RECLAMATION
Managing Water in the West

Intake Vortex Formation and Suppression at Hydropower Facilities
Research and Development Office

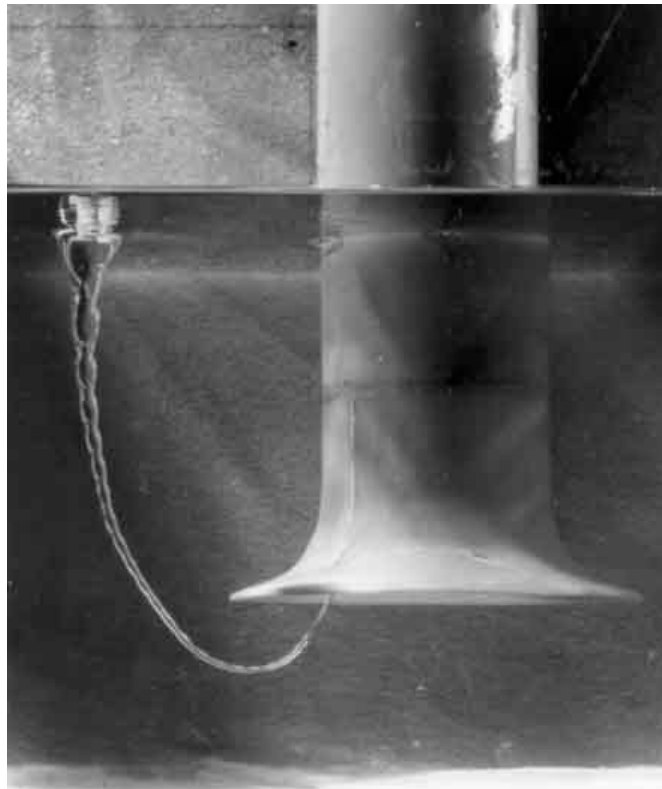**Science and Technology Program**
Final Report ST-2016-6359-1

HL-2016-09

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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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14. ABSTRACT Literature review of existing studies on vortex formation were investigated to answer these primary research questions; Is there any generalized guidance to avoid vortex formation, are pump station guidelines applicable for hydropower intakes, how is turbine efficiency impacted with vortex formation, what is the minimum submergence to avoid vortex formation, are vortices dependent on individual penstock flow or total flow, are vortex suppressors capable to arrest development without impacting generating efficiency and how dependent is vortex formation on site specific geometry and operating conditions. Selected Bureau of Reclamation projects were interviewed to determine the presence of vorticies.			
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Acknowledgements

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Introduction

Free surface vortices are a concern for any system that draws water by either gravity or pumping. These can include outlet works at non-hydropower facilities, hydropower intakes, pump stations, navigation locks, spillway intakes, or any intake located below a free water surface. With the variety of structure types, there are also many different types of intake designs. For many hydropower facilities, a horizontal or an angled penstock is common, while for many pump facilities, a vertical or inverted vertical intake are common as shown in Figure 1.
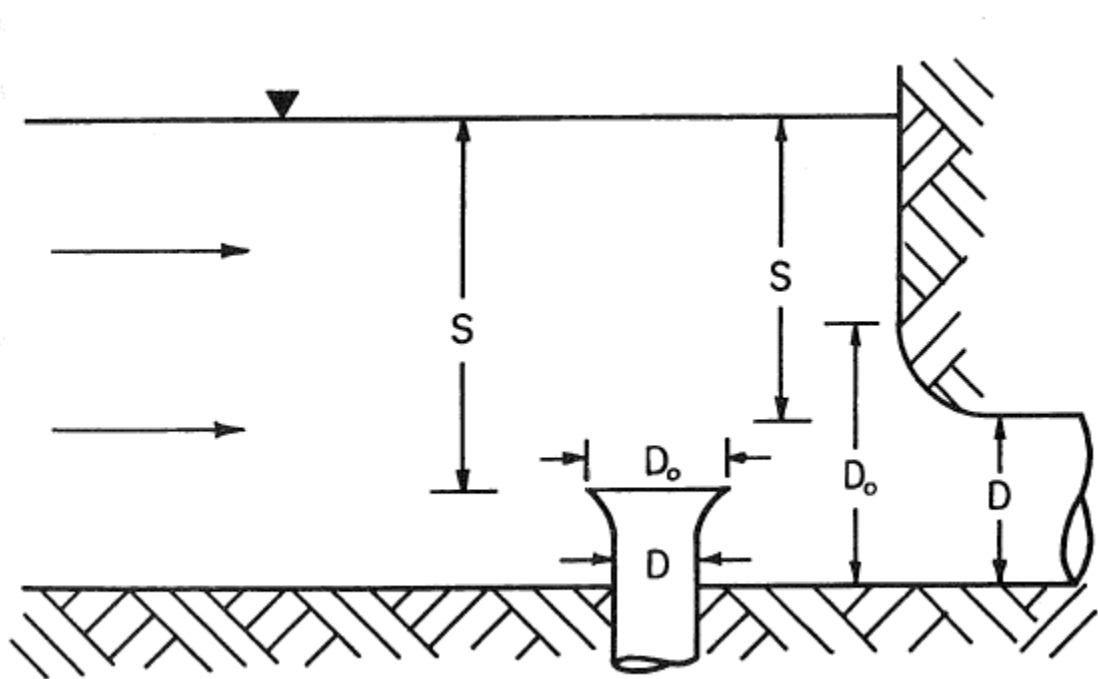
Figure 1. Horizontal and Vertical Intake Designs (note, inverted vertical intake not shown). D represents the pipe diameter, D_o is the diameter of the bellmouth intake, and S is the submergence to the intake (Rindels and Gulliver, 1983)

A vortex is defined as a region of flow that is rotating around an axis that can either be straight or curved. Vortex formation occurs when the transition from open channel (free surface) flow to pressure flow is not smooth and uniform. When flow does not maintain gradual transitions that attempt to keep a uniform velocity distribution and acceleration, then vortices can occur (Bottazzi, Floreale and Molina, 2007). The main causes of vortex formation are non-uniform approach flow to the intake, shear layers of high velocity gradients and rotational wakes caused by obstructions in the approach flow (Durgin and Hecker, 1978). Chang (1977) lists these sources as well as flow passing diffusers and baffles that can also cause small eddies to shed and that any swirl action in the approach flow can be magnified as it converges at the intake due to the conservation of angular momentum. Vortices can also be formed as flow passes piers between intake gates as they are located directly adjacent to the opening and span the full depth

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of the intake which allows strengthening of the vortex along the length. Other modifications to flow patterns caused by wind, waves, ice, debris, or turbulence can also produce vortices, or can conversely lead to reduction in vortex formation (Suerich-Gulick, Gaskin, Villeneuve and Parkinson, 2014).

The majority of researchers that have studied vortex formation indicate the intake Froude number is the dominant parameter that influences vortex intensity (Suerich-Gulick, Gaskin, Villeneuve and Parkinson, 2014b). However, in addition to the intake Froude number, the dimensions of the structure and more critically the penstock, the submergence of the intake, and the bulk circulation of the approach flow are all very important (Jain, Ranga, and Garde, 1978). While these parameters are important for any intake, these are especially important at low head hydropower facilities where the lower levels of submergence can result in vortex formation in a facility where power optimization is essential and intake losses can be significant compared to the available head (Bottazzi et al., 2007).

The term critical submergence (S_c) was defined by Jain et al. (1978) as the smallest depth at which strong and objectionable vortices will not form. If the submergence is less than the S_c, a vortex will form, however the converse is not necessarily true since a vortex may form, as long as it is not objectionable. Gulliver, Rindels and Lindblom (1986) state that a dye core vortex is the limiting vortex type and may be acceptable for designs (shown in Figure 2). For design purposes, the conservative approach is to not to allow any subsurface swirl. A dimensionless submergence defined as the submerged length to the top of the intake divided by the conduit diameter has also been used as a uniform approach of evaluating vortices (Reddy and Pickford, 1972).

Classification of vortices is qualitative, but research by Durgin and Anderson resulted in a map of vortex types that correspond to the strength of the vortex (Durgin and Anderson, 1972). This resulted in the 6 types of vortex intensity which are listed below and can be found in Figure 2;

1. Very weak eddies without observable surface depression
2. Coherent swirl at surface with a small depression
3. Vortex core through the intake structure observable with dye
4. Vortex that does not entrain air, but can pull surface trash / debris into the intake
5. Vortex that allows intermittent air introduction to the intake
6. A fully developed air core vortex
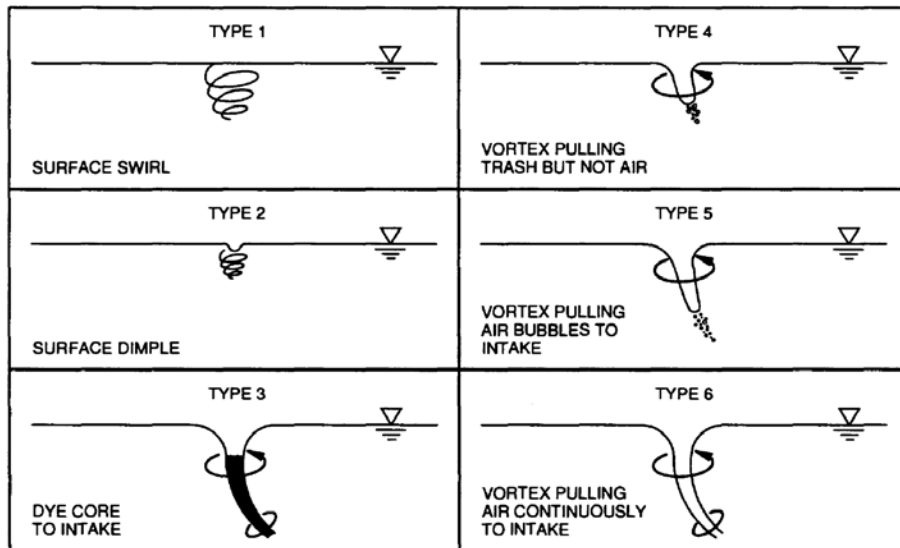
Figure 2. Vortex Types (image from Knauss, 1987)

Problems associated with vortices are numerous and can include vibration, surging, efficiency loss, structural damage, cavitation, flow reduction, safety hazard, unbalanced pump loading, noise, damage from trash drawn into the intake, lost revenue, increased maintenance, premature pump replacement, operational restrictions, structural modifications, and additional study. Vortices can become very powerful and a vortex at the St. Anthony Falls Lock and Dam claimed the life of a lock employee in 1974 when his small boat was drawn into the vortex (Ables, 1976).

Purpose

The purpose of this literature review is to study available materials to be able to answer research questions that were outlined in the research proposal. These questions are;

1. Are pump station guidelines applicable to hydropower installations?
2. How is turbine efficiency impacted by vortex formation?
3. What is the minimum submergence to avoid vortex formation?
4. Are vortices dependent on individual penstock flow or total flow?
5. Are vortex suppressors capable to arrest development without impacting generation efficiency?
6. How dependent is vortex formation on site specific geometry and operating conditions?
7. Can general guidelines be made that are applicable to a wide range of hydraulic facilities, structures and equipment throughout Reclamation?

In addition to researching literature to answer the above questions, personnel from a few Reclamation projects were interviewed to discuss the past history of vortex occurrence at the project. Projects that were contacted include Black Canyon Dam, Caballo Dam, Davis Dam, Glen Canyon Dam, Hoover Dam, Parker Dam, and Shasta Dam. A previous Hydraulics Laboratory report had already been created for Grand Coulee Dam, and was therefore not contacted.

Research Questions
Are pump station guidelines applicable to hydropower installations?

Some of the earliest recommendations for pump station intake designs were made by Prosser (1977). It is recommended that the approach flow should be uniform across the channel width and below 2 ft/s, support pillars should be streamlined to eliminate flow separation, stagnant flow areas should be filled, and trash racks should be designed to act as flow straightening vanes. He further advises the following factors to be poor channel design and should be eliminated. These include; abrupt changes in flow direction, rapidly diverging channels, steep slopes and blunt support pillars. Larsen and Padmanabhan (1986) expand on Prosser's recommendations by creating a list of circumstances where a physical model study is recommended during the design phase and includes; asymmetric or expanding approach flows, pump stations with multiple sumps and one approach channel, high capacity pumps and pumps with potential for screen blockage.

If all of the intake conditions by Prosser (1977) can be met, a minimum intake submergence is recommended as shown below, and if the above conditions cannot be satisfied, then a physical model study is recommended (Prosser, 1977).

$$S = 1.5 * D_o$$

Where D_o is the diameter of the bellmouth intake.

Reddy and Pickford (1972) were the first to use a dimensionless submergence to evaluate the likelihood of vortex formation and found when plotted, that most free surface vortices occur when the dimensionless submergence is less than;

$$S/D = 1 + Fr$$

Analysis of the Alden Research Laboratory data on modeled pump intake structures by Pennino and Hecker (1980) found no acceptable design standard that would ensure vortex free operation. Pennino and Hecker did find a region of a reasonable design guideline when plotting dimensionless submergence and Froude number when the dimensionless submergence is greater than 0.5 and the Froude number is less than 0.23. This region was expanded slightly with further evaluation by Rindels (1983) that found a region where vortices are less likely to occur if the dimensionless submergence was greater than 0.7 and the Froude number was less than 0.5. Rindels states that extremely poor approach conditions can still create vortices in this region. Rindels found the envelope curve proposed by Reddy and Pickford did not always hold true since there are locations with uniform approach conditions and high Froude numbers that do not experience vortex problems. Figure 3 below contains data collected by Rindels from many different sources and shows the region where vortices are less likely to occur (Rindels, 1983). Gulliver et al. (1986) removed the plotted points from the

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vertical intakes on this figure and tested combinations of higher submergence and Froude numbers which confirmed that the region of "safe" operation is the narrow band of low Froude numbers and higher dimensionless submergence.

Many researchers have published correlations of the minimum acceptable submergence using only dimensionless submergence and Froude number but the predictive accuracy is limited due to parameters such as the bulk circulation and approach conditions that are being neglected (Suerich-Gulick, Gaskin, Villeneuve and Parkinson, 2014c). It has also been found that in addition to the larger scale uniform approach velocity that localized impacts from either horizontal or vertical obstacles such as piers, walls, rock sloped banks, etc. can create flow separation. Even to the extent that at Untra hydropower facility the upper portion of the intake piers which were square edged (they were rounded below normal Water Surface Elevations) created flow separations that lead to vortex formation (Rahm, 1953).
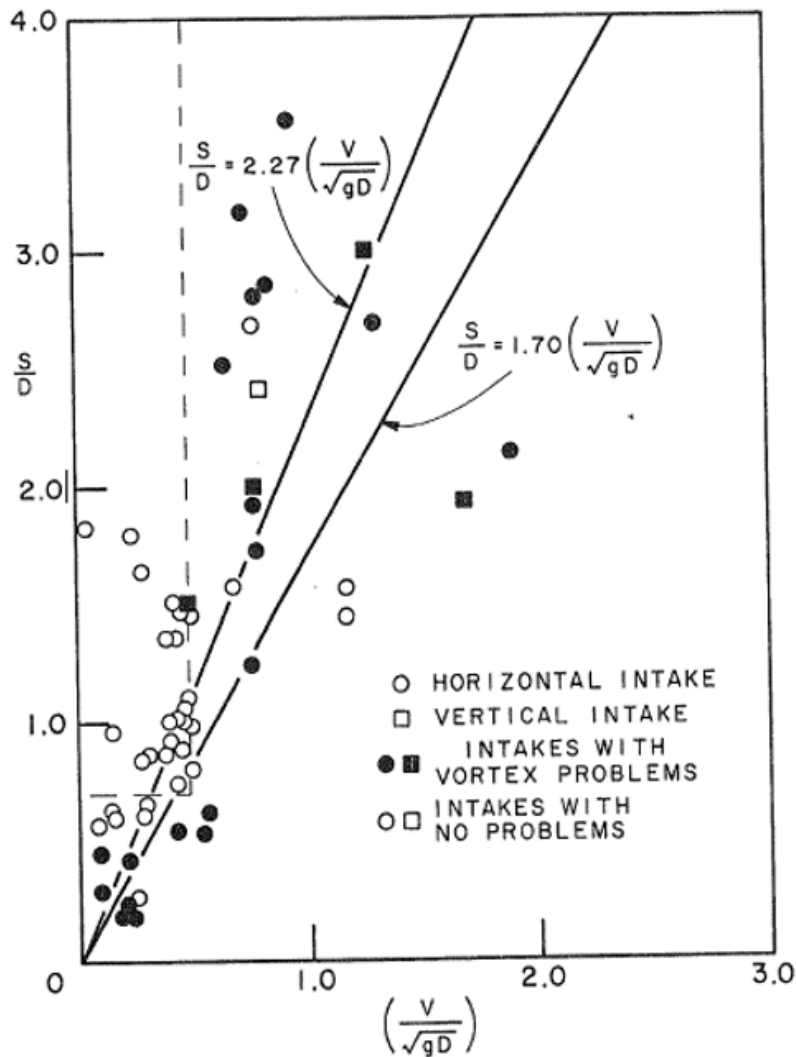

Figure 3. Dimensionless submergence vs. Froude (Rindels 1983)

Since the literature appears to contain very little true guidance other than for optimal conditions, many researchers and manufacturers have published operational criteria for safe operation. One such set of criteria was developed by the Iowa institute of Hydraulic Research which include the following (Nakatyo and Yoon, 1992);

1. No detectable boundary attached vortices extending to the pump bell
2. No free surface vortices stronger than type 2
3. No velocities measured at the pump throat that vary by more than 10% from the average of all local velocities measured in the cross section
4. Vortimeter-tip velocity angles (swirl angles) no greater than 5 degrees
5. No detectable, large scale, persistent "unsteadiness" or "waviness" in the pump bell approach flows, no indication of large scale turbulence, and no flow anomalies judged objectionable by investigators experience with pump intake model tests.

Similar restrictions are recommended by Ingersoll-Rand as acceptable standards for pump operation as a surface dimple no more than 0.3 ft deep and a surface swirl less than 5 RPM (Bauer, 1997).

While it is not mentioned by a majority of the literature, Rindels (1983) determined that vertical bellmouth intakes may be more susceptible to vortex formation than horizontal intakes, and Allen (2008) states that vertical intakes have a greater tendency to develop free surface vortices than other orientations. Only one study was found that includes impacts from multiple intakes that are operated differently (Bauer, 1997).

In conclusion, it appears that the same parameters that are recommended for pump intakes is very similar to those recommended for hydropower facilities. Figure 3 (1983) has not been refuted from more recent literature, but has also not been expanded on to confirm areas of the curve that remain safe beyond the study by Gulliver et al. (1986). While there might be some trend in higher likelihood of vortex formation with vertical intakes at pump facilities, it seems that the condition of both the incoming flow velocity uniformity as well as the structural detail govern the determination of vortex formation.

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How is Turbine efficiency impacted with Vortex Formation?

This topic was not discussed in the literature that was reviewed for this Scoping level study. Many authors acknowledged that swirling flow can lead to reduced effectiveness of an intake with only one study that reported that vortices can cause nearly an 80% reduction in the intake coefficient of discharge (Posey and Hsu, 1950). A few authors mentioned that the guide vanes upstream of the turbine runners will help reduce swirling flow (Rindels, 1983). It was also stated that an intake with a long penstock may reduce a small amount of swirl due to pipe friction (Gulliver et al., 1986) but neither author presented any information on reduction in turbine efficiency due to a vortex.

Anwar (1966) found that transient vortices do not seriously affect efficiency of the intake structure, hydraulic machinery, or cause significant vibration, but leaves the converse of the statement unstated and it is assumed that stationary vortices do result in energy loss, reduced discharge and potential for vibration and damage, but the type of vortex and the extent of the impacts are undefined. For the case of pump intakes, vortices can lead to higher long term operating costs (Bauer, 1997), but no data was given as to how much losses were created. Tullis (1979) stated that a vortex can alter the angle of attack on the impeller blades which can also reduce pump efficiency, but does not state by how much.

What is the minimum submergence to avoid vortex formation?

This topic was found to be very similar to the general discussion presented in the Introduction, as well as the discussion in the pump guidelines section. It is apparent from the research that evaluating the dimensionless submergence is more appropriate than just looking at the submergence value, and can make application more general. However, while many authors have attempted to quantify the amount of dimensionless submergence required to prevent vortex formation, the bulk circulation, design of the structure and the approach conditions of the flow can lead to vortex formation with very high submergence depths. Jain et al. (1978) created a predictive equation for critical submergence that includes a term for the bulk circulation, however it relies on knowing the circulation values in the prototype in the design phase which are very difficult to obtain without a physical model. Jain et al. later states that bulk circulation is difficult to measure, and predicting it during design of an intake is extremely difficult (Jain et al, 1978).

In general, a higher submergence value (or dimensionless submergence) will tend to decrease the likelihood of vortex formation. However, Wang and Chunbo (2010) found that at Xiluodu hydropower station flow was steady (and without vortices) at S=15m (S/D=1) and progressed to a dye core, trash pulling vortex and eventually a full air core vortex as the submergence depth increased to 47m (S/D=3.13). Froude numbers for the flows were not presented, but this case shows that even trends that most authors agree on can be negated due to site specific conditions.

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Are Vortices dependent on individual penstock flow or total flow?

This is another topic that was only minimally presented in the literature reviewed during this scoping level study. Suerich-Gulick et al. (2014) stated that vortices can also occur when one or more turbines is not in full operation which produces skewed flow towards the intake. This statement probably defines why this question was not answered, as a multiple intake system would need to consider the total approach flow rather than just the flow to individual penstocks. In addition, from interviews with Bureau of Reclamation powerplant operators, generation efficiency is generally greater if multiple units are operated equally (Personal communication Ernest Bachman at Black Canyon Dam 2016).

A physical model study performed by Ables (1976) at USACE's Waterways Experiment Station to investigate a strong vortex at the St. Anthony Falls Lower Lock and Dam, measured slight variations in the intake flow distribution of the 4 culverts when the radial gate for lock filling was opened. This variation was not found to be the cause of the vortex, but was mentioned to show how the flow distributed amongst 4 identically sized adjacent intakes. This system is analogous to a hydropower facility with numerous penstocks, but the difference in flow was a maximum of 6% between the 4 culverts, and may not reflect approach conditions to a powerhouse where only one turbine is not operational in a bay.

Bauer (1997) performed a study on a single sump, multiple pump intake facility and varied which pumps were operated, sump design and vortex suppression to determine the effect on subsurface vortices. In the unmodified sump, subsurface (side, back wall and floor attached) vortices were observed with all 4 pumps operating, and both subsurface and free surface vortices were observed when only 3 of the 4 pumps were operated. Triangular floor and wall splitters were utilized for vortex suppression, and were able to eliminate the subsurface vortices, but actually lead to formation of free surface vortices. Bauer also produced a list of configurations that were either recommended or not recommended for sump designs (Bauer, 1997).

Are vortex suppressors capable to arrest development without impacting generation efficiency?

No information was found on the loss of power generation with vortex suppressors, however many documents acknowledged that the design of a trash rack can create head loss which could reduce power generation of a turbine. However, there are many case studies of successful vortex suppression devices that have eliminated air entrainment and associated drawbacks at both hydropower or pump facilities.

Many authors state that the cost to modify or re-design and construct an intake structure at an existing facility with vortex problems is both cost prohibitive and may be physically impossible. Available solutions to reduce vortex formation include; increasing submergence, disrupt the angular momentum, force the vortex into a zone in which formation is difficult, increase the area of the intake to reduce velocities, or create a longer flow path to the surface. Since none of these methods reduce upstream angular momentum, some amount of swirl may remain (Rindels, 1983). Some of the more common designs include floating rafts (Denny and Young, 1974), although Ziegler (1974) found that a raft on the surface is not the best location as circulating water remained below the raft. Ziegler found that the optimum distance of a submerged raft removed the swirling water both above and below. Ziegler also found that extending the trash rack thickness increased vortex suppression (Ziegler, 1974).

Bauer (1997) found that a submerged raft with horizontal grating as little as 4-6 inches below the free surface was successful at reducing free surface vortices. Bauer also stated that curtain walls to smooth the flow, a surface beam that protrudes into the approach channel flow, and guide vanes may also be enough to disrupt the vortex from forming. Allen (2008) performed a physical model test on a vertical water supply intake and found that a debris cage was effective at reducing the likelihood of vortex formation. Allen recommended design of a debris cage with bars oriented in both directions and bar spacing be at the maximum possible for the desired debris blockage for best vortex suppression. Following the debris cage tests, Allen tested a submerged raft and found that its performance was the best of any configuration tested. (Allen, 2008). Therefore, while trash racks have been successful at reducing vortices, a dedicated structure that reduces the surface and near surface swirl provides better performance.

Taghvaei, Roshan, Safavi and Sarkardeh (2012), studied 13 different configurations of vortex suppression devices of a pumped storage plant intake and found the best performance was from a horizontal wall that extended out above the dam intake and increased the direct flow path from the surface to the intake.

How dependent is vortex formation on site specific geometry and operating conditions?

This is one area where all authors in the literature review agree that the site specific conditions of the approach flow is one of, if not the key parameter in determining if a vortex will form. When listing the ideal conditions that pumps should be designed for, Prosser (1970) recommends a hydraulic model study if there are any deviations from the stated design guidelines. Anwar (1981) and Pennino (1980) both advise that it is very difficult to estimate the bulk circulation without the use of a scale physical model since the circulation is dependent on many factors in the approach conditions which are entirely site specific. The approach flow is just as important if not more so than the dimensionless submergence and Froude number, and "there is virtually no submergence at which an intake designer can be certain of vortex-free operation" (Pennino, 1980). Bauer (1997) elaborates on this and states that it is difficult to detect submerged vortices unless studied in a laboratory that can investigate with dye or air injection.

Figure 3 by Rindels (1983) and the similar work by Gulliver et al. (1986) can give a rough idea of vortex risk, but they cannot account for approach flow and geometry that can significantly influence vortex formation. More rigorous evaluation of vortex risk can only be achieved by construction of a physical model and visually inspecting for vortices (Suerich-Gulick et al., 2014). It is very important that the construction of a physical model to investigate vortices match the geometry and flow approach conditions exactly, as was found with the initial model of the St. Anthony Falls Lower Lock vortex study. The first model was constructed at the St. Anthony Falls Hydraulics Laboratory and due to space constraints the full prototype approach topography was not modeled. Tests on this model did not observe vortex formation, and lead to the second physical model study at WES (Ables, 1976).

Most laboratory scale models employ Froude number similitude which match the Froude number of the model flow to the Froude number of the prototype flow and allow the dominant forces of gravity and inertia to scale correctly (Jain et al., 1978). However, with water being the predominate test material, it is impossible to match the Weber and Reynolds numbers which leads to scale effects of both surface tension and viscosity (Suerich-Gulick et al., 2014b). Rindels (1983) recommends that the Reynolds number of scaled model flows be greater than $5x10^4$ to avoid viscous scale effects which is similar to standard guidance for general Froude scale physical model studies (Hydraulic Laboratory Technique, 1980).

Surface tension scale effects are only applicable when an air core vortex is observed in a physical model, and is stated that the development from a surface dimple to an air core would occur more rapidly in the prototype than in a Froude scale model (Rindels, 1983). Jain et al. (1978) performed research on surface tension with a water & cepol (carboxyl-methyl cellulose) mix that matched the

kinematic viscosity but had differing surface tensions. This study found the surface tension does not affect development of an air core vortex. Similar tests to determine differences using iso-amyl alcohol to determine matching surface tensions and different kinematic viscosity did result to changes to the air core vortex, but only in a specific range of Reynolds numbers (Jain et al., 1978). Rindels (1983) recommends Weber number be greater than 3×10^3 to avoid surface tension scale effects, and to use the most conservative of the criteria for surface tension or viscosity when designing a model study.

While new studies are still being published for specific prototype model studies with vortex problems, the trend in vortex research has been to move away from research on the likelihood of vortex formation, and towards attempting to define the exact shape of the vortex. Part of this may be because the existing data strongly support the site specific approach conditions that ultimately determine the generation of vortex unless the structure is designed in the very small region of "safe" dimensionless submergence vs. Froude number. Therefore, the current research is focusing on parameters to define the core shape, radius, the depth of the surface depression, and the tip depth. Many of these studies have produced empirical equations with coefficients that are generated from a given model, and have been caveated by the researcher that the coefficients may not broadly apply to other models or prototypes (Suerich-Gulick et al., 2014).

While many of the investigated studies were performed before sophisticated computational fluid dynamic (CFD) models and computing resources were powerful enough for detailed studies, many current researchers still recommend physical model studies. Simulations that match physical model results have been obtained by researchers such as Nakayama and Hisasue (2010), Wang (2010), Aybar (2012), and Noid (2015), but many others have unsuccessfully attempted to recreate a vortex with CFD models.

One benefit of CFD models is the ability to estimate the bulk circulation of the approach flow which is a key parameter in determining if a vortex will form, but no predictive equations based on bulk flow values have been published. On the other hand, a benefit of physical models is that they allow the investigation of the interaction between flow and intake geometry, and are generally easy to modify to evaluate and compare alternative designs (Suerich-Gulick et al., 2014).

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Can general guidelines be made that are applicable to a wide range of hydraulic facilities, structures and equipment throughout Reclamation?

The information presented in this report suggest that there are very few circumstances where the potential for vortex formation can be ruled out. With that in mind, Figure 3 does contain a small window when the dimensionless submergence is plotted against the Froude number where researchers have not observed vortex formation. Depending on the type of structure, and the site specific conditions, there may be instances where detailed study is not required.

Many guidelines have been published for pump intakes, and if the constraints stated by Prosser (1977) are met and none of the constraints for a specific model study by Larsen and Padmanabhan (1986) are needed, then a physical model study may not be required. In addition to the determination on likelihood of vortex formation, the risk of potential by a vortex should be compared to the needs of the project. If a project is small and costs for repair and replacement should vortex damage shorten the projected lifespan are not major, a physical model study may not be warranted.

Interviews with Selected Bureau of Reclamation Projects

Note: At any of these projects, there is potential for future vortex issues should the water surface elevation drop due to drought, maintenance or any other circumstance. A study would be required to estimate a water surface elevation at which a potential vortex could form.

Black Canyon Dam

A type 2 to type 3 vortex has been observed at Black Canyon Dam when the WSE is drawn down about 15-18 feet from the normal pool elevation. The submergence to the top of the horizontal intake is about 4 feet at the lower WSE where vortex formation has been observed. This elevation does occur with some regularity as the reservoir is drawn down for maintenance on the drum gates. There is currently an operational restriction to shut down the two turbine units if the WSE is 2 feet below the top of the intake gates. It has been observed that there is some instability in the power output when a vortex is present. During irrigation periods, the WSE is considerably higher and has around 21 feet of submergence to the top of the intake gates. During this fall, the reservoir will be drawn down to allow construction of an additional penstock and turbine unit at the Dam. The elevation of the new intake will be lower, which will reduce the likelihood of vortex formation. There have not been any attempts to reduce vortex formation with a vortex suppression device.

Caballo Reservoir

Caballo reservoir is currently being drawn down in an attempt to remove trash and obstructions from the trash rack at the outlet works. When the reservoir WSE was near the top of the trash rack (about 35' above the invert), vortices were observed. Operation staff have been using compressed air and have been able to remove some debris from the rack, but a large amount is still wedged between the bars. Since only the top of the trash rack is visible, there is no current estimate of the amount of obstruction, but structural members are observed to be bent due to the forces. A fire in the watershed in 2014 is likely responsible from some of the debris in addition to a vegetation management plan that raised WSE and therefore mobilized some debris. As the WSE is dropped for irrigation demands, that debris is likely being pulled towards and into the trash rack.

Davis Dam

From the description of the operators, a type 3 vortex has been observed occasionally at Davis Dam. They are typically located near the piers between the intakes, and can be as large as a pie plate on the surface with a depression that goes down potentially 20 feet. When a vortex is present, no impacts to the

efficiency has been observed, but vortex formation has not been tracked. Typical submergence is about 120 feet at normal WSE, but can drop to about 100 feet with normal operational releases. Since it is an uncommon occurrence, no vortex suppression has been attempted. From investigation using Google Earth, the approach flow makes a 90° turn as it enters the intake which is like responsible for the vortex formation at lower WSEs.

Glen Canyon Dam

Even with nearly the lowest WSE at Lake Powell recorded since the initial fill, no vortex formation has been observed. This is due to the design of the intake, and its centerline elevation that is about 150 feet below the current WSE.

Grand Coulee

No interview was made at Grand Coulee Dam, however a hydraulic model study of the 3rd powerhouse was performed at the Bureau of Reclamation's Hydraulics Laboratory in Denver Colorado during the design phase. The design was modified to reduce an air core vortex that was formed as flow separated past a corner leading to the penstock. This was remedied by an elliptical guidewall that reduced the flow separation and removed the vortex that had been observed at intake #19. Approach flows for the 3rd powerhouse also contained a sharp bend that increased likelihood of vortex formation, but were carried through to the final design following the successful mitigation with the physical model.

Hoover Dam

Due to the design of the pin connections on the Hoover Dam penstocks, some leakage occurs if warmer surface waters are passed through the penstocks. Therefore, flows through the penstocks are typically drawn from deeper in the reservoir which has greater submergence and has not lead to vortex formation.

Parker Dam

Shortly after completion of the hydropower units at Parker Dam, a vortex was observed. A surface raft of Styrofoam blocks was installed many years ago and are still in place today which has been effective at eliminating vortex formation. The water surface elevation of Lake Havasu is operated in a typical range of about 5 feet, and therefore does not change the vortex likelihood during different seasons. The typical submergence on the intake structure is 20-25 feet.

Shasta Dam

Shasta Dam has a Temperature Control Device that allows flows to be pulled from many different elevations of the reservoir and has therefore not had any issues with vortex formation. During the recent California drought, cooler water

was being pulled from deeper in the reservoir for the downstream temperature demands.

Summary

One of the goals of this literature review was to determine if there are any generally applicable guidelines for design of hydraulic facilities to ensure against vortex formation. With only a small area of what was considered safe against vortex formation in Figure 3, there is almost no guarantee that any specific facility will not encounter vortex formation. Unless the design is able to follow well established guidelines, a physical model study may be the only way to determine if a vortex will form. This may also be the case for existing projects that are operated below the design WSE due to drought or other circumstances.

While a majority of the research questions for this scoping level study found a large quantity of published reports and scale physical model studies, much of this information is up to 50 years old. Current studies with vortex problems are typically designed to solve a site specific problem and are not research based to develop general guidance to avoid vortices at other facilities. It appears that the trend in current vortex research is for the vortex shape profile and include development of empirical equations to define the core shape, radius, surface depression depth, tip depth and other parameters. Furthermore, the data that is presented on the shape characteristics is caveated that it may not be broadly applicable to other models or prototypes.

There were also a few research questions that were not well addressed in the available literature. Topics that could be considered for future study are changes to turbine efficiency with a vortex being present and changes to the turbine efficiency or head loss with vortex suppression devices. In addition to potential laboratory research projects, of the selected Bureau of Reclamation projects that were interviewed, 3 currently have intermittent vortex occurrence that have not been studied or attempted to mitigate with vortex suppression. One of these is due to obstruction of the trash rack leading to localized high velocities, but the other two are unknown. Of the 7 projects that were interviewed, 3 had intermittent vortices formed, and 1 project would have had a vortex issue if it had not been for a physical model study during the design phase.

Recommendations

Based on the results of this literature review, there are significant gaps in research that may be important to Reclamation as well as the hydropower industry. These include;

1. A study to determine the loss of turbine efficiency when a vortex is present.
2. A study to determine the loss of turbine efficiency when a vortex suppression device is install to reduce the formation of a vortex.
3. A study that will perform a full inventory of Reclamation facilities (both hydropower and non-hydropower) to determine occurrence of vortex formation, and if vortex suppression is advised.

References

Ables, Jackson H., "Vortex Problem at Intake Lower St. Anthony Falls Lock and Dam Mississippi River, Minneapolis, Minnesota," Tech. Report HL-79-9, U. S. Army Engineer, Waterways Experiment Station, May, 1979.

Allen, Skyler D., "The Influence of Debris Cages on Critical Submergence of Vertical Intakes in Reservoirs". Utah State University, All Graduate Theses and Dissertations. Paper 120. 2008.

Anwar, H. 0., "Formation of a Weak Vortex," Journal of Hydraulic Research, Vol. 4, No.1, 1966.

Anwar, H. 0., "Measurement of Non-dimensional Parameters Governing the onset of Free Surface Vortices--Horizontal and Vertically Inverted Intakes," Hydraulic Research Station, Wallingford, England, Report No. IT 216, Aug., 1981.

Anwar, H. 0., Weller, James A., and Amphlett, Michael B., "Similarity of Free-Vortex at Horizontal Intake," Jour. of Hydraulic Research, Vol. 16, No.2, 1978.

Aybar, Akin, "Computational Modelling of Free Surface Flow in Intake Structures using Flow3D Software" Middle East Technical University, Master Thesis. 2012.

Bauer, Deborah I., "Subsurface Vortex Suppression in Water Intakes with Multiple Pump Sumps", Tech. Report No 389, Iowa Institute of Hydraulic Research, October, 1997.

Bottazzi, Emanuele, Floreale, Guiseppe, and Molina, Luigi. "Optimization of a Penstock Intake Based on a Simplified Physical Model". Hidroenergia Conference, Slovenia June, 2008.

Chang, E. (1977). "Review of Literature on the Formation and Modelling of Vortices in
Rectangular Pump Sumps." BHRA.

Denny, D. F. and Young, G. A. J., "The Prevention of Vortices and Swirl at Intakes," British Hydromechanics Research Association, Harlow, Essex, England, Proc. 7th General Meeting IAHR, p. G1-Gl-16, 1957.

Durgin, W. W. and Anderson, F. A., "Davis Pumped Storage Project Hydraulic Model Studies; Intake Model, Upper Storage Reservoir," Alden Research Laboratories, Worcester Polytechnic Institute, Holden, Mass., Oct., 1972.

Durgin, W.W., and Hecker, G.E., "The Modelling of Vortices at Intake Structures." Proc. IAHR-ASME-ASCE Joint Symposium on Design and Operation of Fluid Machinery, Vol. I. and II., CSU, Fort Collins, Colorado, 1978.

Gulliver, J. S., Rindels, A. J., and Lindblom, K. C., "Designing intakes to avoid free-surface vortices." Int. Water Power Dam Constr., 38(9), 24–28, 1986.

Jain, A. K., Ranga Raju, K. G., and Garde, R. J., "Vortex Formation In Vertical Pipe Instakes," Proc., ASCE Hydraulic Division, Vol. 104, No.HY10, Oct., 1978.

Hecker, George E., "Model-Prototype Comparison of Free Surface Vortices," Proc., ASCE Hydraulics Division, Vol. 107, NO. HY10, Oct. 1981.

Hydraulic Laboratory Techniques, United States Department of the Interior, Bureau of Reclamation, Water Resources Technical Publication, 1980.

Knauss, J., "Introduction." IAHR Hydraulic Structures Design Manual, Vol. 1, A.A. Balkema, Rotterdam, Netherlands, 1987.

Larsen J. and Padmanabhan, M. "Intake Modeling". Pump Handbood, McGraw-Hill Book Co. St. Louis, Missouri, 1986.

Nakato, T., and Yoon, B., "A Model Study of the Proposed St. Louis County Water Company's Water Intake near River Mile 37 on the Missouri River." Report No. 187, Iowa Institute of Hydraulic Research, 1992.

Nakayama, Akihiko & Hisasue, Nobuyuki, "Large Eddy Simulation of Vortex Flow in Intake Channel of Hydropower Facility", Journal of Hydraulic Research, Vol 48:4, p415-427, 2010.

Noid, Lovisa "CFD Computations of Hydropower Plant Intake Flow using Unsteady RANS", KTH School of Industrial Engineering and Management, Stockholm, Master Thesis SE-100-44, 2015.

Pennino, Bruce J. and Hecker, G. E., "A Synthesis of 'Model Data for Pumped Storage Intakes," ASME Fluids Conf., Chicago, 1980.

Posey, C.J., and H.C. Hsu. "How the Vortex Effects Orifice Discharge". Engineering-News Record 144(10):30. 1950.

Prosser, M. J., "The Hydraulic Design of Pump Sumps and Intakes," BHRA Fluids Engineering, Cranfield, Bedford, England, July, 1977.

Rahm, "Flow Problems with Respect to Intakes and Tunnels of Swedish Hydroelectric Power Plants," Bulletin No. 36, Hydraulic Institute, Swedish Royal Institute of Technology, Stockholm, 1953.

Reddy, Y. R. and Pickford, J. A., "Vortices at Intakes in Conventional Sumps," Water Power, March, 1972.

Rindels, Alan J. and Gulliver, John S. "An Experimental Study of Critical Submergence to Avoid Free Surface Vortices at Vertical Intakes", St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Report No. 224, 1983.

Suerich-Gulick, Frank, Gaskin, Susan J., Villeneuve, Marc, and Parkinson, Etienne. "Characteristics of Free Surface Vortices at Low Head Hydropower Intakes", Journal of Hydraulic Research, Vol. 140, p291-299, 2014.

Suerich-Gulick, Frank, Gaskin, Susan J., Villeneuve, Marc, and Parkinson, Etienne. "Free Surface Intake Vortices: Scale Effects due to Surface Tension and Viscosity", Journal of Hydraulic Research, 52:4, p513-522, 2014b.

Suerich-Gulick, Frank, Gaskin, Susan J., Villeneuve, Marc, and Parkinson, Etienne. "Free Surface Intake Vortices: Theoretical Model and Measurements", Journal of Hydraulic Research, 52:4, p502-512, 2014c.

Taghvaei, S.M., Roshan, R., Safavi, Kh., and Sarkardeh, H., "Anti-Vortex Structures at Hydropower Dams". International Journal of the Physical Sciences, Vol 7(28) p5069-5077, 2012.

Tullis, J.P., "Modelling in Design of Pumping Pits." Journal of Hydraulics. Div., ASCE,
Vol. 105, No. 9. 1979.

Wang, Yinkui & Jiang, Chunbo. "Investigation of the Surface Vortex in a Spillway Tunnel Intake". Tsinghua Science and Technology ISSN 1007-0214 11/17 Vol 15 No.5, p561-565, 2010.

Yildirim, N. and Jain, S. C., "Surface Tension Effect on Profile of a Free Vortex," Proc., ASCE Hydraulics Division, Vol. 107, No. HY1, Jan. 1981.

Ziegler, E. R., "Hydraulic Model Vortex Study Grand Coulee Third Powerplant," REC-ERC-76-2, Engineering Research Center, Bureau of Reclamation, Denver, CO, Feb., 1976.

Appendix

General Information on Vortices

Title	Selective Description of Lit Review Topic
Rindels, 1983	Issues include vibration, surging, efficiency loss, structural damage, cavitation, flow reduction, safety hazard, and potential loss of life. For pumps, unbalanced loading of impeller, noise and trash drawn into the intake. Note that hydropower has guide vanes upstream of the runner that will reduce swirling flow
Bauer 1997	Swirl defined as any flow condition where a tangential velocity component exists in addition to the axial velocity component.
Jain, 1978	Most important parameters are dimensions submergence (S/D), intake Froude # (either at intake entrance (V/sqrt(gD) or with submergence replace D with S) and bulk circulation.
Bottazzi 2007	Penstocks are the transitions from open channel flow to pressure flow and aim to maintain a uniform velocity distribution and acceleration, and a gradual transition. To reduce energy losses, flow should be gradually guided and abrupt acceleration and deceleration will cause turbulence and flow separation. The main causes of vortex formation are non-symmetrical approach conditions, inadequate submergence, flow separation and eddy formation and approach velocities greater than 0.65 m/s. This is especially relevant for low head hydropower facilities where power optimization is essential and intake losses can be significant compared to the available head.
Durgin and Hecker (1978)	Main causes of vortex formation are non-uniform approach flow to the sump (geometry, intake piers, etc.), shear layers of high velocity gradients (boundary layer separation), and rotational wakes by objects or obstructions in the approach flow to the sump.
Prosser (1997)	Can also increase costs due to delay (lost revenue), maintenance, pump replacement, operational restrictions, modifications to the structure, model tests.
Chang (1977)	Flow processes that generate vortices in a pump sump are asymmetric approach flow (the approach flow has a swirl that can be magnified as it converges on the intake due to conservation of angular momentum), boundary discontinuities (changes in channel cross section, diffusers, baffles, can cause small eddies to shed)

Suerich-Gulick (2014)	Vortices can be generated by flow separation (channel expansion or contraction), shear layer (boundary or velocity), wake from piers at the intake. These can often generate vortices because they are located directly adjacent to the intake opening and span the full depth of the intake which therefore strengthens the vortices along the entire length. Vortices can also occur when one or more turbines is not in full operation producing skewed flow towards the inlet. Other concerns include wind, wave, ice, turbulence or debris that can modify the flow pattern to produce vortices. Many of these can either produce vortices, or help to reduce vortices.
Suerich-Gulick (2014b)	Widely recognized that the dominant parameter influencing vortex intensity is the Froude number.

Are Pump Station Guidelines applicable to hydropower installations?

Title	Selective Description of Lit Review Topic
Prosser (1977)	Recommended pipe intake submergence be a minimum of 1.5*D where D= bellmouth diameter (wider than the pipe diameter). Gives a list of 5 parameters to maintain, and 4 things to avoid. If all above conditions cannot be met, recommends a model study.
Penino and Hecker 1980	Comparison to Alden laboratory with modeled pumped storage intakes found no acceptable design standards. However, also stated that F=Vo/sqrt(gSn) <0.23 and S/D>0.5 is reasonable for design
Rindels 1983	Determined that vertical bellmouth intakes may be more susceptible to intake vortex formation than horizontal intakes
Gordon, 1970	Creates a relationship S=CVD^1/2. C values range from 0.3 for symmetrical to 0.4 for lateral approach conditions. These define upper and lower envelope curves. Pennino stated that the parameters are not dimensionless and cannot be considered a universal relationship
Reddy and Pickford 1972	Applied Gordon data to make it dimensionless S/D=v/sqrt(gD). Found most of the free surface vortices occurred above S/D = Froude. Found that all critical submergence occurs between S/D=F and S/D=1+F.
Rahm, 1953	Found that a leading parameter in vortex formation is flow separation past some obstacle (either vertical or horizontal). Applies to Untra powerplant where flow separation was occurring on a horizontal discontinuity between concrete wall and rock sloped banks. Also found separation on vertical piers of the intake structure (piers were rounded below normal WSE, but square edged above normal WSE elev).
Rindels, 1983	A long narrow forebay will reduce the tendency for vortex formation. (This reduces circulation and assumes a straight alignment to the intake). The amount of acceptable swirl before impacting turbine performance has not been documented. Conservative approach is to not any subsurface swirl. Case studies indicate the importance of a straight and uniform flow upstream of the intake to prevent vortex formation. However, ideal approach conditions are rarely possible, and site design is a compromise. Figure 19 provides a region in which vortex are less likely to occur where F<0.5 and S/D>0.7 (page 51).
Rindels 1983	Jain et al [4] defined critical submergence as the smallest depth at which strong and objectionable vortices will not form. If the intake is set such that S<Sc a vortex will form. Appears to only consider air core vortices as they are the only vortex type detrimental to pumps or turbines. Defines Sc as a function of pipe diameter, bellmouth diameter, discharge, bulk circulation, fluid density, viscosity, surface tension, gravity, location parameter (length, approach walls, height, etc). Surface Tension effects can be neglected if pV2D/sigma >120 (Jain et al [4]) or weber number pV2h/sigma >1.5x10^4. (Anwar 1978b).

Gulliver, Rindels Lindblom 1986 (from Allen)	State that dye core vortices is the limiting vortex type, and may be acceptable for pump intakes. They further state that an intake with a long penstock may reduce a small amount of swirl due to pipe friction.
Gulliver Rindels, Lindblom (1986)	The smallest depth at which a given type of vortex will not form is called the critical submergence for that vortex type.
Larsen and Padmanbhan (1987)	Recommended minimum submergence equal to $S=D(a+bF_d)$ where $a=1\text{-}1.5$ and $b=2\text{-}2.5$. F_d= Froude # in the pipe
Nakato and Yoon (1992)	Iowa Institute of Hydraulic Research set of design criteria. 1. No detectable boundary attached vortices extending to the pump bell. 2. No free surface vortices stronger than type 2. 3. No velocities measured at the pump throat that vary by more than 10% from the average of all local velocities measured in the cross section. 4.Vortimeter-tip velocity angles (swirl angles) no greater than 5 degrees, and 5. No detectable, large scale, persistent "unsteadiness" or "waviness" in the pump bell approach flows; no indication of persistent large scale turbulence; no flow anomalies judged objectionable by investigators experienced with pump intake model tests.
Bauer 1997	Performed a laboratory test of a multiple pump/single sump setup since previous research appears to have been performed on single pump intakes (Larsen and Padmanabhan list of specific conditions where a model study is recommended). Many of the causes of the vorticity match between hydropower and pumped intakes. Quotes Ingersoll-Rand acceptable standards for pump operation as a surface dimple no more than 0.3 ft deep and the surface swirl should be less than 5 RPM. Intermittent rotation or direction changes need to be further studied. Recite studies by Padmanabhan and Hecker that no significant scale effects on the subsurface vortices exist when approach flow Reynolds number is greater than 3×10^4), but state that additional research on the influence of scale effects on subsurface vortices is needed to improve the hydraulic modeling of pump sumps with subsurface vortices.
Allen (2008)	States that vertical intake have a greater tendency for development of free surface vortices than other intake orientation and that approach flow path has a significant impact of vortex development.
Suerich-Gulick (2014c)	The minimum acceptable submergence has been estimated since early laboratory studies by Pennino and Hecker (1979), Daggett and Keulegan (1974), Jain (1978) and Anwar (1983) as well as prototype vortex surveys by Gordon (1970), Pennino and Hecker (1979), Gulliver (1986). However the predictive accuracy of these correlations is limited by the fact that vortex characteristics such as radius, bulk circulation, tip depth are very sensitive to the geometry of the intake structure and the approach conditions.

How is turbine efficiency impacted with Vortex formation?

Title	Selective Description of Lit Review Topic
Rindels 1983	Note that hydropower has guide vanes upstream of the runner that will reduce swirling flow. The amount of acceptable swirl before impacting turbine performance has not been documented. Conservative approach is to not allow any subsurface swirl.
Bauer 1997	Many pump intakes for cooling water experience swirling flow which reduce the effectiveness of the intake and lead to an increase in operating costs of the pump plant.
Posey and Hsu (1950)	Not directly related to loss of hydropower efficiency, but performed a study on an intake Coefficient of discharge and found that vortices could cause nearly an 80% reduction in the coefficient of discharge for the orifice.
Anwar, 1966	Found that transient vortices (growth and decay) do not seriously affect efficiency of the intake and hydraulic machinery or cause significant vibration. However, the converse is that stable vortices do result in energy loss, reduction in discharge and potential for pipe vibration / damage to equipment.
Tullis, 1979	It also alters the angle of attack of the impeller blades thereby potentially reducing pump efficiency
Gulliver, Rindels Lindblom, 1986	State that dye core vortices is the limiting vortex type, and may be acceptable for pump intakes. They further state that an intake with a long penstock may reduce a small amount of swirl due to pipe friction.

What is the minimum submergence to avoid vortex formation?

Title	Selective Description of Lit Review Topic
Jain, 1978	Critical submergence is the typical value used to determine the minimum submergence of a given intake structure. During the design phase, many researchers have tried to solve for a value of Sc that will not result in vortex problems with the prototype.
Yildirim and Kocabas (1995)	Developed a polynomial equation for still water reservoir conditions with other assumptions for Sc.
Yildirim and Kocabas (1998)	Polynomial equation (far right). Yildirim and Kocabas (1995 and 1998), present two polynomial equations that can be used to calculate the critical submergence assuming a uniform approach flow velocity (1995) and for still water reservoir conditions where approach flow velocity is assumed to be negligible (1998).
Jain, Raju and Garde (1978)	Also uses a prediction equation for critical submergence, but includes a term for bulk circulation which relies upon knowing the circulation values in the prototype (very difficult in the design phase). Circulation is difficult to measure, and extremely difficult to predict during design of an intake
Knauss (1987)	$S = (D*(1+2.3*Fr))$ = is a conservative value used for design purposes - Forms the basis for the ANSI recommended equation.
Wang (2010)	Generally the higher the dimensionless submergence (H/D), the less likely a vortex is to form. However, in this study of the Xiluodu hydropower station, cortex formation started at 41 m submergence (H/D=2.73), and reached a full air core at S=47m (H/D = 3.13).
Gordon (1970)	For symmetrical approach conditions, critical dimensionless submergence $(S/D)c = 1.7*Fr$. For asymmetrical approach, $(S/D)c = 2.3*Fr$. Found critical dimensionless submergence was linearly related to intake Froude number.

Are Vortices dependent on individual penstock flow or total flow?

Title	Selective Description of Lit Review Topic
Suerich-Gulick (2014)	Vortices can be generated by flow separation (channel expansion or contraction), shear layer (boundary or velocity), wake from piers at the intake. These can often generate vortices because they are located directly adjacent to the intake opening and span the full depth of the intake which therefore strengthens the vortices along the entire length. Vortices can also occur when one or more turbines is not in full operation producing skewed flow towards the inlet. Other concerns include wind, wave, ice, turbulence or debris that can modify the flow pattern to produce vortices. Many of these can either produce vortices, or help to reduce vortices.
Bauer 1997	Performed a laboratory test of a multiple pump/single sump setup since previous research appears to have been performed on single pump intakes (Larsen and Padmanabhan list of specific conditions where a model study is recommended). Many of the causes of the vorticity match between hydropower and pumped intakes. Quotes Ingersoll-Rand acceptable standards for pump operation as a surface dimple no more than 0.3 ft deep and the surface swirl should be less than 5 RPM. Intermittent rotation or direction changes need to be further studied. Recite studies by Padmanabhan and Hecker that no significant scale effects on the subsurface vortices exist when approach flow Reynolds number is greater than 3×10^4), but state that additional research on the influence of scale effects on subsurface vortices is needed to improve the hydraulic modeling of pump sumps with subsurface vortices.

Are vortex suppressors capable to arrest development without impacting generation efficiency?

Title	Selective Description of Lit Review Topic
Rindels 1983	Physically impossible or cost prohibitive to modify an existing design that is susceptible to vortex. Therefore 3 possible solutions; disrupt angular momentum, force the vortex to form in a zone where formation is difficult, increase the area of the intake to reduce velocities. None of the three methods reduce upstream angular momentum, and therefore an amount of swirl may still remain.
Denny and Young, 1957	List several devices. Most popular and inexpensive is floating raft.
Ziegler, 1976	Found water surface is not the best location for a floating raft. Circulating water remained below the raft. Submerging the raft removed swirling water. Optimum distance is the depth where raft is able to provide resistance both above and below the raft. Also found that testing various trashrack thicknesses increased vortex suppression
Ables, 1976	Tested elongated scaled bar trashracks as vortex suppressor. NO RESULT PRESENTED BY PENNINO
Song, 1974	Developed a vertical wedge shape device that dissipated angular momentum. Worked well by dissipating circulation near the surface. Also stated that vortex formation is diminished if the plan of the approach canal is less like a circle.
Blaisdell 1958	Found good results with circular cover over a vertical intake that increased cross sectional area and therefore reduced velocities.
Humphreys, 1970	Stated the cover from Blaisdell 1958 results in head loss and is therefore not often used in hydroelectric.
Bauer 1997	Performed a physical model study on a 4 pump intake structure with vortex problems. Suppression of subsurface vortices is typically achieved by altering wall and floor clearance, vertical flow splitters, horizontal floor splitter, a floor cone beneath the bell, installing fillets in the corners of the sump floor / fill regions of flow separation and/or stagnation, and turning vanes placed on the floor upstream of the pump column to improve flow alignment into the pump bell. Suppression of surface vortices can be achieved by increasing the minimum submergence or using vortex suppressors. Vortex suppressors can be horizontal grating placed 4-6" below the water level at which strong free surface vortices appear, a grating cage placed just below the minimum water level, floating rafts placed in the vicinity of the pump column, and a curtain wall or surface beam protruding into the water and across the approach channel. Baffle bars, a curtain wall to reduce surface swirl, guide vanes can also be used.
Gulliver, Rindels and Lindblom (1986)	State that successful vortex suppression can be achieved by submerged rafts including grating near the intake (debris racks), reduction of intake velocities with head loss devices, improvement of approach flow.

Allen (2008)	Debris cages typically used to prevent large objects from being introduced into the pipe system where they can cause damage or obstruction. However, it has been found that physical model of SNWA intake at lake Mead was much more likely to have vortices present without debris cages. Constructed various trash rack configuration into a physical model and tested the occurrence of air core vortices. Found that on all tests where the top surface of the debris cage was below the WSE, no air core vortex was formed. There were some tests that a surface dimple was observed, as well as tests where the WSE was below the top surface of the debris cage (that did exhibit an air core vortex). A follow-on test that compared different top bar configurations of the debris cage resulted in the following recommendations - bar spacing should be at the maximum spacing possible for the desired debris blockage up to 15% of the intake diameter. If feasible, bars oriented in both directions are favourable for vortex suppression. A submerged raft (without side walls / cage) was found to be the best configuration for vortex suppression.
Taghvaei (2012)	Studied 13 different configurations of vortex suppression devices on a physical model of the Siahbisheh pumped storage power plant intake located in Iran. The physical model included the prototype trash rack, and tested thin vertical walls, thin sloped walls, wall extensions with thin vertical walls, and horizontal wall above the intakes. A range of S/D values from 2.1 to 3.5 were used. It was found that the horizontal wall that extends out from the face of the dam that increases the direct flow path from the surface to the intake was the most effective at reducing vortex formation.
Aybar (2012)	Typical methods are increasing submergence, improving approach flow conditions, and anti-vortex devices (where increasing submergence is the most practiced). Used a hemispherical screen, an "X" shape of vertical walls (4), and 8 walls with cylindrical screen on a vertical intake. Wall height was full depth (H=S), and was effective for both 4 and 8 wall at preventing circulation.

How dependent is vortex formation on site specific geometry and operating conditions?

Title	Selective Description of Lit Review Topic
Prosser, 1977	Recommends a hydraulic model study if there are any deviations from this stated design guidelines.
Anwar, 1978	Gives guidance for critical submergence as a function of bulk circulation- however this is often not known prior to the design.
Pennino and Hecker, 1980	Very little design guidance, therefore the only way a designer can be certain that a given design will be free from vortices is to use a scale model. The circulation is dependent upon many factors in the approach conditions which are entirely site specific. Any general guidelines are problematic because the approach flow in each installation are unique. This approach flow appears to be as important or more important than dimensionless submergence and Froude numbers. During design, submergence, diameter, and velocity can be calculated, but approach circulation is not possible (currently, CFD models can be used). From figure 19 found that "there is virtually no submergence at which an intake designer can be certain of vortex-free operation"
Rindels 1983	Very little information from which initial designs of a structure can be based off of before requiring a hydraulic model study.
Bottazzi 2007	At low head hydroelectric plants intake losses can be significant compared to the available head. At high head plants, the cost of a smooth hydraulic transition profile may not always be justified, but poor intake geometries can still produce vortex problems that require study. This physical model study was used to solve a swirl and head loss with a drop inlet head box that connected to a penstock pipe. A bellmouth inlet was found to smooth the transition and lower the head loss in the physical model and was constructed in the prototype and has been successful.
Bauer (1997)	Performed a physical model on a 4 pump sump configuration to reduce vortex formation at a pump intake. It is difficult to detect submerged vortices unless a laboratory studies is performed that can investigate using dye and/or air injection. A model study should be performed to locate submerged or free surface vortices, to suppress their formation and to avoid subsequent problems. Hydraulic modeling of multiple sumps is essential for solving flow problems because computation fluid dynamics cannot yet effectively simulate the flow characteristic in a multiple pump sump.
Larsen and Padmanabhan 1987	Recommend that a model study of an intake structure be carried out before the prototype is constructed in order to minimize costs of operating

Gulliver, Rindels and Lindblom 1986	Recommend that for installations where vortex development is a concern that a model study be performed to more accurately assess vortex development and to determine possible solutions.
Suerich-Gulick (2014)	The safe vs. Dangerous plot created by Gulliver 1986 can give a rough idea of vortex risk, but it cannot fully account for particular conditions at a given intake such as flow asymmetry or geometry that can significantly influence vortex formation. More rigorous evaluation of vortex risk is achieved by construction of a physical model of the proposed intake and visually inspecting for vortices. Physical models allow investigation of the interaction between flow and intake geometry, and are generally easily modified to evaluate and compare alternative designs. Research is presented that gives equations for certain parameters (characteristic radius, bulk circulation, free surface depression depth (tip depth), and shape of the vortex), but are based on coefficients that are unique to the physical model studied and may change for other physical models or prototypes.
Suerich-Gulick (2014b)	Since water is used in physical models in Froude scale similitude, it is impossible to match the Weber and Reynolds numbers with laboratory tests that match prototype Froude number that can cause scale effects on surface tension and viscosity.
Rindels 1983	Provided a synthesis of results from several physical model studies to assess the validity of scaling vortex processes to physical models. The dominant forces are gravity and inertia, which scale with Froude Similitude, however surface tension and viscous forces do not scale simultaneously and result in scale effects. He summarizes that is the Reynolds number of the inlet flow is greater than 5×10^4, then Froude scaled flows will minimize effects of viscous scale effects. Surface tension effects will generally only be applicable when an air core vortex is observed in a physical model, but it is stated that scale effects from Froude scale modeling will allow a more rapid transition from a surface dimple to an air core vortex to form in the prototype. Also found that in many cases, observed vortex intensity comparisons did not match between physical models and prototypes and were mostly a result of insufficient attention to approach geometry, topography and boundary roughness in the model, viscous scale effects on flow devices and density stratification in the prototype.
Jain, Raju, and Garde (1978)	Performed research on water compared to a water & cepol (carboxyl-methyl cellulose) to ascertain the differences to surface tension on materials with matching kinematic viscosity but different surface tensions. They found that surface tension does not affect the development of an air core vortex. Similar tests to determine differences with matching surface tension and different kinematic viscosities using iso-amyl alcohol resulted in differences to the air core vortex formation in a specific range of Reynolds numbers.

Ables (1976)	Lead researcher at Waterways Experiment Station (WES) for USACE. Performed research on the Lower St. Anthony Falls Lock and Dam on the Mississippi River. Discussed an earlier model study performed at St Anthony falls hydraulics laboratory that found no vortex problems - however the approach conditions were not adequately modeled. Found that to remove the vortex at design flows would require changing the intake to horizontal (from vertical), increasing submergence from 13.7 ft to 26.2 ft, adding a vortex suppressor, and extending the bullnose pier 28.75 feet further upstream and changing the pier shape to elliptical rather than circular. the cost of redesigning / construction the structure was too great and deemed not cost effective. Therefore the lock was not operated at design flow for the remainder of its service (locks were decommissioned in 2015).