# Letting it All Out: Hydraulic Design of Outlet Works

## Introduction

The purpose of an outlet works is to regulate or release water impounded by a dam. This is done for a variety of reasons, including (1) passage of storm or run-of-river inflow; (2) releasing flow to meet demands downstream; or (3) draining the reservoir (in the case of a low-level outlet). In some cases, the outlet works might also be referred to as the principal or service spillway, if it is the primary outlet used to control the reservoir level.

This article will discuss the major components of outlet works, the hydraulic analyses required to size and design each component, and general design considerations associated with outlet works of small dams. Structural analyses are an important component of outlet works design but they are not addressed in this article.

Reservoir operation requirements for a dam vary based on federal, state, or local regulations, utility providers, and in some cases private individuals, group owners, or stakeholders. Because no two dams are the same and their operations, obligations, and impacts are specific to individual circumstances, this article will discuss outlet works design in generalities. For additional specific design information, the reader is encouraged to acquire the Embankment Dam Reference Toolbox (EDRT) described on Page 1 of this technical note and available from ASDSO.

## Outlet Works Components

**Intake Structures** – Intake structures are those that draw water in from the reservoir for release. They can be located within the dam (with an inlet that extends to the reservoir), or immediately upstream of a dam as a free standing structure within the reservoir. It is often desirable to incorporate a combination of intakes within a single structure. For example, a gated conduit located near the bottom of a reservoir allows for draining the reservoir (see the article How Low Can You Go (Vol. 2 Issue 3) from our last issue), while a drop inlet located high in the reservoir allows for the uncontrolled spillway-type release to maintain normal pool levels. Intake structures can either be gated or un-gated (aka unregulated or uncontrolled). Most commonly, the intake for a principal or service spillway outlet is uncontrolled. Some examples include risers, drop inlets, and weir towers. Intakes set at elevations lower than the normal pool levels are generally gated. The elevation of the intake crest or sill is dependent on the desired control elevation of the reservoir. Gated intakes set at elevations below the maximum desired operating pool level may be required to control temperature of released water, to manage water quality considerations; and for reservoirs that have large fluctuations in pool levels, to allow release of water during low pool seasons.

**Photo 1: A glory hole is one type of drop inlet**

The choice of intake structure(s) depends on a number of factors including design capacity, available materials, cost, maintenance requirements, and degree of control required. See References [9], [10], and [13] for more information regarding the design of intake structures.

**Trash Racks** – It is possible for debris in the flow to clog or damage the outlet works, especially during flood events. Trash racks are typically constructed around the intake structure to capture debris, which can later be removed. Trash racks reduce the hydraulic capacity of the intake structure, especially if they are designed with small openings or become clogged. Therefore, it is necessary to size the trash racks appropriately and ensure that they are regularly maintained. A good rule of thumb is: the rack spacing should be half the diameter of the pipe to pass small debris but also catch big debris that might clog the pipe.

**Photo 2: Trash racks surrounding an intake structure**

**Conduit Operating Conditions** – The conduit that discharges water from the intake structure is called the outlet conduit. The outlet conduit should operate under one of two conditions throughout its length: (1) fully pressurized pipe flow or (2) non-pressurized, open-channel flow conditions. Mixed flow conditions in which only a portion of the conduit is pressurized are undesirable because air trapped within the pipe may lead to burping, surging, cavitation, and vibration. As a result, venting becomes an important component for both types of systems (see discussion of cavitation and venting below).

Fully pressurized systems require a flow control mechanism (typically a valve) at the downstream end, which is used to regulate the flow while maintaining full pipe flow throughout the conduit.

Non-pressurized conduit systems require the outlet conduit to be large enough that open channel flow conditions are sustained throughout the length of the conduit over the entire range of operating flows. Flow is regulated at the upstream end with a slide gate or valve, and the flow discharges freely at the downstream end.

**Control Mechanisms** – Various control mechanisms are used for gated intakes and conduits. Common flow control mechanisms include gates and valves, which can be controlled manually or hydraulically. The control mechanism can be positioned at various locations including at the upstream intake, along the conduit within the embankment, and at the downstream end of the conduit.

Gates are one type of control mechanism often used. Gates are suitable for flow regulation under low head conditions. However, under high head, partially open gates may vibrate and cavitate. For these reasons, the gates should only be operated to be fully open or fully closed.

Valves are another common type of control mechanism used along the conduit. Common types of valves include knife gate, butterfly, fixed cone, and pivot. Butterfly valves are generally cost-effective, but are susceptible to severe vibration and cavitation when partially open. Therefore, they are typically used for full-open or full-closed operation rather than for flow regulation. Flow regulation valves are typically placed at or near the downstream end of the outlet conduit, which allows them to discharge freely to the atmosphere, eliminating most of the potential for cavitation. However, placing the control mechanism at the downstream end causes the conduit to be pressurized through the embankment, which induces additional risk if cracking or rupture of the conduit occurs due to deterioration, differential settlement, joint separation, or other structural failure.

**Photo 3: Angled intake gate parallel with upstream face of dam**

**Conduits** – A variety of options are available for outlet conduits ranging from small pipes to large tunnels. Common conduit materials historically are reinforced concrete (cast-in-place or precast), metal pipe (steel, corrugated metal pipe [CMP], ductile iron, cast iron), and high density polyethylene (HDPE). A summary of common conduit materials used today is presented in Table 1. Cast-iron, ductile-iron, and CMP are no longer recommended for use. Considerable care should be used when selecting HDPE due to the considerations listed in Table 1.

**Table 1. Summary of common conduit materials**

| Conduit | Pros | Cons |
|---|---|---|
| HDPE | - Resistant to corrosion<br>- Flexible<br>- Inexpensive at small diameters | - Lower strength, susceptible to collapse<br>- Thermal expansion and contraction<br>- Does not bond well with other materials |
| Steel | - Cost-effective at small diameters<br>- Easy to attach valves, vents, flowmeters, etc. | - Relatively expensive at large diameters<br>- Susceptible to corrosion |
| Concrete Pipe | - Cost-effective at large diameters<br>- Can be cast in a variety of shapes<br>- Can be reinforced for higher strengths | - Relatively expensive at small diameters<br>- Susceptible to leaking at joints |

It is important to consider the forces that will be acting on the conduit, internal and external. Pipes are often encased in concrete to resist external embankment forces, protect the pipe during placement of embankment material, allow for more efficient compaction and distribution of soil stresses and minimize vibration under transient conditions. Non-pressurized conduits must withstand external pressure from the dam embankment, and should be water tight to prevent any leakage. Pressurized conduits must withstand internal water pressures in addition to external embankment pressure and should be air tight.

Potential problems to consider include:

- Differential settlement of the embankment which can deform the conduit
- Separation of joints
- Corrosion and deterioration
- Erosion or abrasion of internal surfaces
- Misalignment

Factors to consider when selecting a material include strength, durability, resistance to corrosion, ease of maintenance, and cost. Some relative pros and cons associated with various conduit materials are presented in Table 1. See Reference [3] for more information regarding design of conduits.

**Filter Diaphragm** – Dam failures often occur in the vicinity of the outlet conduit due to defects in the conduit, separated joints, uneven compaction of material around the conduit, or concentrated seepage along the interface between the conduit and the embankment, eventually leading to internal erosion. Historically, cutoff collars were installed along outlet conduits as an attempt to disrupt seepage paths and prevent internal erosion. However, these have been found to be ineffective and have been replaced by sand filter diaphragms as the preferred method for reducing the risk of internal erosion and piping.

A filter diaphragm is a zone of filter material surrounding the outlet conduit. The diaphragm is designed to prevent erosion of material caused by concentrated seepage paths that may develop along the conduit due to poor compaction or differential settlement. A detailed discussion about filter diaphragm design and construction considerations is presented in Filter Design and Construction (Vol.1 Issue 1). See Reference [4] for more information regarding design of filter diaphragms.

**Photo 4: Piping failure along outlet conduit**

**Energy Dissipation** – Flow from the outlet, whether in a pressurized or non-pressurized system, will have a high velocity. If the downstream channel consists of bedrock, this flow can be released directly. However, if erodible materials are present, some form of energy dissipation is required to prevent erosion at the dam toe. Common energy dissipation devices associated with outlet works are stilling wells, impact basins, stilling basins, plunge pools, hydraulic jumps, and cone valves.

Stilling wells are concrete structures located at the end of the outlet conduit. The outlet conduit typically discharges horizontally at the bottom of the well and energy is dissipated through turbulence and diffusion within the well. The flow then rises upward and discharges to the downstream channel through the top of the well.

Stilling basins can be designed in several ways but generally dissipate energy through a hydraulic jump, which is the natural transition from supercritical flow to subcritical flow. There are several variations of stilling basins including impact, hollow-jet, and baffled.

Plunge pools are deep areas of water into which the outlet conduit discharges. Turbulence within the pool dissipates energy before the flow is released into the downstream channel. The size and depth of the plunge pool is determined by the velocity and trajectory of the outlet conduit jet.

Cone valves release flow downstream in a highly dispersed jet, dissipating energy in the process. Design criteria for cone valve energy dissipaters vary by manufacturer. Cone valves are generally not suitable in very cold climates as the spray that is generated is highly susceptible to freezing.

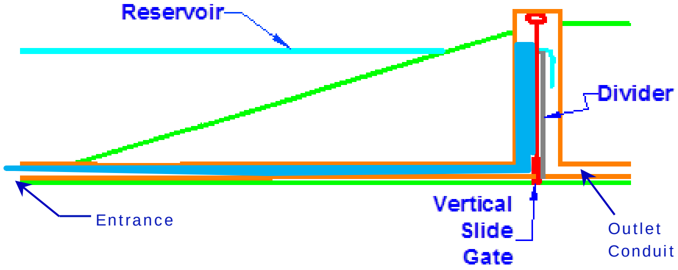
Flow exiting the outlet conduit is typically supercritical, characterized by shallow flow depths and high velocities. The high energy at the outlet must be dissipated through properly designed energy dissipators. Hydraulic design of stilling basins and similar structures induces a hydraulic jump within the structure to dissipate energy. This significantly reduces the flow velocity exiting the structure. The structure dimensions are related to the tailwater depth and the Froude number of the flow at the exit of the outlet conduit. Hydraulic jumps can dissipate 50 to 70 percent of the outflow energy. The outflow conditions should be evaluated carefully to ensure adequate flow conditions in the downstream channel to prevent erosion. See References [8] and [10] for more information regarding the design of energy dissipation structures.

**Photo 5: A cone valve dissipates energy downstream of an outlet works**

## Potential Configurations

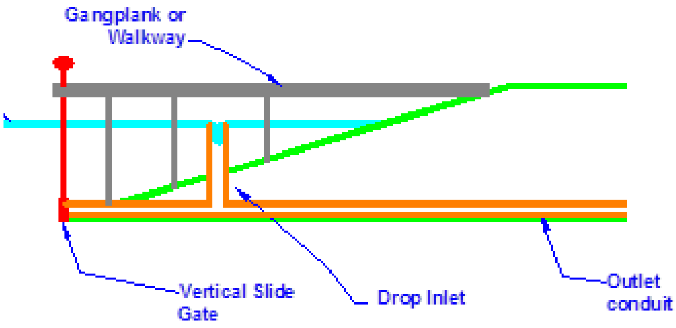
Some potential outlet works configurations for small dams are presented below.

### Drop Inlet with Gate Near Dam Centerline



| Pros | Cons |
|---|---|
| - Easy access to gate for operation<br>- “Spilled” water is conserved (in delivery system)<br>- Gate is protected from ice damage<br>- Easy to operate | - Can be hydraulically inefficient if tailwater is present (high losses)<br>- Expensive at larger diameter installations<br>- Complicated hydraulics<br>- Only feasible for low head dams |

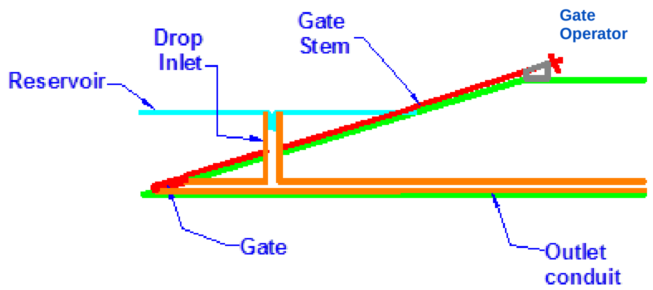
### Drop Inlet with Gated Low Level Intake on Upstream End of Conduit



### Drop Inlet with Gated Low Level Intake on Upstream End of Conduit (Continued)

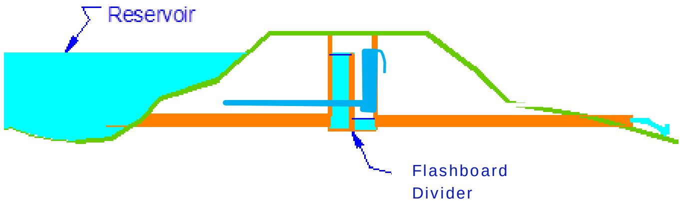
| Pros | Cons |
|---|---|
| - Easy access to gate for operation<br>- Relatively easy installation<br>- "Spilled" water is conserved (in delivery system)<br>- Cost-effective<br>- Hydraulically efficient gate position | - Stem is easily damaged by ice<br>- Need to drain reservoir to work on gate in the dry |

### Drop Inlet with Inclined Low Level Slide Gate



| Pros | Cons |
|---|---|
| - Hydraulically efficient gate position<br>- "Spilled" water is conserved (in delivery system) | - Gate stem must be buried to protect from damage<br>- Easy to damage by mis-operation – operator must be careful not to bend stem<br>- Susceptible to clogging with debris – trash rack important |

### Drop Inlet with Flashboards (No Gate)



| Pros | Cons |
|---|---|
| - "Spilled" water is conserved (in delivery system)<br>- Good for remote locations<br>- Less expensive than systems with gate & gate operators<br>- Difficult to mis-operate | - Limited control<br>- Making low level releases can be difficult (must remove all flashboards underflow)<br>- Only reasonable for small low head dams |

## Hydraulic Analyses

**Outlet Works Capacity** – To identify the capacity of the outlet works over the entire range of design reservoir levels, it is necessary to analyze the hydraulics of each condition individually. Generally, there are three potential types of control within the system:

1) Weir inlet control
2) Orifice inlet control
3) Outlet control (full pipe flow within the conduit)

Weir inlet control (drop inlet or conduit entrance) typically occurs at low heads where free flow conditions exist over the inlet crest. Weirs are very efficient with capacity computed as:

$$Q = CLH^{1.5}$$

where C is a weir discharge coefficient, L is the length of the weir crest, and H is the head over the weir. At some point as the reservoir level increases, conditions transition from weir flow to submerged orifice flow. Orifice flow is much less efficient with capacity computed as:

$$Q = CA\sqrt{2gH}$$

Where A is the area of the orifice entrance, $g$ is gravitational acceleration, and H is the head above the orifice. The coefficients associated with the weir and orifice equations will vary depending on the shape of the entrance and the control mechanism (slide gate, valve, uncontrolled, etc.). See References [9], [10], and [15] for more information.

A relationship between reservoir level (stage) and the discharge volume can be developed for each flow condition (weir and orifice) at each inlet based on the above equations. The resulting stage-discharge relationship for each inlet is based on the minimum discharge of the weir and orifice curves. The combined inlet stage-discharge relationship is the sum of the individual inlet stage-discharges.

Full conduit control (outlet control) occurs when the capacity of the conduit is exceeded by the combined capacities of the inlets. This often results from submergence at the downstream end due to tailwater.

Flow under these conditions is fully pressurized and a stage-discharge relationship can be developed based on Bernoulli's Equation where discharge, $Q$, is computed as follows:

$$Q = a\sqrt{\frac{2gH_T}{K_L}}$$

where $a$ is the flow area, $g$ is the gravitational acceleration, $H_T$ is the total head needed to overcome various losses to produce discharge, and $K_L$ is a function of the head losses associated with trash racks, gates, valves, bends, transitions, friction and exit losses. See References [9] and [10], for more information.

The stage-discharge relationship for the entire outlet works system is based on the minimum discharge of the inlet and outlet control relationships (see Figure 1). There are a number of commercial computer modeling tools available for evaluating outlet works hydraulics, but spreadsheets are commonly used for simple systems. See Reference [9] for more information.

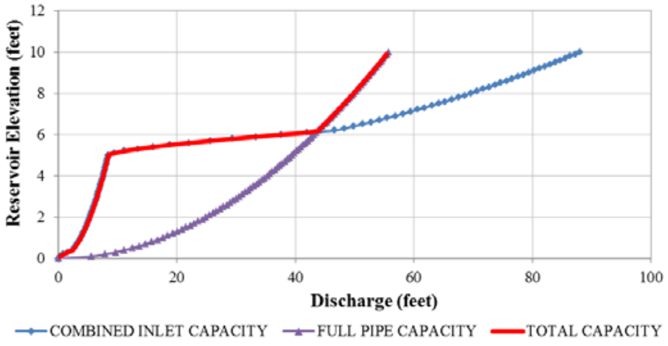


**Figure 1: Combined stage-discharge curve of an outlet works**

**Tailwater Effects** – It is possible for tailwater in the downstream channel to impact the outlet works flow hydraulics, especially at high flow rates. For open channel flow systems, it is important to ensure the tailwater does not submerge the outlet and create mixed flow conditions within the outlet conduit. For pressurized systems, submergence of the outlet is acceptable; however, it reduces the capacity and must be considered in the analysis. For energy dissipation purposes, tailwater can be beneficial and may potentially reduce the required size of the energy dissipation structure.

For simple downstream channel geometries, tailwater rating curves can be developed using Manning's equation. For more complicated geometries, it may be necessary to model the tailwater using a program such as HEC-RAS.

**Cavitation and Venting** – As flow passes through a gate or valve, the contraction produces separation downstream in which negative pressures may develop. When the pressure in the flow drops below the vapor pressure, cavitation, which is the formation of vapor bubbles within the water, may develop, causing damage to the control structures or conduits. When the water is subjected to higher pressures again, the bubbles implode, generating intense shock waves that can be extremely damaging to the outlet conduit. To maintain positive pressures in the flow, it is necessary to vent the region immediately downstream of a gate or valve located within the outlet conduit (See Figure 2). Vents typically consist of a pipe located within the embankment of the dam with an outlet near the dam crest. Vents must be sized appropriately to allow adequate airflow. See References [1], [7], and [14] and our previous article Design Considerations for Outlet Works Air Vents (Vol. 1 Issue 2) for more information.

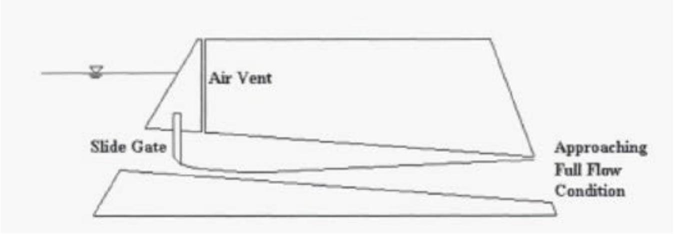


**Figure 2: Air vent downstream of a slide gate**

## Hydrologic Considerations

The design flow rates for the outlet works are dictated by a variety of factors including downstream needs, storage considerations, power generation requirements, reservoir depletion requirements, and legal requirements. For outlet works that act as the only spillway, the capacity should be sufficient to pass the inflow design flood (IDF). A discussion about flood inflows was presented in Turning Rainfall to Runoff (Vol. 2 Issue 1).

The outlet works design capacity for most low-level outlets is driven by the time required to drain the reservoir or impoundment. Criteria vary by location and governing agency, but generally require the reservoir to be drawn down at a specified rate for inspection/maintenance purposes or in case of an emergency. The draw-down rate is a function of the combined stage-discharge relationship for the outlet works. A hydrologic modeling program such as HEC-HMS is commonly used for this analysis, although it can be done using a simple spreadsheet as well.

A key consideration for water storage dams is to not draw down the reservoir too quickly. When the reservoir is full, the embankment becomes saturated and pore pressure within the embankment is high. During rapid drawdown, the pressure decreases on the upstream face of the embankment much more rapidly than the pore pressure within the embankment, causing instability that may result in failure of the dam.

A discussion about reservoir drawdown was presented in How Low Can You Go (Vol. 2 Issue 3). Drawdown criteria vary by location.

## Summary

Outlet works are a key component of most dams. Their purpose is to regulate flow through the dam, whether it is for flood control, water storage, or diversion. The major components of the outlet works include the intake structure, outlet conduit, energy dissipation device, filter diaphragm, and flow regulation and control mechanisms.

Outlet works can operate as either pressurized or non-pressurized systems. It is important to avoid mixed flow conditions that may result in cavitation within the outlet conduit. Venting downstream of gates and valves within the outlet conduit is an important consideration.

Hydraulic analysis of the outlet works involves evaluating the capacity of each control condition individually. Tailwater must be considered as well. Types of flow control include inlet weir control, inlet orifice control, and full pipe control with the outlet conduit. A stage-discharge relationship can be developed for each type of control and a combined stage-discharge relationship can also be developed based on the minimum flows over the range of reservoir elevations.

This article presents general guidelines and considerations for the hydraulic design and analyses of outlets and provides the reader with references to more detailed approaches. Design criteria and regulations vary by location and readers should consult state and local regulations and guidelines when designing outlet works.

## Useful References

[1] Brown, C. H., Tullis, B. P and Lindon, M. C. (2006). *Air Venting Requirements for Low-Level Outlet Works, Does Size Really Matter?* Association of State Dam Safety Officials.
[2] Federal Emergency Management Agency (2007). Technical Manual: Plastic Pipe Used in Embankment Dams: Best Practices for Design, Construction, Problem Identification and Evaluation, Inspection, Maintenance, Renovation, and Repair.
[3] Federal Emergency Management Agency (2005). Technical Manual: Conduits through Embankment Dams.
[4] Natural Resources Conservation Service (2007). National Engineering Handbook Part 628 – Chapter 45: Filter Diaphragms.
[5] Natural Resources Conservation Service (2005). Earth Dams and Reservoirs: TR-60.
[6] State of Colorado: Department of Natural Resources. (2007). Rules and Regulations for Dam Safety and Dam Construction.
[7] Tullis, B. P. and Larchar, J. (2009). Low-Level Outlet Works Air Vent Sizing Requirements for Small to Medium Size Dams. United States Geological Survey.
[8] United States Department of the Army: US Army Corps of Engineers. (1975). *ER-1110-2-50: Low-Level Discharge Facilities for Drawdown of Impoundments.*
[9] United States Department of the Army: US Army Corps of Engineers. (1980). EM 1110-2-1602: Hydraulic Design of Reservoir Outlet Works.
[10] United States Department of the Interior: US Bureau of Reclamation. (1987). Design of Small Dams.
[11] United States Department of the Interior: Bureau of Reclamation. (1990). *Criteria and Guidelines for Evacuating Storage Reservoirs and Sizing Low-Level Outlet Works.*
[12] United States Department of the Interior: Bureau of Reclamation. (1984). Engineering Monograph No. 25: Hydraulic Design of Stilling Basins and Energy Dissipators.
[13] United States Department of the Interior: Bureau of Reclamation. (2011). Appurtenant Structures for Dams (Spillway and Outlet Works) Design Standards.
[14] United States Department of the Interior: Bureau of Reclamation. (1980). Engineering Monograph No. 41: Air-Water Flow in Hydraulic Structures.
[15] United States Geological Survey, 1907. Weir experiments, coefficients, and formulas. Water Supply and Irrigation Paper No. 200.
[16] Walther, Martin (2004). Guidance for Air Vents for Drop Inlet Spillways. Washington State Department of Ecology: Water Resources Program/Dam Safety Office.