Horizontal Trash Rack
a New Intake Concept for Efficient Backflushing

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Abstract

At many hydropower intakes in rivers there are extensive problems with debris fouling the trash rack. An alternative to manual or mechanical cleaning is the hydraulic concept of backflushing, in which water removes debris from the trash rack and flushes it back to the river out of a flushing conduit. A new intake concept with the intake gate located upstream of a horizontal trash rack, for the efficient utilization of backflushing, is tested in a physical model. The experimental results approve the opportunity for energy production during the automatic cleaning. The cleaning efficiency is strongly dependent on the flushing capacity. The costs related to the flushing conduit and a slightly increased head loss can be less important for many cases than the advantages from timely and efficient debris removal, reduced costs for human labor, and improved safety. Additional possibilities for safe fish-passage through the bottom outlet call for further studies.

Keywords: hydraulic structures, trash rack, backflushing, intakes, hydropower

Introduction

A large number of new small hydropower plants are constructed in rivers every year. The intake structure is designed to harvest water from the river over a desired range of headwater levels, and convey clean water to the turbines. The trash rack on intake structures in rivers protects the turbines from damage from branches, stones, ice and man-made waste, but the trash rack may be covered with leaves, moss, grass and trash, thereby causing head loss. There are problems with the trash control facilities at some new and existing hydropower intakes, and according to Wahl (1992), problems with the trash control facilities to hydropower plants cost millions of dollars every year in extra labor and equipment repair costs. A study by EPRI (2007) has shown that the timely and efficient cleaning of some specific intakes can increase the annual electricity production by up to 12 %. There exists a large number of different intake types and different types of mechanical trash racks cleaners (Radhuber 2006; U.S 2011). Nevertheless, it is still a common practice at small hydro power plants to manually clean the trash racks, which is often chosen because of the relatively high investment cost for a mechanical cleaner or because extensive cleaning problems are underestimated. Manual cleaning is time consuming, and involves a safety risk for the operators, in addition to the fact that a shutdown of the power plant is often required in order to perform a successful cleaning. Reliable, fish-friendly and cost-efficient solutions are requested for new hydropower intakes and for the upgrading of intakes with severe problems at the intake. An efficient, but relatively rarely used method for the removal of debris is the hydraulic-based concept of backflushing; by opening a flushing gate, a water flow will remove the clogged debris from the trash rack and flush it back to the river, downstream from the weir. The great advantage of this is that no manual work is needed, and no extra movable components prone to wear and tear, apart from the flushing gate, are required. The disadvantage is the loss of water used for flushing and the extra investment cost for the flushing conduit. For a long time, the backflushing effect has been obtained at hydropower intakes by intentionally creating a water hammer with a rapid shut down of the power plant, whereby a pressure pulsation removes clogged debris from the trash rack (Radhuber 2008). More recent intake structures have successfully been designed with the intake gate and a flushing conduit upstream of the trash rack, in which a reverse water flow releases debris from the rack and conduct it out through the flushing gate and back to the river downstream from the weir (Nø vik et al. 2011). Further innovation on intakes with use of the backflushing concept has led to the so-called H-rack intake, which was specially designed for power plants in rivers where the frequent cleaning of trash racks is needed. The H-rack intake has the intake gate located upstream of a horizontal trash rack in order to provide an efficient removal of debris with backflushing. The main objective of this paper is to assess the hydraulics in the new intake concept for hydro power plants during normal operation and during backflushing. Design recommendations for an H-rack intake are studied, however an optimization of the hydraulic design is not included in this research. The intake design has been tested in a hydraulic physical scale model at the hydraulics laboratory at NTNU, Trondheim, Norway.

The H-rack Intake Structure

The H-rack intake is designed to be cost-efficient, both in terms of construction costs and operation and maintenance in rivers where the frequent cleaning of trash racks is needed. A description of the new concept and the defined success criteria are given below.

The new concept

During a normal intake operation, the water flows from the intake pond through the intake gate, up through the horizontal trash rack, over the weir to the inner intake chamber and to the power plant (see Figure 1a). Debris will accumulate underneath the rack, so a flushing conduit isinstalled under the rack and ends up in the river downstream of the weir. The flushing facility is operated by a flushing gate or valve, while the inlet to the flushing conduit is situated just below the horizontal trash rack. A cleaning sequence starts with reducing the discharge to the turbines and closing the intake gate. When the flushing valve is then opened, a brief water flow across the screen in the direction opposite to the normal production flow will remove the debris underneath the rack and convey it out of the flushing gate (see Figure 1b). The main advantage of the new H-rack intake concept is the efficient and reliable way of cleaning the trash rack whereas the main disadvantage is the extra head loss through the intake structure, and the extra cost of the flushing facilities. Energy production during backflushing allows for a quick start-up of full production after cleaning. With the new H-rack concept, the rack is more submerged and is hence better protected against ice and larger floating debris on the water surface, but a coarse trash rack should protect the flushing conduit from large objects. There should also be provided access to inspections under the rack and in the flushing canal. Any bed load passing through the intake gate will be deposited below the trash rack and can be flushed out with the debris. Another potential advantage is for the downstream migration of eels that prefer to travel along the river bed and have a better chance to pass hydropower intakes through bottom outlets (Gosset et al. 2005; Larinier 2008; Russon and Kemp 2011). For the H-rack intake, the flushing outlet could serve as a bottom outlet for eels, and will be studied in further research.

Success Criteria

In general, the maximum velocity through the trash rack, $\overline{v}_{r,max}$, should be low in order to minimize the head losses, reducing the amount of debris being drawn to the trash rack, and limiting the formation of vortices at the intake. As a rule of thumb, the intake structure for a small hydropower plant should be designed for $\overline{v}_{r,max}$ in the range $0.3 - 1.5\,\mathrm{m/s}$ (ASCE 1995). According to common practice in Norway (Jenssen et al. 2006) $\overline{v}_{r,max} \leq 0.5\,\mathrm{m/s}$ is used in this study, and defined in Eq. 1:

$$\overline{v}_{r,max} = \frac{Q_{max}}{H_r B_r} = \frac{q_{max}}{H_r} < 0.5\,\mathrm{m/s} \qquad (1)$$

where Q_{max} is the design discharge, and H_r and B_r are the height and width of the trash rack, respectively. H_r is used to scale all components in this study according to the unique relation to any given unit discharge, $q_{max} = \frac{Q_{max}}{B_r}$. There is not much literature on debris to trash rack adhesion in field, though a study by Nøvik, et al. (2014) show that debris is quite easily removed from a trash rack. The same study showed that the required pressure difference, or head loss build-up, through a trash rack at the initiation of the flushing, $\Delta h_{r,f}$, and the average flushing velocity over the rack, $\overline{v}_{r,f}$, for efficient cleaning is rather modest, and that an evenly distributed flow over the trash rack at the initiation of the back flushing is important in order to clean the entire rack. The cleaning efficiency in the present study is uniquely assessed according to the hydraulic performance, whereas the success criteria for a well performing H-rack intake is defined based on the results from the study by Nøvik, et al. (2014) suggesting a minimum average flushing velocity over the rack, $\overline{v}_{r,f}/\overline{v}_{r,max} > 0.4$ and a quick head loss build-up at the initiation of the flushing. In addition, the design should provide for a reliable and safe operation, energy production during flushing and a low head loss during normal operation. Optimization of the hydraulic design is not included in this study as the focus is on the concept and the governing main components.

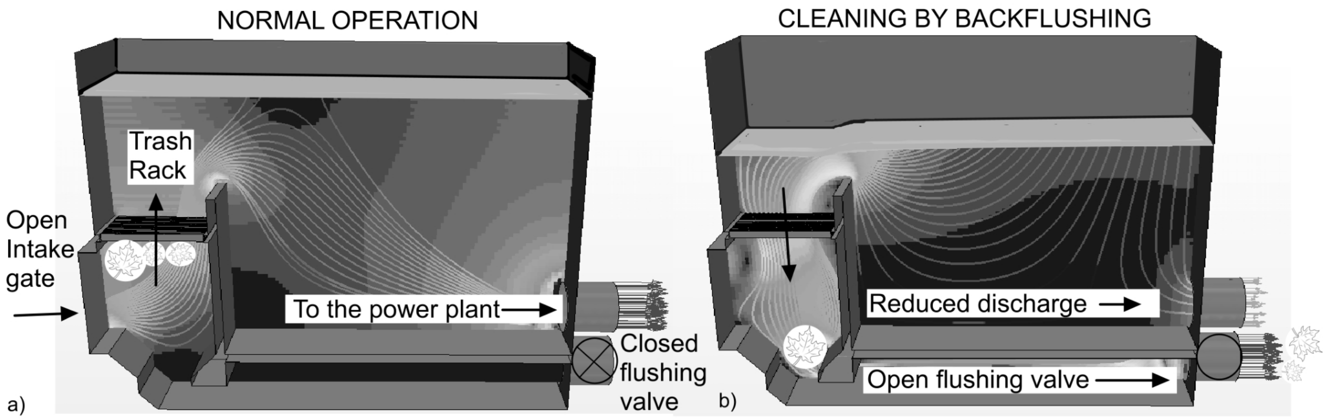

Figure 1: The concept of the H-rack intake structure: a) Normal operation with open intake gate, b) cleaning of the trash rack with backflushing. The flushing valve is open, whereas the production discharge is reduced

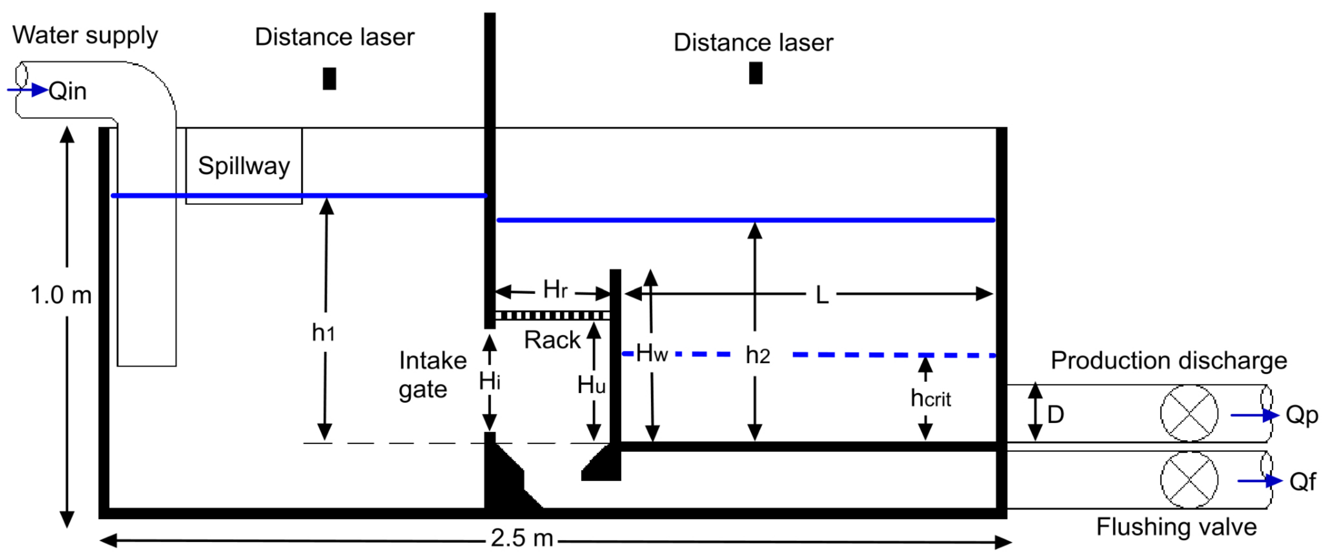

Figure 2: Experimental set-up and definition of test parameters (side-looking view).

Experimental Set-up

The goal of this study is to assess the H-rack intake performance during both normal operation and backflushing, with the aim of at finding recommended operational strategy and range for the principal main design parameters. The experiments with the H-rack intake concept were conducted in a $2.5\,\mathrm{m}$ long, $0.35\,\mathrm{m}$ wide and $1.0\,\mathrm{m}$ deep box, scaled after Froudes scaling law with scale length of $L_r = 1 : 5$. Any smaller scale was not justifiable according to Reynolds scaling law for turbulent flow around the trash rack. The important operational and design parameters tested in this study are defined in Figure 2. There are two outlets from the H-rack model. The upper one represents the penstock with diameter D for the production discharge, Q_p. On the lower level, there is a conduit for the flushing discharge, Q_f. The discharges were measured with two electromagnetic flow meters, Sitrans F M Mag 5100 W (*Data sheet Siemens Sitrans F M Mag 5100 W*). The water supply, Q_{in}, is located in the upstream end of the model and a free overflow spillway provided for a constant water level, $h_1 = 0.8\,\mathrm{m}$, in the tank, which represents a water level in an intake pond or intake reservoir of $4.0\,\mathrm{m}$. The upstream and downstream water depths, h_1 and h_2, were measured with ultra-sonic sensors, mic+130/IU/TC/M30 (*Data sheet, mic+130/IU/TC/M30*), with range of $0.2-1.3\,\mathrm{m}$. The critical water level, h_{crit}, defines the lowest water level without the risk of air entrainment to the power plant. The intake structure consists of a vertical intake gate with an opening H_i for control of the inflow to the intake chamber, a horizontal trash rack with length H_r, at a vertical location H_u, a weir with height H_w and an inner intake chamber with length, L. The rack height was $H_r = 0.28\,\mathrm{m}$, which corresponds to $1.4\,\mathrm{m}$ in prototype, and the width of the trash rack is $0.35\,\mathrm{m}$. According to Eq.1, the design discharge, Q_{max}, for the physical scale model, is

$$Q_{max} = H_r \times B_r \times 0.5\,\mathrm{m/s} \times \sqrt{L_r}$$
$$= 0.28\,\mathrm{m} \times 0.35\,\mathrm{m/s} \times 0.22\,\mathrm{m/s} = 0.022\,\mathrm{m^3/s} \quad (2)$$

The corresponding discharge in a prototype is $Q_{max} = 1.2\,\mathrm{m^3/s}$. All the components in the experimental facilities are designed according to relevant dimensions for a small hydro power intake with the above-mentioned Q_{max}.

Hydraulic Performance and Dependencies during Normal Operation

The head loss through the intake is the main performance criteria for the normal operation of the H-rack intake in this study, whereas the passage of fish will be studied in further research. The head loss is primarily dependent on the production discharge, Q_p/Q_{max}, and the design of the

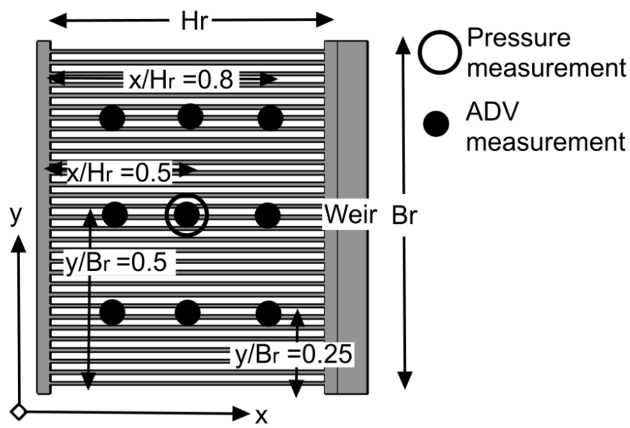

Figure 3: Locations of measurements over the trash rack, plan view.

structure. The relative head loss, namely the absolute head losscompared to the total head of the power plant, defines the acceptable level of head loss through the intake. A high head power plant can accept a much higher absolute head loss than a low head power plant. An optimized hydraulic design will reduce the total head loss, but was in this study considered to be of minor importance compared to the overall layout with the horizontal rack and the weir. Moreover, the head losses caused by the chamber shape, the entrance, the sharp edges, and the trash rack are similar for all model set-ups. In addition, a trash rack design is always site-specific, and the head loss caused by debris fouling can be much larger than the head loss through a clean rack. Hence, the trash rack was built in the model as an exemplification for the completeness of the study, and only one trash rack design was used. The bars were rectangular shaped for easy manufacturing, and with a bar thickness $b_r = 3\,\mathrm{mm}$, bar depth $p_r = 20\,\mathrm{mm}$ and bar spacing $s_r = 8\,\mathrm{mm}$. The head loss was estimated based on a 2^{nd} degree polynomial fitting of a 30 points moving average of the water level difference, $h_1 - h_2$, logged at a frequency of 100 Hz. For assessing the head loss caused by the overall layout compared to a standard intake design, measurements with a vertical rack was conducted. The model was then modified by replacing the weir with the rack installed in a vertical position. Moreover, the wall above the vertical rack was extended above the water surface. The head loss was measured for the range $\overline{v}_r/\overline{v}_{r,max} \in [0, 1]$. The weir height strongly affects the flow path, and the impact on the head loss was tested for various weir heights $H_w/H_r = [1.3, 1.6]$.

Hydraulic Performance and Dependencies during Backflushing

During backflushing, the performance is assessed according to three criteria for an efficient cleaning: the velocity distribution over the trash rack, the average flushing velocity over the rack $\overline{v}_{r,f}/\overline{v}_{r,max} > 0.4$, and a quick head loss development over the trash rack at the initiation of the backflushing (Nvik, Rettedal et al. 2014). Two S-10 type pressure transmitters from WIKA (Wika 2013) were installed $0.05\,\mathrm{m}$ over and under the trash rack to monitor the pressure development during flushing (see Figure 3). The range was from $0-0.4\,\mathrm{bar}$. The head loss build-up caused by clogged debris cannot be estimated due to the random nature of debris, and was hence not measured in this experiment. Nevertheless, the potential head loss build-up during flushing of a clogged rack, $\Delta h_{r,f}(t)$ (in meters) was estimated from measurements of the pressure development under the rack $h_{r,u}(t)$:

$$\Delta h_{r,f}(t) = h_{r,a} - h_{r,u}(t) \tag{3}$$

where $h_{r,a}$ is the pressure (in meters) above the rack before the opening of the flushing valve. The signal triggered when the flushing valve was opened, the discharge data, the water depth, and the pressure was recorded at a frequency of $100\,\mathrm{Hz}$, using a U2355A USB Data Acquisition Module (*Data Sheet, Agilent U2300A Series USB Modular Multifunciton Data Acquisition Devices*). The velocity distribution over the trash rack during back flushing was assessed by measurements of the local velocity in three directions with a Nortek Vectrion Lab Acoustic Doppler Velocimeters (ADV) (*Datasheet Vectrion Lab*), with a sampling rate of $200\,\mathrm{Hz}$. Nine locations $0.05\,\mathrm{m}$ above the rack were measured, see the plan view Figure 3. One location was measured at a time, and tests showed that the measurements had a high degree of repeatability for all flushing sequences. The spatial average of the nine measured points, $\overline{v}_{r,f}$, was calculated. The three above-mentioned criteria are affected by both the operational strategy and design of the structure. The most important parameters concerning the operation strategy are the intake gate opening H_i/H_r, tested in the range $[0-0.8]$, where 0 means a closed intake gate, and the discharge to the power plant during the cleaning, which remained constant $Q_p/Q_{max} = 0.2$ for all the experiments. The intake design parameter of primary importance for the flushing efficiency is the capacity of the backflushing system was tested up to $Q_f/Q_{max} = 1.6$. The weir height, H_w/H_r, was considered to have an influence on the velocity distribution during the backflushing and was tested for $H_i/H_r = [0.8, 1.6, 2.2]$. The length of the inner chamber L/H_r defines the volume of water available for flushing, and was tested for $L/H_r = [1.9, 3.4]$. The vertical location H_u/H_r was expected to have an influence on the relative flushing velocity for tests with an open intake gate. H_u has to be larger than the intake gate height, which again is recommended to be equal or larger than H_r, in order to avoid a decrease in the velocity after the intake gate. But in order to study the effect during flushing, $H_u/H_r = [0.8, 1.3]$ was tested. A total of 24 experimental set-ups were tested during backflushing.

Backflushing Duration

Studies have shown that most of the debris is removed from the trash rack at the initiation of the backflushing. The required flushing duration, t_f, is therefore given by the time needed to convey the debris out of the intake. The maximum flushing time $t_{f,max}$, before a critical water level, h_{crit}, is reached and air entrainment will occur is restricted by the available water volume in the intake chamber, and the water discharge to the power plant, Q_p, during backflushing. h_{crit} is calculated according to formulas presented by Knauss (1987) on critical intake submergence, $h_{crit} = (0.75 + 2Fr)D$. When $Q_p = 0.2Q_{max}$ during the flushing and $D/H_r = 0.55$, the critical water level is $h_{crit} \approx 1.4D$. No water in the inner intake chamber below the weir level can be used for flushing, and this water volume can be regarded as a reservoir for energy production during the cleaning process.$t_{f,max}$ is hence given by:

$$t_{f,max} = \frac{H_w - h_{crit}}{Q_p} L B_r \tag{4}$$

An open or partially open intake gate during the flushing will increase the accessible water volume for flushing, but also reduce the efficiency of the backflushing. The flushing volume over the rack V_r relative to the flushing volume, $V_f = \int_{t_f} Q_f dt$, describes the efficiency of the flushing system. V_r is calculated as the volume the power plant, $V_p = \int_{t_f} Q_p dt$, subtracted from the change of the volume in the inner intake chamber.

Results

Normal operation

The head losses through the H-rack intake are higher than for a standard vertical intake screen, because of the weir and several changes in the water flow direction (see Figure 4). The extra head loss is in the range of $2-8$ times the head loss for a vertical intake. As expected, a high weir significantly increases the head loss through the system although it was unexpected that the head loss in a shorter chamber is smaller than in a longer chamber. The model is scaled after the Froudes number, whereas the head loss over the trash

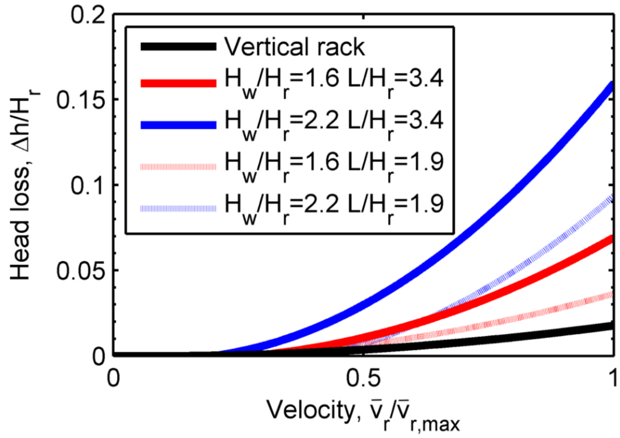

Figure 4: Head loss through the H-rack intake structure during energy production compared to the same intake structure with vertical rack. The intake gate opening $H_i/H_r = 0.8$, and vertical location of the rack $H_u/H_r = 1.3$ are constant, whereas various H_w and L are tested.

rack is related to the drag force through the rack, which again is related to the Reynolds number around each bar:

$$Re = \frac{qb_r}{H_r \nu_w} \quad (5)$$

where ν_w is the kinematic viscosity for water. According to Couret and Larinier (2008) common values for Re in real hydropower plants are in the range of $4000 - 13000$. During the experiments in this study, the Reynolds number was lower, $Re \in [400, 850]$. Nevertheless, the head losses through the clean trash rack, and the experiments were therefore considered to be with-in a valid range.

Backflushing Efficiency

The back flushing efficiency has been assessed according to operational and design parameters. The flushing velocities obtained over the entire H-rack are relatively high and the hydropower plant can maintain its energy production during backflushing.

Operational Parameters

The intake gate opening has an effect on the velocity distribution, and on the average relative flushing velocities. The side looking view in Figure 5a gives a visual indication on the spatial velocity distribution over the trash rack during backflushing with different intake gate openings, whereas Figure 5b shows the measured velocity development for selected model set-ups at all the locations showed in Figure 3. Positive relative velocity is defined according to the flow

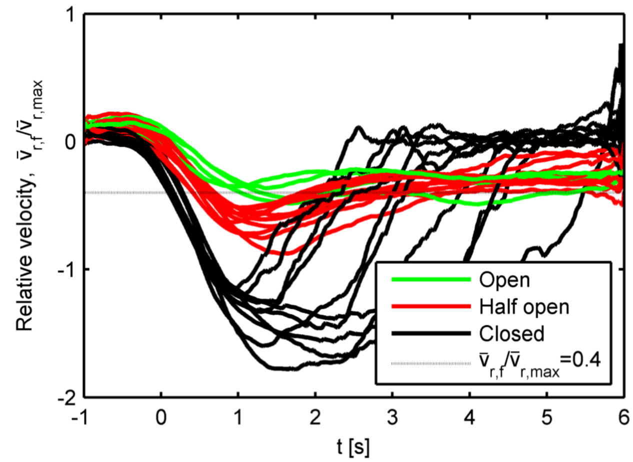

Figure 6: Comparison of the average relative flushing velocities for all 24 set-ups, where the effect of the intake gate opening is the most pronounced.

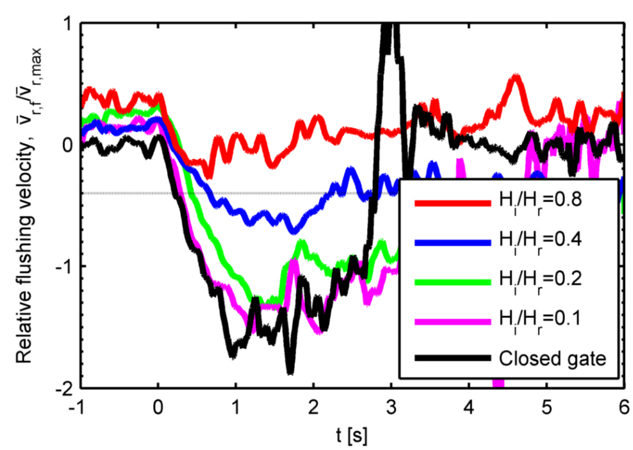

Figure 7: The effect of the intake gate opening, H_i, on the relative flushing velocity for $Q_f/Q_{max} = 1.6$

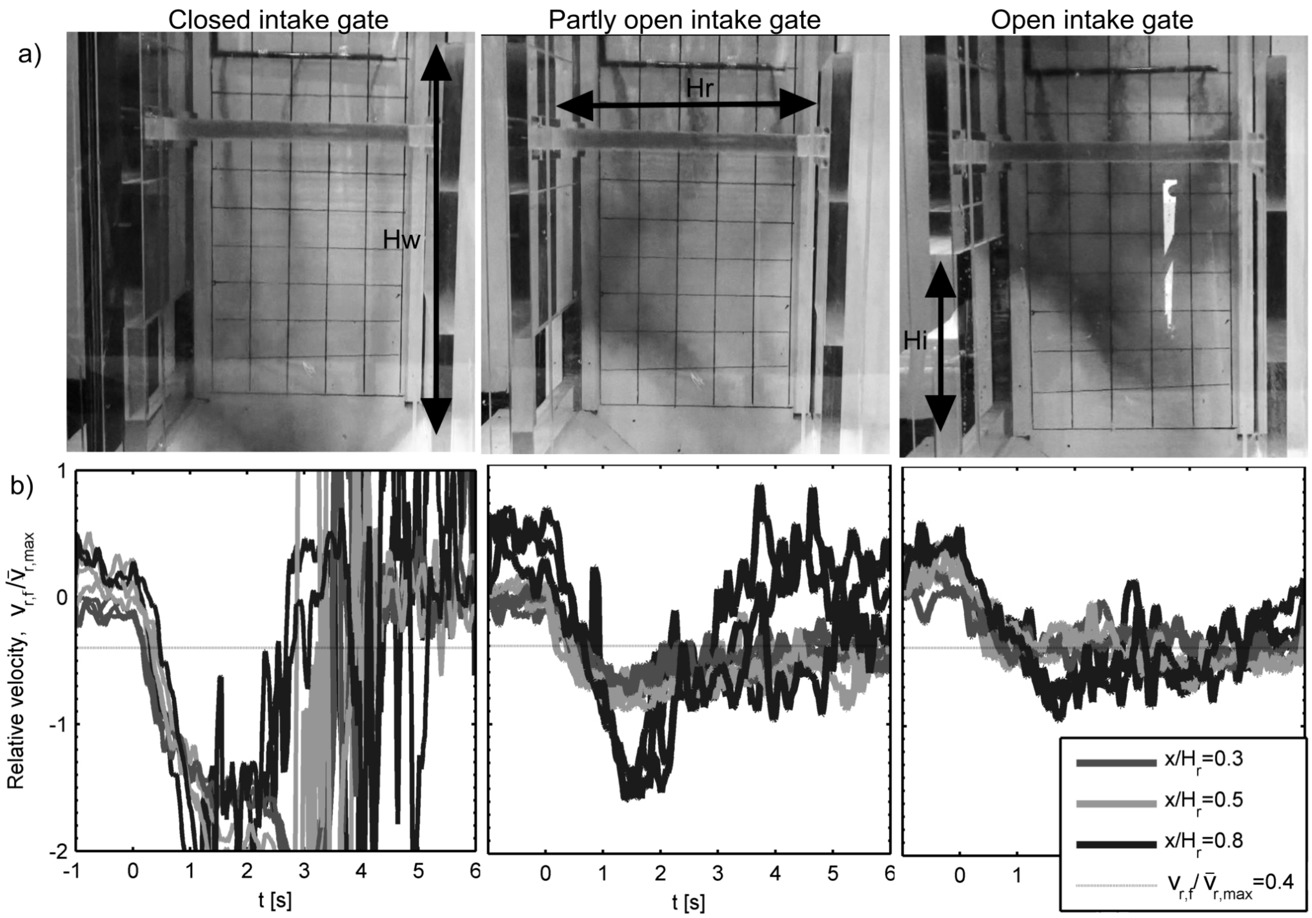

Figure 5: The effect of different intake gate openings on the velocity distribution during backflushing: a) Side-looking view of the spatial velocity distribution, b) time series of the relative flushing velocities at all locations in the x- and y-direction.

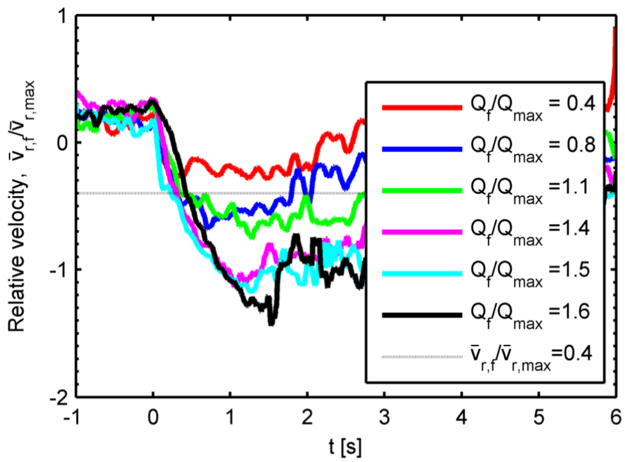

Figure 8: Impact of the flushing discharge on the relative flushing velocity for a set-up with $H_i/H_r = 0.2$

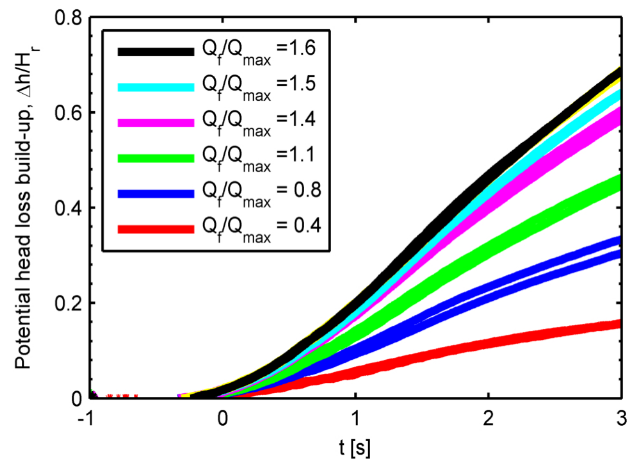

Figure 9: The potential head loss build-up over the rack for various flushing discharges.

direction during normal operation, namely upwards, and $t = 0$ s is the time of the opening of the flushing valve. During the first second of flushing there are only minor spatial differences in the velocity distribution over the rack, which indicate a cleaning of the entire rack. The relative flushing velocities are highest for the series with a closed intake gate. After $2 - 3$ s with flushing with a closed intake gate, the free water surface reaches the trash rack and causes spikes in the measurements. For the partly open intake gate, the location closest to the weir ($x/H_r = 0.8$, blue series) obtain higher flushing velocities than for the two other locations at approximately $1 - 2$ s. Note that the velocity before the flushing is slightly negative closest to the intake gate (red series). The moving time average of the relative flushing velocity for all 24 experimental set-ups is presented in Figure 6, and shows that the intake gate needs to be partially closed in order to obtain the required relative flushing velocity. A closer study of the effect of different intake gate openings for a given set-up with $H_w/H_r = 1.6$, $L/H_r = 1.9$, and a flushing discharge $Q_i/Q_{max} = 1.6$ is presented in Figure 7. For the black data series, closed gate, the free water surfaces reaches the rack after 2.5 s, thereby causing the spike in the graph. A closed intake gate gives the highest flushing velocity, but flushing with a small intake gate opening will also give relative high flushing velocities. One-sided hydraulic pressure on the intake gate is avoided with a partly open intake gate during the backflushing, which will help facilitate a fast and efficient flushing sequence.

Design Parameters

The capacity of the flushing system, Q_f, is identified as the most important design parameter affecting backflushing efficiency. The influence of Q_f/Q_{max} on the relative flushing velocity $\overline{v}_r/\overline{v}_{max}$ is shown in Figure 8 for the set-up with $H_w/H_r = 1.6$, $L/H_r = 1.9$, and an intake gate opening $H_i/H_r = 0.2$. According to the result in Figure 8, there is a certain capacity of the flushing system required in order to obtain a sufficiently high flushing velocity over the trash rack, whereby the red line is the only not to exceed the threshold value. The potential head loss development, $\Delta h_{r,f}(t)$ (Eq.3) during the first seconds of flushing for different flushing discharges is shown in Figure 9, with two tests for each discharge. The results shows that the potential head loss increases most rapidly for the highest flushing capacities. As a general remark, Q_f/Q_{max} should be larger than 1.0 in order to obtain a high enough flushing velocity and rapid head loss build-up. The impact on the flushing velocity development from the three other design parameters, H_w, H_u, and L, are studied for $Q_f/Q_{max} = 1.6$ and $H_i/H_r = 0.4$. The time series from fourteen various set-ups are presented in Figure 10, whereby a long L slightly increases the flushing velocity, whereas neither H_w nor H_u have any unique impact on the results.

Flushing Duration

According to previous studies, the required flushing time, is the time needed to transport the debris out of the flushing intake. Moreover, after approximately six seconds after the flushing gate opening, all the flushing velocities are reduced below the defined limit $\overline{v}_r/\overline{v}_{max} > 0.4$ (see Figure 5). The efficient flushing time is therefore six seconds at the most, while the critical water level, h_{crit}, was never reached within the efficient flushing time, but h_{crit} restrict the available flushing time $t_{f,max}$. Nevertheless, a flushing duration exceeding the efficient flushing time seems unnecessary, and thus the length of the flushing conduit could

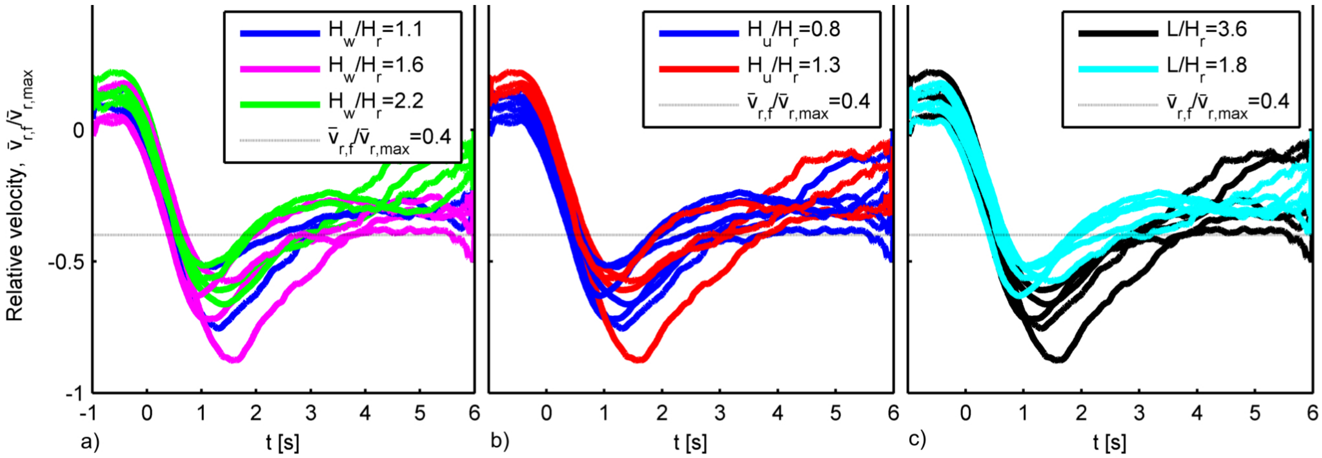

Figure 10: The relative flushing velocity development for fourteen various model set-ups, presented according to a) weir heights, H_w, b) vertical rack locations, H_u, and c) chamber lengths, L.

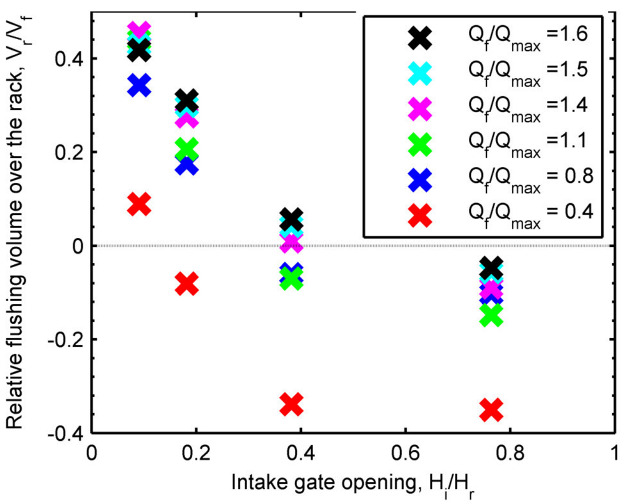

Figure 11: The relative volume of water over the trash rack during the backflushing compared to the volume out of the flushing outlet as a function of the intake gate opening and flushing discharge.

Figure 12: Opening of the intake gate with hydraulic pressure on one side. A jet hits the rack and the weir.

be restricted by the efficient flushing time. Additionally, as long as all debris is removed from the intake chamber within the flushing time, it will be flushed out in the next sequence. The ratio of the water volume flowing over the trash rack, V_r, compared to the total volume used for flushing, V_f was calculated for the first six seconds with efficient flushing, and is strongly dependent on both the intake gate opening and the flushing discharge (see Figure 11). A negativeV_r means that more water flows in the positive direction over the rack than in the negative direction during the flushing, hence the cleaning is not efficient.

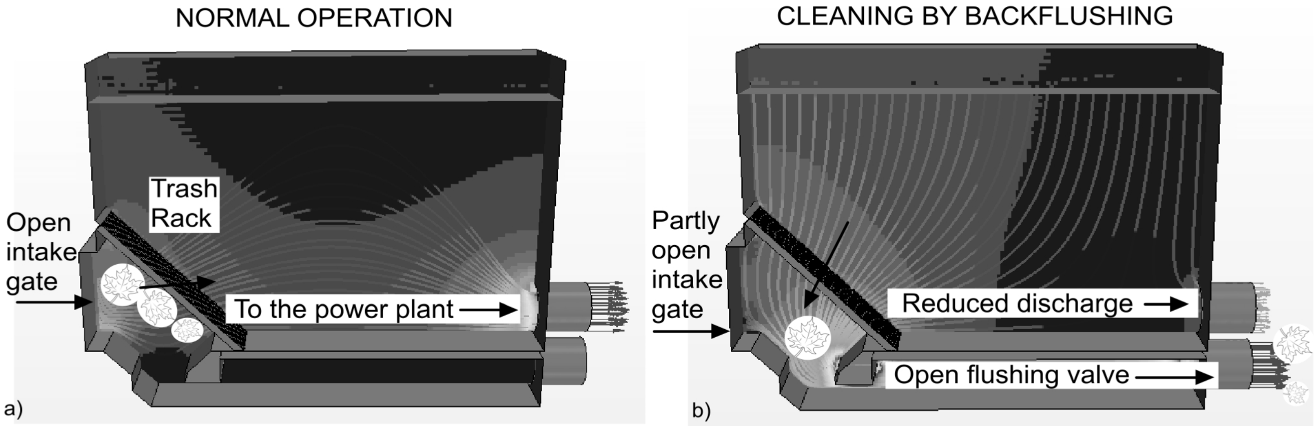

Figure 13: The concept of the backwardly inclined rack: a) Normal operation with open intake gate, and b) cleaning of the trash rack with backflushing. The flushing valve is open, whereas the production discharge is reduced.

Discussion

The experiments shows that the H-rack intake structure provides for a reliable method for cleaning the trash rack while the power plant is running. The additional head loss through the H-rack intake might be insignificant compared to the total head of the power plant, and the extent of head loss caused by debris fouling. The flushing capacity, given by the design of the flushing conduit, is of primary importance for the flushing efficiency. As a minimum, the flushing capacity, Q_f, should be equal to Q_{max} in order to obtain a satisfactory flushing velocity and head loss build-up for flushing. In addition to the flushing conduit and the flushing valve, the weir inside the intake structure is the only extra components compared to a standard intake. The design and dimensions of the other components of the H-rack intake are comparable to standard intake structures with a vertical trash rack. Neither the length of the intake chamber, L , nor the weir height, H_w, significantly affect the flushing velocities. A high weir is not recommended because of the extra head loss, and does not improve the velocity distribution either. A longer chamber will increase the available volume for power production during backflushing. Furthermore, the vertical location of the trash rack was not very important. The highest flushing velocities were obtained with a closed intake gate, and flushing with a closed intake gate will lead to a free surface flow over the trash rack, which is very efficient for cleaning. On the other hand, high forces are required to open an intake gate with a one-sided hydraulic pressure. Figure 12 shows a jet hitting the weir while opening the intake gate. For a reliable and efficient cleaning sequence, the intake gate should be set in a low, but open position during backflushing. Based on the experiments, the H-rack intake structure is evaluated to be a recommended concept, and an example of a full scale intake is presented to give an overview of the experimental results. Given a discharge $Q_{max} = 1.2\,\mathrm{m}^3/\mathrm{s}$, the H-rack intake structure could have a design with $H_r = 1.4\,\mathrm{m}$, $B_r = 1.8\,\mathrm{m}$, $H_w = 2.3\,\mathrm{m}$, $D = 0.75\,\mathrm{m}$ and $L = 2.5\,\mathrm{m}$, which represents a relative compact intake structure. The absolute head loss for tjhe intake structure with a clean rack during normal operation would be $\Delta h_a \approx 0.04 H_r \approx 0.06\,\mathrm{m}$. Given a closed intake gate, the available flushing time before the critical water level is reached, is: $t_{f,max} = \frac{H_w - h_{crit}}{Q_p} L B_r = \frac{2.3\,\mathrm{m} - 1.4 \times 0.75\,\mathrm{m}}{0.2 \times 1.2\,\mathrm{m}^3/\mathrm{s}} 2.5\,\mathrm{m} \times 1.8\,\mathrm{m} = 23\,\mathrm{s}$. Assuming a capacity of the flushing conduit $Q_f = 1.5 Q_{max}$ and a flushing duration equal to the efficient flushing time, $t_f = 14\,\mathrm{s}$, the volume used for flushing would be $\forall_f \approx 25\,\mathrm{m}^3$.

Based on the results from the experiments, a further improvement of the solution has emerged, and is shown in Figure 13. Instead of the horizontal trash rack, the rack is backwardly inclined. The streamlines will be straighter, and thus the head loss will be reduced. The velocity over the trash rack will conceivably be quite evenly distributed, as the rack will be tangential to the velocity field around the flushing conduit inlet. Energy production during the backflushing is possible, but there will not be any water volume unique to the turbines, as for the H-rack. The solution with an inclined rack will be studied in further research.

Conclusions and recommendations

The new intake concept with a horizontal trash rack provides a reliable and efficient cleaning of the trash rack at small hydro power plants, with possibilities for remote control. The advantages are the timely and efficient cleaning and energy production during the cleaning, the safety of the person in charge, and the reduced cost for human labor, in addition to a better protected rack against ice and larger floating debris. Moreover, the bottom outlet has the possibility to serve as fish by-pass, but further research to ensure fish-friendly passage is needed, especially on the flushing conduit design, the recommended flushing frequency and flushing discharge, and any need for continuous bottom outlet flow. For many cases, the advantages can be more important than the extra head loss and the extra components. Based on the experiments, we can recommend the design for new hydropower plant intakes, while further studies on the passage of fish and on the backwardly inclined rack can further improve this promising concept.

Notation

b_r	= Bar thickness (mm)
B_r	= Rack width (m)
D	= Pipe stock diameter (m)
Fr	= Froude number (-)
g	= Gravity acceleration constant (m/s^2)
h_1	= Upstream water depth (m)
h_2	= Downstream water depth (m)
$h_{r,a}$	= Pressure above the rack before flushing (m)
$h_{r,u}$	= Pressure under the rack during flushing (m)
$\Delta h_{r,f}$	= Head loss through the rack during flushing (m)
h_{crit}	= Critical water level (m)
H_r	= Rack height (m)
H_i	= Intake gate opening (m)
H_u	= Vertical trash rack location (m)
H_w	= Weir height (m)
L_r	= Length scale (-)
L	= Chamber length (m)
ν_w	= kinematic viscosity (s/m^2)
p_r	= Bar depth (mm)
Q_f	= Flushing discharge (m^3/s)
Q_in	= Supply discharge (m^3/s)
Q_p	= Discharge to the power plant (m^3/s)
q_{max}	= Maximum unit discharge to the turbines (m^3/s/m)
Q_{max}	= Maximum discharge to the turbines (m^3/s)
Re	= Reynolds number (-)
s_r	= Bar spacing (mm)
t_f	= Flushing duration (s)
$t_{f,max}$	= Maximum flushing duration (s)
$v_{r,f}$	= Flushing velocity at the trash rack (m/s)
$\overline{v}_{r,f}$	= Space averaged flushing velocity over the trash rack during flushing (m/s)
$\overline{v}_{r,max}$	= Maximum average velocity over the trash rack (m/s)
V	=Volume used for flushing (m^3)
V_r	=Volume over the rack during flushing (m^3)
V_p	=Volume to the power plant during flushing (m^3)
x, y	= Location variables at the rack (m)

References

Agilent. *Data Sheet, Agilent U2300A Series USB Modular Multifunciton Data Acquisition Devices*.

ASCE (1995). *Guidelines for Design of Intakes for Hydroelectric Plants*. Amer Society of Civil Engineers.

Couret, D and M Larinier (2008). *Guide pour la conception de prises d'eau "ichtyocompatibles" pour les petites centrales hydrolectriques. Agence De l'Environnement et da la Matrise de l'Energie (ADEME)*. Report.

EPRI (2007). *Hydropower Technology Roundup Report: Trash and Debris Management at Hydroelectric Facilities, TR-113584-Vol10*. Report.

Gosset, C. et al. (2005). "Tests of two types of bypass for downstream migration of eels at a small hydroelectric power plant". In: *River Research and Applications* 21.10, pp. 1095–1105.

Jenssen, Lars et al. (2006). *Inntakshåndboken*. NVEs hustrykkeri.

Knauss, J. (1987). *Swirling Flow Problems at Intakes (IAHR Design Manual)*. Rotterdam, Balkema. ISBN: 9061916437.

Larinier, M. (2008). "Fish passage experience at small-scale hydro-electric power plants in France". In: *Hydrobiologia* 609.1, pp. 97–108.

Microsonic. *Data sheet, mic+130/IU/TC/M30*.

Nø vik, H. et al. (2011). *Backflushing of trash racks at intakes to small hydropower plants*. Conference Proceeding. Hydro2011, Practical Solutions for a Sustainable Future, 17-19 Oct 2011, Prague. The International Journal on Hydropower and Dams.

Nø vik, H. et al. (2014). "Hydraulics of backflushing for efficiently cleaning hydropower trash racks". In: *Canadian Journal of Civil Engineering* 41.1.

Nortek. *Datasheet Vectrion Lab*.

Radhuber, W. (2006). *Trashrack cleaners types - experiences*. Conference paper 14th International Seminar on Hydropower Plants, Vienna University of Technology.

– (2008). *Trashrack cleaning, The past- the present- the future*. Conference paper 15th International Seminar on Hydropower Plants, Vienna University of Technology.

Russon, Iain J. and Paul S. Kemp (2011). "Advancing provision of multi-species fish passage: Behaviour of adult European eel (Anguilla anguilla) and brown trout (Salmo trutta) in response to accelerating flow". In: *Ecological Engineering* 37.12, pp. 2018–2024.

Siemens. *Data sheet Siemens Sitrans F M Mag 5100 W*.

U.S, Deparment of Energy (2011). *Best Practice Catalog: Trash Racks and Intakes*. Report. Hydropower advancement project. U.S. Department of Energy.

Wahl, T.L (1992). *Trash Control Structures and Equipment: A Literature Review and Survey of Bureau of Reclamation Experience*. Report R-92-05. Denver, Colorado.

Wika (2013). *Datasheet S-10, General Purpose Pressure Transmitters*. Web Page. URL: http://www.wika.us/upload/DS_PE_S_10_en_us_16325.pdf.