Best Practice Catalog

Flumes and Open Channels

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This best practice for flumes and open channels addresses how innovations in technology and design, proper condition assessments, and improvements in operation and maintenance practices can contribute to maximizing overall plant performance and reliability.

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1.1.1 Components

Flumes and open channels are free-flow water conveyance systems for hydroelectric facilities. In certain hydro facilities the surface water reservoirs are not located directly adjacent to the generating station and the topographical or geological condition is not suitable for tunneling; therefore, necessitating the use of flumes or open channels to divert flow from the reservoir and convey the water over long distances. The primary purpose of flumes and open channels is to carry adequate water flows with minimized hydraulic losses [4]. Both flumes and open channels operate under the laws of open channel flow. The long distance open channel flow system is usually designed and constructed for water diversion (i.e., run-of-river) scheme of hydro projects with lower head and/or lower power capacity.

Flumes: A type of free-flow, man-made hydraulic channel generally square, rectangular, or semicircle constructed primarily of wood, steel, concrete, or masonry. Flumes can be supported on grade, piles, structural steel framing, concrete piers, or wood framing as show in Figure 1. Typically flumes are costly to construct; therefore, they are generally used to convey smaller quantities of water than open channels/canals or when the surrounding terrain necessitates the use of flumes.

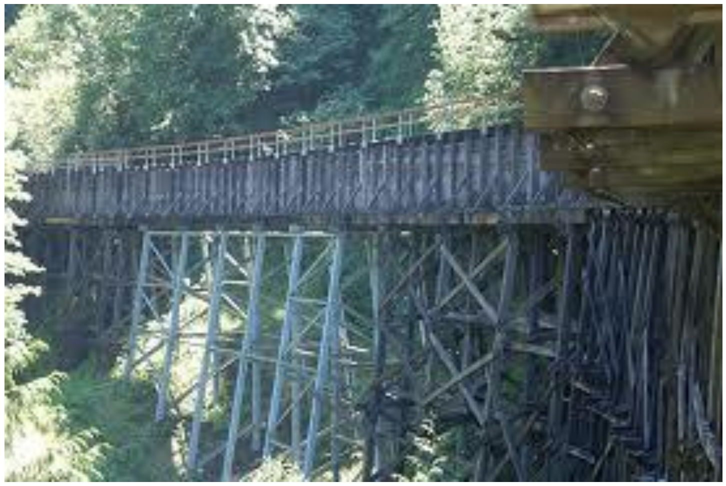

Figure 1: Wood Flume (Bull Run Hydro Project, Oregon)

Open Channels: An upstream open channel is a type of free-flow water conveyance system used to transport water from its source (river, impounded lake, etc.) to the powerhouse, which is also referred to as intake canal, power canal, or headrace channel. A tailrace is often designed as an open channel (i.e., tailrace channel), rather than a tailrace tunnel, for discharging the tailwater collected from the turbines back into the original river/lake or to other rivers downstream. Open channels differ from flumes in that they are hydraulic channels excavated in the earth or rock (see Figure 2) whereas flumes are generally elevated man-made structures. Open channels can be constructed in various shapes and sizes and may either be lined or unlined.

Figure 2: Open Channel (Sir Adam Beck #1 Power Station, Niagara River, Canada)

Forebay Structure: The primary function of a forebay structure is to provide limited storage for hydroelectric facilities during operational changes. These structures are typically sized to provide the initial water supply needed when increasing plant output while water in conveyance components is being accelerated; as well as to accept the rejection or surplus water due to a decrease in plant output. Forebay structures may be a separate head pond or integral with the intake canal or open channel [4].

De-silting Chamber: A tank or chamber generally located upstream from water conveyance systems used to trap suspended silt load, pebbles, etc. so as to minimize erosion damage to the turbine runner.

1.2 Summary of Best Practices

1.2.1 Performance/Efficiency & Capability - Oriented Best Practices

- Routine monitoring and recording of head loss through flumes and open channels.
- Trend head loss through flumes and open channels comparing Current Performance Level (CPL) to Potential Performance Level (PPL) to trigger feasibility studies of major upgrades.
- Maintain documentation of Installed Performance Level (IPL) and update when modifications to components are made (e.g., replacement of liner).
- Include industry acknowledged "up-to-date" choices for flume and open channel design component materials and maintenance practices to plant engineering standards.

1.2.2 Reliability/Operations & Maintenance - Oriented Best Practices

- Develop a routine inspection and maintenance plan.
- Routinely inspect flume supports for signs of settlement or erosion.
- Regularly inspect structural joints for leakage, corroded or missing rivets or bolts, cracked welds, damage, etc.
- Routinely clean and remove debris from flumes and open channels.
- Routinely inspect and maintain debris removing systems (i.e. trash boom).
- Periodically remove sedimentation by dredging, flushing, vacuum extraction, or other available methods.
- Document any operational changes such as an increase in the Probable Maximum Flood (PMF), changes in flow requirements due to unit upgrades, changes in seismic criteria, or changes in operational regimes to compare with the original

design criteria to ensure that the water conveyance component is functioning optimally and safely.

- As compared with a headrace channel, a tailrace channel is usually shorter and flow velocities are slower; therefore, head loss and water loss are less of a concern. However, flow capacity and safety of tailrace operations should not be compromised (i.e., sudden blockage of the tailrace might cause a severe accident).

1.3 Best Practice Cross-references

- Civil – Trash Racks and Intakes Best Practice
- Civil – Leakage and Releases Best Practice
- Civil – Penstocks, Tunnels, and Surge Tanks Best Practice
- Civil – Draft Tube Gates Best Practice

2.0 Technology Design Summary

2.1 Material and Design Technology Evolution

Channel liners can be used to increase the hydraulic performance of open channels and flumes. Historically, open channels have been unlined or lined with erodible material such as sand or gravel. Unlined channels are plagued by several operational and maintenance-related issues such as erosion of embankment slope material, water seepage, hydraulic losses due to frictional resistance, and loss of hydraulic area due to vegetation growth or buildup of eroded material. Linings can improve hydraulic performance by improving discharging capacity, reducing frictional head losses, improving operational efficiency, extending channel life expectancy, preventing buildup due to vegetation such as weeds, reducing maintenance costs, and reducing seepage losses [1]. There have been recent innovations in liner materials and application processes. The use of geo-membranes has been used in recent years due to its ease of application and water-tightness.

The US Bureau of Reclamation conducted a 10 year study of various channel lining arrangements and their effectiveness on reducing seepage [5]. The three primary arrangements included concrete, exposed geomembranes, and a combination of concrete with a geomembrane under-liner. The concrete liner proved to have excellent durability; however, the long term effectiveness of preventing seepage was poor due to cracking. The installation and maintenance of a concrete liner is generally cost effective since plants are familiar with concrete and better equipped to provide routine maintenance such as crack repair. Figure 3 shows an example of a canal concrete lining project. The exposed geomembrane liner proved to be very effective in reducing or eliminating water losses due to seepage; however, they are more susceptible to damage than concrete and have a shorter service life (15 to 20 years) [5]. Geomembranes have a lower initial installation and maintenance cost, but the long term maintenance costs can be almost twice as much as concrete. This is due to the fact that plant personnel are generally not familiar with the material and special equipment or training may be required for even minor repairs. The third arrangement proved to be the most effective and easily maintained. By providing a geomembrane under-liner for the concrete lining, they were able to achieve the desired water tightness of a membrane while still having the durability and protection of the concrete. The maintenance costs are also lower since only the concrete top coat requires maintenance. Other material combinations that were tested included geosynthetics, shotcrete, roller compacted concrete, grout mattresses, soil, elastomeric coatings, and sprayed-in-place foam [5]. The appropriate channel liner should be addressed on an individual plant basis. Factors to consider when determining the most appropriate liner should include plant economics (maintenance and construction expenses), availability of local materials, local terrain limitations (use of heavy construction equipment may not be possible), amount of excavation or subgrade preparation necessary, environmental constraints, and desired hydraulic characteristics.

Figure 3: Coachella Canal Concrete Lining Project (Coachella County, California)

2.2 State of the Art Technology

For designing a new open channel system or considering a replacement of an existing open channel or flume when it is severely deteriorated or no longer meets the operational requirements , computer-aided modeling can be used to develop the most efficient hydraulic arrangement (channel shape, longitudinal slope, side slope, minimum and maximum permissible velocities, type of lining, etc.) while balancing plant economics, site specific limitations, and construction limitations. For example, from a hydraulics stand point, the most efficient section for open channel flow is a semicircle since for a given area it has the least wetted perimeter than any other shape; however, a semicircle shape may not be the most economical solution since it costs more to excavate and line the curved surface, it may not be feasible for the available natural condition, or the arrangement may be limited by the channel slope. The use of scaled physical models has become standard procedure in recent years for the design of open channels. Scaled hydraulic models allow for performance to be checked while still in the design phase. Advances in computer technology can aid in the development of hydraulic models for testing. Both the numerical model (e.g., HEC-RAS) and physical model should simulate the unsteady flows with wave propagation and backwater effect along the channel under either routine or emergency plant operations. By checking performance, any necessary design changes or modifications that could potentially result in savings in operating and construction costs can be identified [8]. Therefore, computer-aided modeling can be beneficial in helping to balance hydraulic efficiency with plant requirements and economics.

In addition to advances in computer-aided modeling, construction techniques have also advanced. Historically, channels have been trapezoidal in shape due to limitations in constructability. As of recent years, advances in both lining and excavation techniques have allowed for curved bottomed channels which are hydraulically more efficient [9].

3.0 Operation and Maintenance Practices

3.1 Condition Assessment

Since flumes and open channels (including the forebay, de-silting chamber and tailrace channel) are periodically exposed to severe service conditions such as turbulent water or severe weather, they are prone to the following maintenance issues:

- Erosion of channel embankment slopes
- Structural deterioration
- Concrete spalling (canal linings, flumes, or guide walls)
- Steel corrosion (flume structural components or linings)
- Increased surface roughness due to aquatic growth/vegetation and erosion
- Sedimentation
- Water loss due to seepage through linings, joints, embankments, etc.
- Ice and debris collection or blockage
- Deterioration of linings
- Foundation settlement or deterioration
- Instability of adjacent slopes

It is important that flumes and open channels be routinely inspected for not only efficiency related maintenance issues but also safety, since failure of a flume or channel can have dire consequences. Condition assessments are primarily conducted by visual examination and physical measurements. The purpose of any water conveyance condition assessment is to determine the structural integrity of the components, the remaining life expectancy, and any necessary upgrades to improve overall efficiency. A visual inspection typically includes assessments of corrosion, lining deterioration, joint conditions (bolts, weld, etc.), evidence of embankment erosion or instability, foundation conditions, stability of supporting and adjacent earth slopes, and flow blockage due to debris or ice accumulation. Since the interiors of flumes and open channels are often underwater and difficult to inspect, it is recommended that when components are required to be dewatered for other reasons, the plant should inspect the interiors and remove any debris or buildup of sedimentation. Flume exteriors should be visually inspected for any signs of leakage while in operation.

Data records from previous inspections, maintenance, and upgrades should be obtained. By reviewing any previous records potential problems can more easily be identified such as worsening conditions or chronic issues. It is important to identify any previous repairs or repair recommendations that might not have been implemented. Another key to an effective inspection plan is to review the original design documents. This can help to identify if: 1) obsolete construction methods were used such as copper waterstops or unlined channels, 2) there are any obsolete components, configurations, equipment, or other features in use such as poor hydraulic shape for channels, 3) materials are nearing the end of their life expectancy, 4) there were any problems encountered during construction such as a fault zone across a channel or a soft zone in the foundation material, 5) inadequate inspection during construction, and 6) foundation issues such as geologic faults or differential settlement [3].

Plants should schedule routine and thorough inspections of all flume and open channel components. This will help to identify defects or other maintenance issues so that unscheduled shutdowns for repairs can be minimized. When developing an inspection program, it is also important to acquire information regarding operational records which should show any changes in operation or upgrades. It will allow for comparison of current operating conditions with the original design criteria.

The frequency and extent of condition assessments will be based on various plant and site specific factors including accessibility, age of structure or component, previous maintenance or reliability issues, public safety or environmental concerns, changes in operation, etc. An efficient and comprehensive inspection plan should be developed after considering all contributing factors. If significant issues are discovered during the condition assessment, then the plant should have a qualified engineer perform a special inspection to determine what repairs are necessary or if replacement is required. It is also recommended that plants perform special inspections after floods, earthquakes, or any other unusual event (e.g., load rejection) that may have resulted in damage [3].

3.2 Operations

Routine removal of debris and ice should be performed using trash/ice booms or similar. If debris or ice buildup is a recurrent issue, it is recommended that the plant consider installing permanent structures for aid in removal. Sedimentation can also have a negative impact on plant operations. Sediment should be routinely removed using methods such as dredging, vacuum extraction, flushing, mining dry while conveyance system is dewatered, or in more severe instances the addition of a stilling basin upstream to allow settlement of sedimentation or a sediment collection device. Also, increasing the flow velocity by reducing channel cross-sectional area can help the flow achieve ‘flushing velocity’; however, this is generally only a consideration in new design. By achieving the ‘flushing velocity’, accumulation of sedimentation is reduced; however, the sediment is passed downstream where it might still pose operational or maintenance issues such as turbine erosion. The addition of a de-silting chamber can also be installed upstream to help trap suspended silt particles. Buildup of sedimentation can increase surface roughness and reduce cross-sectional area, therefore increasing head losses due to frictional resistance. In addition, the removal of debris or ice buildup can increase flow. Thus routine cleaning practices can improve hydraulic performance through water conveyance systems and increase overall plant efficiency. It is important to note that not only does debris and ice buildup have a negative effect on operation, they can also cause blockage and lead to failure as was the case with the forebay skimmer wall failure at the Safe Harbor Hydroelectric Project in Pennsylvania as a result of ice accumulation [4].

Plants should routinely evaluate any changes in the Probable Maximum Flood (PMF) from the original design criteria. If the PMF increases, structures should be re-evaluated through hydraulic model tests to determine that the existing conveyance system is still adequate. Miscalculation of PMF in the original design or failure to account for changes in PMF from recent hydrological analysis of watershed, may lead to overtopping of the canal embankment or failure. If the structural integrity of the system is not compromised, an increase in PMF can be addressed by raising channel embankments or constructing parapet walls; however, in some cases construction of a new conveyance system may be necessary [4].

Another important phenomena to consider in channel operations is hydraulic jump or hydraulic drop (fall). When high velocity flow (supercritical) is introduced to a section of slow moving flow (subcritical) resulting in a rapid reduction of flow velocity over a short length, the channel will experience an abrupt rise in water surface known as a hydraulic jump. Alternatively, a hydraulic drop is caused by the introduction of subcritical flow to supercritical flow causing a rapid increase in flow velocity and abrupt drop in water surface level. Sudden changes in channel bed slope can result in hydraulic jumps or drops. Hydraulic jumps and drops in the intake channel can negatively affect plant efficiency by dissipating energy and leading to head loss. Hydraulic jumps can be avoided by ensuring that transitions at the intake channel are gradual. Alternatively, hydraulic jumps may be desirable at the discharge when erosion in the downstream channel or river is a concern. Through hydraulic jump basins, the discharge energy can be dissipated before flow is returned to the downstream channel limiting erosion problems [2]. If hydraulic jumps or drops are observed, plants should consider further investigation into how the phenomena is impacting operations and if corrective action is warranted. Generally, this occurrence is only considered during the initial design since any upgrades to reduce jumps or drops are not economically feasible for improving efficiency alone.

Other operational considerations include increased flow requirements due to unit upgrades, changes in seismic criteria, changes in operational regimes, or any condition changes unaccounted for in the original design such as degradation conditions or increased surface roughness; as well as potential emergency circumstances (e.g., load rejection causing wave propagation and backwater effect) when the operational regimes and conditions have been changed. Plant personnel should routinely evaluate flumes and open channels to ensure that they are functioning properly and efficiently for the current operational characteristics.

3.3 Maintenance

Flumes and open channels are designed to convey water from its source (river, lake, reservoir, etc.) over a long distance to the intake or pressurized conduit (penstock or tunnel) or discharge water from the powerhouse to the downstream river/lake, while limiting losses due to hydraulic friction, seepage, and leakage. Reduction of these losses through installation or repair of a liner or replacement of the conveyance system can help improve plant efficiency and generation; however, these upgrades can be costly and not likely justifiable on the grounds of reducing head losses alone [7]. Therefore, upgrade or replacement of a water conveyance component such as flumes or open channels is generally only viable if safety of the structure is a concern, the component no longer satisfies the operating requirements, there is significant seepage or erosion, or the water conveyance has severe degradation. Since upgrades or replacement can be costly, it is important to routinely perform any necessary maintenance or life-extending repairs so as to limit unscheduled shutdowns which can affect plant availability and generation.

Foundations and supports should be regularly checked for signs of seepage. Seepage is the slow percolation of water through an embankment or foundation [3]. Seepage not only results in loss of water it can also saturate the supporting soil and either undermine the foundation or cause it to shift or collapse. Other foundation issues can include erosion, settlement which can lead to misalignment, foundation faults, heaving due to expansive foundation material such as clay. Erosion and stability of surrounding slopes are also a concern. Eroded material from surrounding slopes can cause blockages in channels or increase the hydraulic roughness. Failure of a surrounding slope can also negatively impact the structural integrity of flumes and channels, as was the case with the Ocoee River Flume in Tennessee. In April 2010, a rock slide destroyed a 70 ft section of the historic wood flume. The rock slope was stabilized using 90 bolts, some 40 ft long as shown in Figure 4 [6]. Other means of slope stabilization can include the addition of retaining structures or shotcrete. If large amounts of sloughed materials from surrounding slopes are present in flumes and channels, further investigation of slope stability is warranted.

Figure 4: Slope Stabilization (Ocoee River Flume, Ocoee, Tennessee)

Photo Courtesy of J. Miles Cary

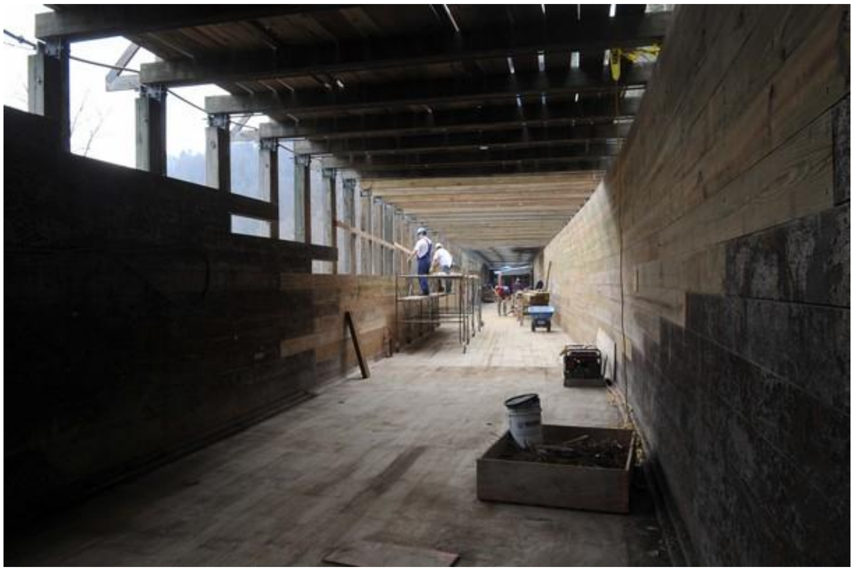

Figure 5: Wood Flume Repair (Ocoee River Flume, Ocoee, Tennessee)

Photo Courtesy of Jason Huffine/TVA

It is critical that any obstructions within flumes or open channels be removed promptly so that the flow capacity is not negatively impacted. Obstructions can result from overgrown vegetation, aquatic growth, sloughed materials from adjacent slope failures, debris such as dead trees or limbs, or ice accumulation [3]. Obstructions such as these will not only impede the flow capacity, but can also lead to damage of the structure or liner, increased hydraulic roughness, or sudden failure due to blockage. Debris should be routinely removed so as to avoid buildup.

Since flumes and open channels are often subject to turbulent flow, concrete liners, structures, or foundations are likely to experience a range of concrete problems. These issues include cracking, surface defects, cavitation, erosion, and leakage at joints. Concrete cracking is a common phenomenon in hydroelectric facilities and does not necessarily require immediate action. Cracks should, however, be routinely monitored, measured, and documented for future comparison. It is necessary to have ongoing records documenting any cracks so that any significant changes can be identified. If new cracks suddenly appear or existing cracks become more severe or extensive, then further investigation by a qualified engineer is warranted [3]. Concrete surface defects may include shallow deficiencies in the concrete surface, textural defects from improper installation, and localized damage caused by debris [3]. Any surface defects should be recorded and any necessary repairs performed. Concrete deterioration due to either cavitation or erosion should be routinely monitored and repaired as necessary. Concrete repairs can include shotcrete applications, localized grouting of cracks, replacement or patching, or overlays for concrete liners.

Water loss through joint leakage is another common issue for open channels and flumes. Concrete channels often have waterstops which are continuous strips of waterproof material embedded in joints, usually made of metal, PVC, or rubber [3]. When waterstops are damaged or begin to deteriorate, water can seep through the joints. Not only does this lead to water loss, it can also lead to erosion of the foundation material or further joint damage due to freeze/thaw. Channel joints should be inspected when dry if possible. Evidence of joint problems can include soil fines seeping through the joint, vegetation in joints, or damaged or missing joint sealant [3]. Joints can be repaired by grouting, replacement of joint material or waterstops, sealing joints with epoxy, or the addition of a watertight membrane over the entire channel.

Figure 6: Waterstop Repair in Concrete Channel

Steel can be used for flume supporting structures, channel liners, or flume liners. Since steel in hydroelectric facilities is repeatedly exposed to moisture, corrosion is oftentimes a recurrent problem. Evidence of steel corrosion can include scaling, flaking, pitting, or color changes. If left unchecked, corrosion can lead to loss of material, leakage, and in some instances failure of the structure. Corrosion can be limited or avoided by either painting the steel or installing cathodic protection. Other steel problems include fatigue due to repetitive loading, erosion by abrasive debris, tearing or rupture due to debris impact, cavitation due to high flow velocities, cracking, and deformation [3]. Plant personnel should regularly inspect all steel surfaces for any signs of deterioration or problems.

4.0 Metrics, Monitoring and Analysis

4.1 Measures of Performance, Condition, and Reliability

The fundamental equations for evaluating efficiency through flumes and open channels are Manning's equation for open channel flow, the equations for head losses due to friction and geometrical changes, and water losses due to seepage, leakage, or unexpected overflow (water loss from evaporation is minimal and unavoidable) [2 and 9]. Losses due to leakages or unexpected overflow are more difficult to quantify and require more detailed analysis based on a plant specific basis. Avoidable head losses can be directly related to overall power/energy loss and subsequent loss of revenue for the plant. These equations are defined as follows:

Flow quantity, $\boldsymbol{Q}$ (ft^3/sec):

$$\boldsymbol{Q = \frac{1.486}{n} A R^{2/3} \;\; \overline{S}}$$

Where:
- $\boldsymbol{Q}$ is the flow quantity (ft^3/sec)
- $\boldsymbol{n}$ is the Manning roughness coefficient
- $\boldsymbol{A}$ is the cross-sectional area (ft^2)
- $\boldsymbol{R}$ is the hydraulic radius (ft)
- $\boldsymbol{S}$ is the slope of energy line or energy gradient (ft/ft)

Head loss due to friction, $\boldsymbol{h_f}$ (ft):

$$\boldsymbol{h_f = n^2 \frac{Lv^2}{R^{4/3}}}$$

Where:
- $\boldsymbol{h_f}$ is the head loss due to friction through the conveyance component (ft)
- $\boldsymbol{n}$ is the difference in Manning roughness coefficients for existing roughness conditions and roughness conditions after potential upgrades.
- $\boldsymbol{L}$ is the length of the conveyance component (ft)
- $\boldsymbol{v}$ is the average flow velocity or flow rate per cross-sectional area (ft/sec)

· R is the hydraulic radius (ft)

Head loss due to minor losses (e.g. channel bends, adjacent slopes), h_m (ft):

$$h_m = K_b \frac{V^2}{2g}$$

Where: · h_m is the head loss due to minor losses from geometrical changes (ft)
· K_b is the difference in the head loss coefficient for existing conditions and for conditions after potential upgrades computed as follows for channel bends: $K_b = \frac{2W}{R_c}$
· W is the channel width (ft)
· R_c is the center-line radius of the channel curve (ft)
· V is the mean velocity or flow rate per cross-sectional area (ft/s)
· g is the acceleration due to gravity (ft/s^2)

Moritz formula for water losses due to seepage in unlined channels, S (ft^3/s/mile):

$$S = 0.2C(\frac{Q}{V})^{1/2}$$

Where: · S is the losses due to seepage (ft^3/s/mile)
· C is the rate of water loss (ft^3/24 hours/1 ft^2 of wetted area). Average values of C can range from 2.20 for sandy soils to 0.41 for clays.
· Q is the flow quantity (ft^3/s)
· V is the mean velocity (ft/s)

Avoidable power loss, ΔP (MW), associated with head losses:

$$\Delta P = (Q\,\gamma\,\Delta h + \Delta Q\,\gamma\,h) / 737{,}562$$

Where: · **Q** is the average volumetric flow rate through the water conveyance component (ft^3/sec)
· **γ** is the specific weight of water (62.4 lb/ft^3)
· **Δh** is the avoidable head loss
· **737,562** is the conversion from pound-feet per second to megawatts

Avoidable energy loss, ΔE (MWh):

$$\Delta E = \Delta P T$$

Where: · **ΔP** is the avoidable power loss (MWh)
· **T** is the measurement interval (hrs.)

Avoidable revenue loss, ΔR ($):

$$\Delta R = M_E\,\Delta E$$

Where: · $\mathbf{M_E}$ is the market value of energy ($/MWh)
· $\mathbf{\Delta E}$ is the avoidable energy loss

4.2 Data Analysis

Determination of the Potential Performance Level (PPL) will require reference to the flow characteristics of the modified geometry and/or surface roughness of the flume or open channel components. The PPL will vary for each plant. However, the maximum PPL will be based on the flow characteristics of the most efficient available upgrade.

The Current Performance Level (CPL) is described by an accurate set of water conveyance component performance characteristics determined by flow and head measurements and/or hydraulic modeling of the system.

The Installed Performance Level (IPL) is described by the water conveyance component performance characteristics at the time of commissioning or at the point when an upgrade or addition is made. These may be determined from reports and records of efficiency and/or model testing at the time of commissioning or upgrade.

The CPL should be compared with the IPL to determine decreases in water conveyance system efficiency over time. Additionally, the PPL should be identified when considering plant upgrades.

4.3 Integrated Improvements

The periodic field test results should be used to update the unit operating characteristics and maintenance practices. Optimally, any test results or observations should be integrated into an automated system, but if not, hard copies of the data should be made available to all involved plant personnel (particularly unit operators). All necessary upgrades or maintenance (channel lining, debris removal, slope stabilization, etc.) and methods to routinely monitor unit performance should be implemented.

5.0 Information Sources:

Baseline Knowledge:

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10. Zipparro, Vincent J. and Hans Hasen, *Davis' Handbook of Applied Hydraulics*, 4th Edition, 1993.

It should be noted by the user that this document is intended only as a guide. Statements are of a general nature and therefore do not take into account special situations that can differ significantly from those discussed in this document.

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