore, and 10-year storm for the rest of Maryland, as described in the Stormwater Guidelines. Qp can be estimated for each study point by

1) estimating the runoff volume generated from the drainage area for the alignment using a runoff curve number of 90, and
2) estimating the volume of storage requirement by multiplying the runoff volume with 0.4 with the assumption that 40% of the runoff will have to be stored.

Q100 requires more specific analysis, and requires guidance from the Highway Hydraulics Division.

Approximate locations of stormwater management facilities should be identified on the topographic map. In cases where existing streams cross the alignments, the locations could be the corners on both sides of the stream on upstream and downstream side of the alignment. General concepts such as separate water quality facilities versus all-in-one facilities should be developed with due diligence towards the context of the areas. In rural areas, all-in-one stormwater management facilities may be acceptable. In developed areas, it may be desirable to break up the management into components with a view to distributing the stormwater management into many smaller facilities. The above volume calculations should be made based on what area is likely to drain to those facilities.

Since some of the facilities may face feasibility problems during detailed design, the at least 30% more volume than needed should be identified. In order to accomplish this, the four corner locations described above will have to account for 30% more storage volume than required. Conveyance may be accomplished using drainage systems that will be designed later.

2.3.4 Estimating Surface Area Needs

Surface storage areas for the stormwater management facilities can be estimated using an assumed depth and the volumes computed in Section 2.3.3, above. Water quality facilities such as bioretention typically have an average depth of 8” to store the WQv. Recharge volume is accomplished within the facility itself.

For detention ponds and all-in-one facilities such as wet extended detention ponds, infiltration basins, extended detention marshes, surface area should be determined based on depth guidance in the Stormwater Design Manual. An approximate method to accomplish this is to assume a depth of 1.5 ft for the CPv to compute the surface area, and a depth of 3 ft for Qp. The greater of the surface areas for Qp, CPv and WQv should be used. This estimated surface area should be multiplied by 1.25 to account for grading and outfalls.

2.3.5 Placing Footprints on Planning Maps

Once the surface area is determined as described above, it is then necessary to place the footprints on the topographic or planning maps. With the assistance of the environmental manager and a landscape architect, outlines of the stormwater management facilities should be drawn on the maps with an eye towards addressing terrain slopes, regulated resources and land use impacts. The special care is needed in case adjacent property owners request visual renderings of the future facilities.

2.3.6 Concept Presentations

Once the draft concepts are completed, the concepts should be presented at a meeting to the SHA Project Manager, SHA Environmental Manager, and the Highway Hydraulics Division Chief. It may be necessary to go through more than one presentation since refinement is necessary on most projects.

2.3.7 Concept Refinement

Once the first evaluation is complete, several conflicts, such as impacts to natural or cultural resources will inevitably be identified for at least a few of the outfalls. This will require a more in-depth study to reduce the impacts and develop alternative concepts such as underground detention, watershed approach to stormwater management, micro scale stormwater management, etc. This should be undertaken once the initial concept presentation is made and direction is received from SHA.

2.4 Contents of a Stormwater Management Planning Concept Report

The Stormwater Management Planning Concept Report should contain:

1) Description of the project area
2) Description of the environmental resources
3) Description of the outfalls and how identified
4) Regulatory requirements
5) Stormwater Management Concept descriptions along with assumptions made
6) Surface area and volume tabulation
7) Approximate construction cost estimates
8) Appendices

a. Existing and Proposed Drainage Area Maps used for the study, including alternate footprints and study points.
b. Pictures, if any
c. Computations, including for cost estimates.
d. Alternative concepts, if any

2.5 Using Planning Concept Report

The planning concept report can be used in the NEPA studies to:

1) assess direct impacts due to stormwater management facilities,
2) assess the benefits provided to the resources as mitigation concepts, and
3) support EIS and FONSI.

The planning concept reports should also be used to develop or refine project cost estimates and will be the basis for updating cost estimates when significant time has elapsed after the study is complete.

3.0 Stormwater Management Concepts in Design

Development of stormwater management design concepts starts at the design initiation for the project. It involves the use of detailed surveys and developing design information to produce conceptual designs that are refined as the project progresses. For projects that have a planning concept report, the work done during project planning phase should be the basis for developing design concepts.

3.1 Previous Process

Until recently, the stormwater management design process involved a preliminary stormwater management report, a draft final stormwater management report, and a final stormwater management report. Typically, the preliminary report was prepared around 40% plan stage. The contents of the preliminary report were existing conditions hydrology, preliminary proposed conditions hydrology, identification of waivers, and related computations/maps.

This process created problems because the waiver assumptions were often incorrect and time delays required to secure sufficient right-of-way and community support were common. The designs were often formed after significant highway design was completed and public commitments were made. Consequently, the designs were not integrated into their surroundings, and their environmental value was not often optimal. The Stormwater Guidelines added several new requirements that now made it necessary to complete stormwater management designs early.

3.2 New Stormwater Management Conceptual Design Process

The new conceptual design process replaces the previous preliminary stormwater management report stage with a more aggressive approach to completing conceptual design by 30% plan stage and including the concepts on Preliminary Investigation (PI) plans. This requires the hydraulics engineers to start the design earlier to identify conflicts, solutions and costs before a PI cost estimate is created. The new process requires final stormwater management design be completed by Semifinal Review (65% plans), and final erosion/sediment control design be completed on Final Review (90% plans).

3.2.1 Regulatory Needs

This process is very similar to the regulatory needs section for the project planning conceptual design. During design, it is important to develop more precise information regarding waivers in order to get concurrence from MDE at the conceptual stormwater management stage. When in doubt, assuming that waivers will not be obtained will put the project in a safer position.

All Eastern Shore projects are required to provide Qp for the 2-year storm, unless a waiver can be obtained. For determining whether Qp is needed for non-Eastern Shore projects, the appropriate table in the MDE Stormwater Guidelines for State and Federal Projects should be referred to. If the table indicates that Qp is optional for the county where the project is located, further research is needed to determine how the county stormwater review section views the outfall channel in question and if there are any known or perceived flooding problems in the area. If adverse conditions exist, then Qp should be provided.

For projects in the interjurisdictional watersheds, consultation with the Highway Hydraulics Division is required to determine whether Q100 management is needed.

3.2.2 Study Point Identification

Study point identification is similar to the way it has been done so far, and similar to the description found in the planning concept report section, above. For projects where stormwater leaves the right-of-way in a sheet flow form, lines of study (LOS) should be identified.

Care should be taken to traces the drainage patterns within and outside the right-of-way in order to identify correct study points (also called Points of Investigation or POI). Field investigation is needed to verify office determination of POI or LOS.

3.2.3 Hydrologic Analysis

Hydrologic analysis for the existing conditions, based on existing land use and drainage conditions should be prepared using NRCS TR-20, or as directed by SHA and MDE. The standard methods accepted by SHA and MDE as described in the Stormwater Design Manual and Highway Drainage Manual are acceptable. Drainage area maps using the best available information and as directed by the manuals should be developed for existing conditions.

Hydrologic analysis for proposed conditions should be developed simultaneously with development of 30% plans. The risk of design changes will be high but manageable if conservative assumptions are made based on the objectives and known constraints of the project.

3.2.4 Outfall Condition Investigation

Outfalls at all POIs should be evaluated thoroughly. MDE requires that the outfall channel is stable until it reaches the next confluence where the drainage area is at least double that at the POI. The evaluation should be complete with pictures and stability assessments for the entire reach, not just at the outfall point. In some cases, geomorphic assessments, and hydraulic computations demonstrating adequate capacity and stability may be required.

For connections to a closed storm drain, waiver evaluation should include the capacity of the downstream drainage system. This evaluation should include the outfall of the downstream system, unless a closer stopping point is agreed to by MDE. Again, the requirement for investigating at least to a point that double the drainage area when compared to the POI is still valid. In order to obtain a waiver, the downstream system must be publicly owned.

3.2.5 Identifying Loss of Existing Water Quality Treatment

If the proposed project reduces existing water quality treatment in existing grass channels and buffers by adding new curb or reducing existing sheet flow buffer, the pre-construction pavement draining towards such grass channels and buffers must be identified to compensate for the lost water quality treatment. Calculations should be made to determine the amount of water quality that will need to be compensated through other means.

Similarly, if the existing pavement is receiving treatment from other sources such as stormwater management facilities and do not in the post-construction condition, compensatory designs will be needed.

3.2.6 Stormwater Management Facility Locations

Once the hydrologic analyses are complete and outfalls are investigated, the stormwater management requirements will become clearer to the designer. With this information, potential sites for stormwater management should be located on the topographic map. These sites should be ranked based on constraints such as impacts to trees, difficulty in constructing facilities, proximity to residential areas or other developments, and space availability. Since the Stormwater Design Manual includes a multitude of linear and non-linear options, all opportunities, such as grass channels, dry swales, bioretention facilities, sand filters, ponds, and wetlands should be explored.

If any existing stormwater management facilities are available for treatment, an inspection of the condition of the facilities and feasibility for upgrading them for the proposed project should be investigated.

3.2.7 Volumes and Footprints

Once potential stormwater management locations are identified, volume requirements should be developed for the most practical of the locations. Approximate surface area requirements can be developed by dividing the volume requirements with assumed minimum or estimated depths. If multi-use (ex. combined Cpv and Qp) facilities are planned, care should be taken to estimate separate surface area requirements and use the largest requirements. The calculation guide in the appendix can be used to estimate the surface area.

In order to locate the facilities, use at least 25% more surface area than what is estimated above in order to account for fore bays and grading. Keep in mind that steeper terrain will need more footprints in order for the embankments to tie into the existing ground.

Locations of the inflow and outflow structures should be identified on the topographic maps or plan sheets so that impacts can be estimated.

3.2.8 Alternative Concepts and Concept Presentation

Alternative concepts should be developed if some of the constraints could not be determined at this stage of the plan developments. Alternatives should account for addressing the complete stormwater management requirements for the project.

A presentation should be made to the Chief or Highway Hydraulics Division or representative at the 30% plan stage in order to receive approval and/or direction on the stormwater concepts. Some of the discussion items will include alternative stormwater management such as watershed approach, banking feasibility, stream restoration, etc. The presentation should include the condition of the outfalls, existing stormwater management facilities, stormwater concept plans, existing problems, known constraints, flooding problems, etc.

3.2.9 Preliminary Investigation Plans

The preliminary investigation (PI) or 30% plans should include the location, type and the conservatively approximate footprint of the proposed stormwater management facilities. The intent of this is to allow PI comments to include stormwater management and to avoid other conflicts that can develop if design development does not account for the proposed stormwater management locations.

3.3 Contents of Stormwater Management Design Concept Report

Stormwater Management Design Concept Report should be developed and submitted to SHA and MDE after PI, approximately at 40% plan stage. The contents should include:

1) Description of the project area
2) Description of the environmental resources
3) Description of the outfalls and how identified
4) Regulatory requirements
5) Outfall Condition Reports
6) Waiver and Variance Requests
7) Preliminary Water Quality Summary Sheet
8) Potential Stormwater Management Locations
9) Stormwater Management Concept descriptions along with type and treatment of proposed facilities and assumptions made.
10) Surface area and volume tabulation
11) PI Plans and/or Topographic Maps showing footprints of proposed facilities

3.4 Format of Stormwater Management Design Concept Report

The format of the Stormwater Management Design Concept Report should follow the format of final Stormwater Management Report. The approved report format can be obtained from the Highway Hydraulics Division.

Appendix 1. Surface Areas for Facilities

Type of Facility	Volume(s) Needed to Obtain Surface Area	Beginning Depth Assumption	Surface Area Calculation
Stormwater Ponds:			
Micropool ED Pond Wet Pond Wet ED Pond Multiple Pond System Pocket Pond	Cpv computed with worksheet in MDE SDM Qp volume using TR-55 Chapter 6 and add 25% to resultant volume for cushion	12" for WQv For CPv, use Appendix 2 For Qp use 2 ft for Eastern Shore and 2-4 ft for other regions.	Compute area for all volumes separately. Largest area governs
Stormwater Wetlands:			
Shallow Wetland ED Shallow Wetland Pond/Wetland System Pocket Wetland	Cpv computed with worksheet in MDE SDM Qp using TR-55 Chapter 6 and add 25% to resultant volume for cushion	12" for WQv For CPv, use Appendix 2 For Qp use 2 ft for Eastern Shore and 2-4 ft for other regions.	Compute area for all volumes separately. Largest area governs.
Infiltration Practices:			
Infiltration Trench	WQv (quantity storage can be provided downtream of trench)	Use 4' trench depth	Pre-treatment (minimum 25% of Wqv required to be in pre-treatment): For Sizing of Volume, see Appendix D.13 of the MDE Manual. Compute area for all volumes separately. Largest area governs
Infiltration Basin	Cpv computed with worksheet in MDE SDM Qp using TR-55 Chapter 6 and add 25% to resultant volume for cushion	For CPv, use Appendix 2	

Appendix 1. Surface Areas for Facilities

Type of Facility	Volume(s) Needed to Obtain Surface Area	Beginning Depth Assumption	Surface Area Calculation
Filtering Practices:			
Surface Sand Filter	WQ_v or Cpv computed with worksheet in MDE SDM Qp using TR-55 Chapter 6 and add 25% to resultant volume for cushion	Filter Bed Depth: d_f = 1.5 ft. Ponding over Filter Bed: h_f= 1.0 ft. ***Use pond approach for Cpv & Qp.***	**<u>Pre-treatment</u>** (Minimum 25% WQ_v required to be in pre-treatment): $A_s = \frac{Q_0}{W} \times E'$ As = sedimentation basin surface area in square feet Q_0 = rate of flow from the basin = WQ_v ÷ 24 hr. (detention time) W = particle settling velocity (ft/sec) for I = 75%, use 0.0004 ft/sec for I > 75% use 0.0033 ft/sec I = Impervious E' = sediment trapping efficiency constant; for a sediment trapping efficiency (E) of 90%, $E' = 2.30$
Underground Sand Filter	WQ_v	d_f = 2.0 ft. h_f= 1.0 ft.	
Perimeter Sand Filter	WQ_v	d_f = 1.5 ft. h_f= 1.0 ft.	
Organic Filter	WQ_v	d_f = 1.5 ft. h_f= 1.0 ft.	

Appendix 1. Surface Areas for Facilities

Type of Facility	Volume(s) Needed to Obtain Surface Area	Beginning Depth Assumption	Surface Area Calculation
Pocket Sand Filter	WQ_v	d_f = 1.5 ft. h_f = 1.0 ft.	**Filter Treatment**: $A_f = \frac{(WQ_v)d_f}{k(h_f + d_f)(t_f)}$ A_f = surface area of filter bed in square feet d_f = filter bed depth in feet k = coefficient of permeability: for: use sand 3.5 ft/day peat 2.0 ft/day leaf compost 8.7 ft/day SHA bioretention soil 2.0 ft/day h_f = Average ht. of water above the filter bed t_f = design filter bed drain time (days) for sand and organic filters, use 1.67 days, for bioretention use 2.0 days
Bioretention	WQ_v	d_f = 3.0 ft. h_f = 0.5 ft.	**Pre-Treatment:** 20 ft. grass filter strip below a level spreader or optional sand filter layer Gravel Diaphragm Mulch Layer **Filter Treatment:** $A_f = \frac{(WQ_v)d_f}{(h_f + d_f)}$ in square feet

Appendix 2. Compute the Channel Protection Storage Volume (Cp_v)

1. Using NRCS TR-55, compute:
   a. **time of concentration (t_c)**
   b. **one-year post-development runoff depth (Q_a)** in inches
   c. **curve number (CN)**

2. a. Compute the **Initial Abstraction (I_a):**

$$I_a = \frac{200}{CN} - 2$$

$I_a =$ initial abstraction

$CN =$ runoff curve number

   b. Compute:

$\frac{I_a}{P}$ where $P =$ one-year rainfall depth (SDM Table 2-2)

3. a. Find **Unit Peak factor (q_u)** using Table D.11.1, t_c and $\frac{I_a}{P}$.

   b. Compute **one-year post-development discharge (q_i):**

$$q_i = (q_u)A(Q_a)$$

$A =$ drainage area in square miles

4. If $q_i \leq 2.0$ cfs, Cp_v is not required. Provide for water quality (WQ_v) and groundwater recharge (Re_v) as necessary.

5. Find **the ratio of outflow to inflow** $\left(\frac{q_0}{q_i}\right)$ for T = 24 using Figure D.11.2 (use T=12 hours in USE III/IV waters) of SDM.

6. Compute the **peak outflow discharge (q_0):**

$$q_0 = \frac{q_0}{q_i} \times q_i$$

7. Using $\left(\frac{q_0}{q_i}\right)$**,** compute the **ratio of storage to runoff volume** $\left(\frac{V_s}{V_r}\right)$**:**

$$\left(\frac{V_s}{V_r}\right) = 0.683 - 1.43\left(\frac{q_0}{q_i}\right) + 1.64\left(\frac{q_0}{q_i}\right)^2 - 0.804\left(\frac{q_0}{q_i}\right)^3$$

8. a. Compute **extended detention storage volume (V_s)**:

$$V_s = \frac{V_s}{V_r} \times V_r \qquad \text{note: } V_r = Q_a$$

b. Convert Vs to acre-feet:

$$\frac{V_s}{12} \times A$$

V_s in inches, A in acres

9. Determine the **maximum storage depth (h_0)** required to obtain a 3 inch minimum diameter orifice for extended detention:

$$A_0 = p\left(\frac{d_0}{2}\right)^2$$

$$A_0 = p\left(\frac{3}{2}\right)^2 = \frac{9}{4} \times p \qquad \text{Assuming } d_0 = 3$$

Solving $A_o = \frac{q_0}{4.81\sqrt{h_0}}$ for h_0:

$$h_0 = \left(\frac{q_0}{4.81 A_0}\right)^2 = \left(\frac{q_0}{(4.81)\left(\frac{9}{4}p\right)}\right)^2 = \left(\frac{q_0}{10.8225p}\right)^2$$

10. If h_0 in previous step is too small, calculate the **required orifice area (A_o)** for extended detention design using an assumed h_0:

$$A_o = \frac{q_0}{C\sqrt{2gh_0}} = \frac{q_0}{4.81\sqrt{h_0}}$$

where h_0 is the maximum storage depth associated with V_s

11. a. Determine the **required maximum orifice diameter (d_0):**

$$d_0 = \sqrt{\frac{4A_0}{p}}$$

If d_0 is less than 3 inches an internal control for orifice protection is required.