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Trash racks and fish diversion screens

Literature Study and worked-out examples

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Trash racks and fish diversion screens

Literature Study and worked-out examples

Lopez Castano, S.; Vercruysse, J.; Visser, K.P.

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Approval

Head of Division:	Bellafkih, A.	Getekend door:Abdelkarim Bellafkih (Sign Getekend op:2022-02-01 09:47:29 +01:0 Reden:Ik keur dit document goed Abdelkarim Bellafkih

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Abstract

The first part of this work is an explorative review of the state-of-practice regarding the dimensioning of trash racks in culverts and pump/turbine intakes. A historic review of the use of trash racks in channels, their types, the classification of debris and the processes that produce debris, are explained. Relevant methodologies for the prediction of yearly amounts of debris, and for the dimensioning of the trash screens, bar dimensions, and for bar spacings is given. The limitations of these **classical** methodologies are thoroughly discussed and put into context through worked-out examples. These examples are thought to be representative for the theory being discussed and applicable to problems of relevance in Flanders.

The second part of this work proposes a change in perspective regarding trash racks/screens in culverts and pump intakes: from trapping debris to divert/exclude towards a bypass, using screens. This proposal is made in an attempt to remedy the shortcomings in the methodologies needed to calculate the yearly amount of debris that may accumulate on the trash rack, the blockage percentage resulting from the dimensioning of the bar spacings, and the oversizing of the trash racks in case of clogging. Worked-out examples are also given there.

The third part of this work is dedicated to discuss the issue of fish migration/diversion/exclusion at intakes and channels in relation to the design of screens. The techniques presented for trash rack bar spacing dimensioning for culverts are usually favourable for fish migration (that is, the spacings are at least as big as the spacings required for fish migration) but, in general, this is not the only requirement for fish migration: hydrodynamics, and many other stressors, may deter fish from passing through the screen, regardless of the bar spacing. On the other hand, the dimensioning of screens for fish exclusion/diversion seldom agrees with the classical dimensioning techniques discussed in the first part, thus a brief discussion on behavioural fish exclusion facilities are made in order to put this contrasting ideas into context. Worked-out examples are also given here.

The last part presents a short discussion over the different approaches presented and gives recommendations for future studies related to the dimensioning of in-channel screens. It is important to mention that a dedicated manual for the dimensioning of screens lacks in Flanders. Hopefully, this text may serve as a sketch for a manual for the design of in-channel screens for the region of Flanders.

For rapid access and use of the classical methods herein proposed, the author suggests to review section 2.1 and in particular Table 3 for a rapid dimensioning of the trash screen area given a yearly amount of debris that may travel with the flow, or just by using the intake's area. The dimensioning of the trash rack bar spacings can be made using Figure 7; and in case an estimation of the flow velocities are needed then Figure 6 may come in handy. The bar spacing dimensions and flow velocities must be revised against the recommended values for fish migration/exclusion given in Table 5 and in Table 6. The latter tables can be used directly for the estimation of the bar spacings, in case information about the flow conditions is scarse. A workflow for the design of trash screens is presented in Figure 22, following the discussions held in the text.

Lastly, the word 'trashrack' and 'screen' will be used indifferently thorough this text. In principle, a 'trashrack' is a particular type of 'screen' but in the context of floating debris collection/diversion they mean the same.

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1 Introduction

Trash control facilities, or trash racks, at the intakes of hydropower plants, pump stations, and culverts, serve the purpose of blocking the passage of large floating or submerged debris that may hamper the normal operation of equipment and civil infrastructure. Sometimes, these structures are also used as fish (or any other animal) diversion facilities. Historically, the design of trash racks was made in function of its operation and maintenance, that is, initial proposals for the design were made based on the accessibility for a maintenance crew to clean the structure; and then post-construction enhancements were made to the constructed structure whenever necessary (Radhuber 2008). Early designs of trash collection facilities in dams and intakes would only indicate the location of the trash collection facility (see Figure 1), leaving its dimensioning to the constructor/operator. As the demand for hydropower and pumping in rivers and canals grew, this trial-and-error approach became prohibitively expensive, thus demanding for a way of predicting the behavior of such structures. More recently there has been a renewed focus on energy losses caused by debris collection facilities, and the costs that the operator may incur in having a structure that affects the efficiency of dams and pumps (Nøvik, Lia, and Wigestrand 2014).

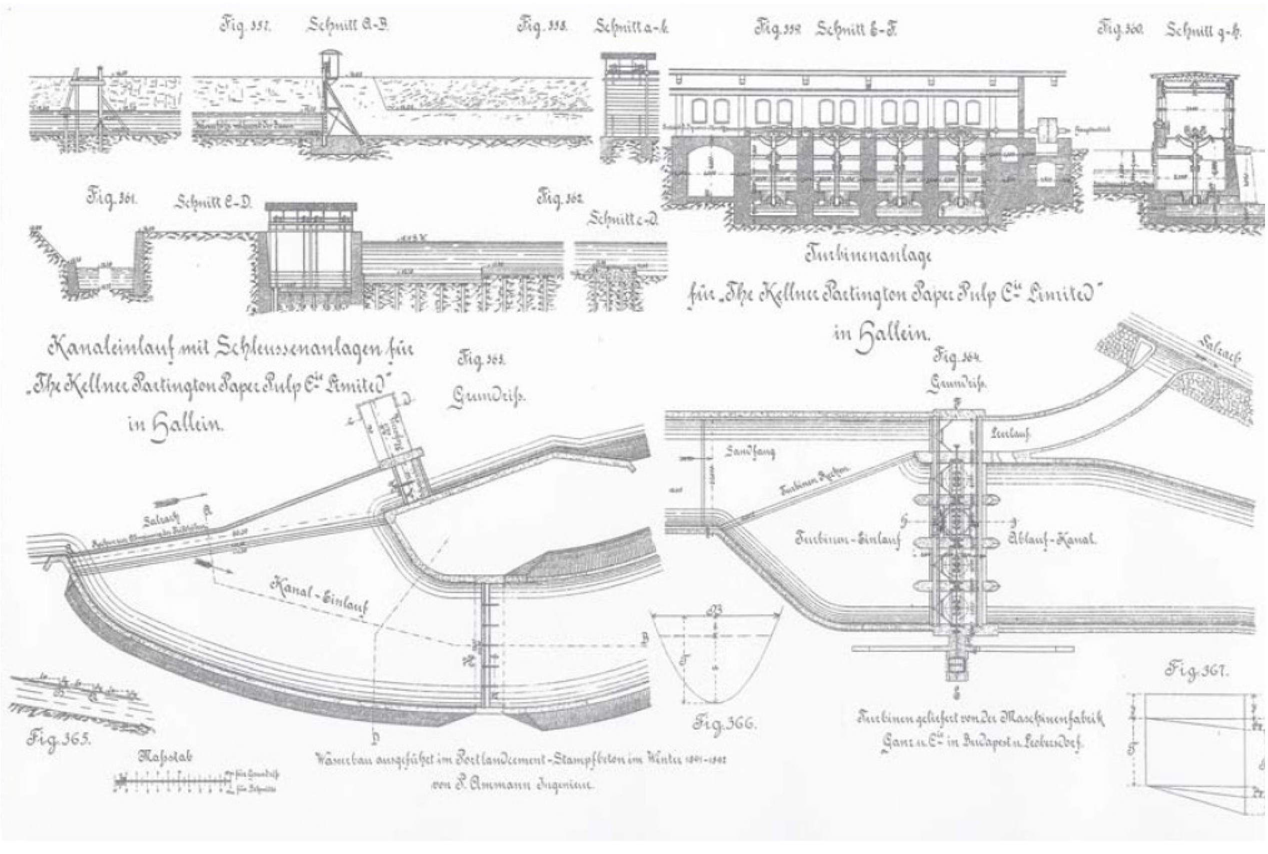


Figure 1 – Hallein Hydropower plant in the Salzach river, Austria (as-built in 1892).
Notice the mention of trash rack rakes “rechen” in the figure.

General design consideration for trash rack structures vary in great measure depending on the location and type of structure is intended to protect (Bureau of Reclamation 2016). In general, trash racks are made of rows of trash bars (or rakes) that impede the passing of debris, but these may be part of a larger debris collection structure, which may use electromechanics equipment for its automatic cleaning. Notice that by debris one may intend foreign material carried by the watercourse such as boulders, logs, mattresses, plastics, shopping carts, to chips of wood, leaves, twigs, reed, and other organic waste. This implies that the design methodologies involved in the dimensioning of the rakes may require a detailed hydrological and geomorphological study of the basins serving the intervened water course. Take for example the cases shown in Figure 2; it is clear that one structure is designed for the trapping and/or diversion large debris (logs, in this case) travelling with the flow, whereas the other is made to divert small floating debris and impede access to unauthorized personnel. The former requires careful study of the river dynamics and hydrology of the catchment and requires careful consideration of the energy losses caused by the structure, the latter is designed based on the minimum allowable size that can go through the equipment and ease of maintenance. This shows that trash rack design guidelines are relative to the structure they serve, besides trapping debris. Additionally, the design of the trash racks might consider fish migration patterns. This will be discussed in a separate chapter.

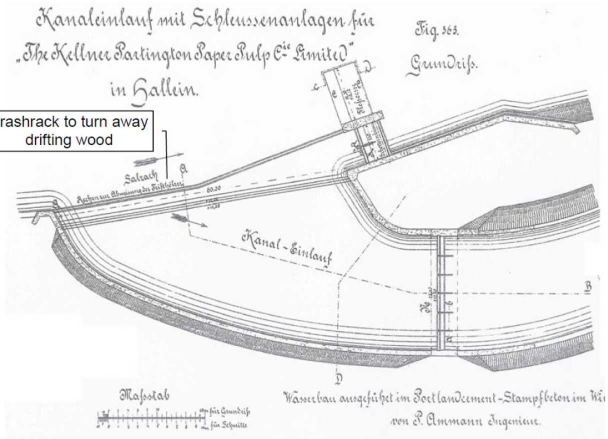


Figure 2 – Types of trash racks depending on the definition of debris.
Left: trash collection facility for a pulping facility. **Right**: trash rack in tidal culverts in Bazel (BE).

It is therefore important to first determine the kind of debris one is intended to manage or collect in order to determine the approach in which the structure will be projected. This classification may exclude bedload and the so-called *debris flows*, product of mud avalanches and landslides. The latter is common in mountainous streams, and its study is rather challenging. However, one may classify debris more generally (Watterstein, N. Thorne, C. R. Abt, S. R. 1997) according to how it is produced/transported:

- **Wind and wave action:** In lakes, river deltas, and waterways controlled by tides (or anthropogenic surges) waves and wind may erode shorelines and riverbanks, producing flotsams (NL: drijfhout) that may be transported downstream. On the other hand, wind action may trap floating debris in recirculating regions and ponds.
- **Ice thawing:** garbage in banks and debris accumulated on top of the ice sheets in lakes/rivers may runoff when temperatures increase during change of season. Ice chunks may also clog, temporarily, the trash racks. In the region of Flanders, this is unlikely to happen, though.
- **Forest/meadows/wetlands litter:** Leaves, branches, and other organic material can be washed-off in early spring during heavy rains.
- **Gardening, farming and forestry practices:** Depending on land use, runoff may arrive faster to the waterways, with or without debris.
- **Anthropogenic:** all sorts of man-made products that may arrive to the waterway, due to bad collection practices or otherwise.

The elements of this list, however, are not mutually exclusive to one another and, worse, one mechanism may produce it and the other transport it. Again, debris/mud flows product of avalanches and flash floods are not considered. Not having a classification where one item is roughly independent from the next makes the analysis or prediction more complex, and non-linear. Any empirical methodology for the prediction of debris runoff based on the current classification will lack generality, and will only be valid in the context where it was calibrated.

This classification is often used for determining the *debris load* that may be transported by perennial watercourses where the trash rack is placed. Such quantity may serve to determine the overall size of the trash rack screen, that is the total wetted area of the screen that must meet the flow. The Environmental Agency in UK (J. Benn et al. 2019) has prepared cumulative-frequency curves for determining the total amount of debris per year accumulated at the outflow of a catchment, which can be later used for determining the said trash rack area. Different curves are given for different land uses, and corrections are suggested accounting for the risk of flooding and deforestation. Notice that the model therein proposed loosely resembles a *unitary hydrograph model*, where it is assumed a rainfall *event* happens uniformly in a certain catchment. This is not at all the case with debris runoff where typically the sources of trash are localized (i.e. avalanches, dumping) and, as previously suggested, it is difficult to assess the validity of the model outside from the context in which it was calibrated (that is, small catchments in the UK). This methodology will be presented in chapter 2, and later it will be revisited as a worked-out example.

A proposal for a method for the dimensioning of bar spacings in trash racks was commissioned by the Environmental Agency to a British University, where a PhD student conducted such research (Blanc, Janice 2013). The experiments therein conducted served to calibrate a model where the bar spacing in a trash rack is function of the incoming flow, bar inclination, and the percentage of debris entrapped by the screen. That is an effort to prepare an empirical formula to determine the spacing between bars, given certain flow conditions and debris catching capacity of the trash rack, was pursued. On debris entrapping, the author is not certain whether the experiments conducted took into consideration the overall *randomness* in the shape of debris/trash. Unlike sediments and boulders, which tend to be either round or elongated, sources of debris produce trash with shapes one may assume as random and *elastic* (think of branches, or twigs). Such objects may, or may not, be blocked by the trash rack but can cause problems to the structure (i.e. clogging, damage to flap gates). For the sake of discussion, this method will be presented as an alternative for the dimensioning of bar spacings, and should be used in the event where is not possible to determine the maximum permitted debris size that can go through the intake.

However, the author cannot find a scenario where the aforementioned method will be needed outside from the design of trash screens in culverts, particularly when the trash rack is proposed for turbine/pump intakes where fish are typically excluded. It is common that the equipment vendor will provide a minimum particle size that may cross through the equipment without hindering its operation.

For the discussion of energy losses a second general classification may be made based on how the trash rack bars are positioned. The Bureau of Reclamation (Bureau of Reclamation 2016) makes the following classification for trash racks before intakes:

- **End Bearing:** The bars are set in a vertical position, and supported at the ends. are used for low-head pumps, run-of-river small hydropower plants, or other canal headworks where the racks do not extend too deep into the water column. Usually the rakes/bars are set in an inclined position.
- **Side Bearing:** The bars are set in a horizontal position, and supported at the ends. Side bearing racks are used when loads and bending moments become prohibitive, that is, when a large portion of the trash rack is deeply submerged.
- **Integral**: typically used for fully submerged inlets. Usually pre-fabricated as a steel cage. Preferable whenever concrete support is undesired, or when it's replacing is not intended. This structure is also desired whenever backflushing is a valid method for cleaning the trash rack.

Notice this classification practice pertains more to the structural design of the trash racks, rather than hydraulic. It is assumed that the dimensioning of the bar spacings and other basic dimensions follow some basic recommendations therein proposed (these will be discussed later), and a design based on hydrodynamic considerations is not sought. That is, the energy losses are a *consequence* of the proposed bar spacing and shape and no attempt in optimizing these is pursued. The reason is that the structural design of the supports for the trash rack may become complex as one attempts optimizing the shape and spacing of the bars comprising the trash screen. This will be discussed in chapter 2.

The methodologies and classifications presented until now are make the following two assumptions: (1) the trash screen either deflects or traps trash which will later be collected, and (2) flow should pass relatively unimpeded through the trash rack. Since the second item only becomes important where energy losses may affect negatively the operation of the whole structure, one may propose flow diversions as a mechanism to *separate* debris flow from the service discharge (the discharge needed for the operation of the system). Vertical screens may be placed at the bottom of low-head spillways in order to divert flow from debris. Another way is to place a vertical drop-shaft where water is percolated by a screen, placed in the center of the shaft intake, through the action of centrifugal forces. These options are not common in navigation and pumping infrastructure but are routinely used in mining operations and water sanitation. These options may be explored later on.

Currently, the use of trash screens in canals and culverts has focused on preventing the clogging of the structure's intakes. The main challenge is that different swimmers have completely different *rheotaxis*, even the same species may have different swimming/migration behaviour during its lifetime. This alone may force the design of several fish passage structures which, in practice, is not feasible. Here, however, a brief description of the species commonly encountered in the Flanders canals is given, and standard approaches to fish collection facilities proposed.

1.1 Scope of the work

Given how ample the topic on the study of trash collection facilities for intakes is, it is important to define which are the scenarios where this report will be relevant. To that end, this section will discuss first what will *not be covered* in this report, and then a precise description of the framework for which this work may be useful will be given afterwards.

As a starting point, there will not be a focus on the design or proposal of automatically operated rake cleaning equipment, or rake cleaning equipment in general. The design criteria herein suggested will consider the necessity of accessing and cleaning the trash rack facility, but detailed maintenance operations are out of the scope of this work.

Second, security screens are treated separately from trash racks/trash screens. Security screens are placed in order to exclude leisure vessels (kayaks, jetski's, etc) and people from passing through an intake or culvert and these are typically different from trash or fish screens. The criteria for their dimensioning tend to enter in conflict with those of trash racks and fish screens, and they respond to local navigation authorities' regulations rather than to aspects responding to fish migration or hydraulics. Thus, the study of security screens are out of the scope of this work.

Discussions relating the structural and geotechnical details needed for the projection of the trash collection facilities will be left out, unless these are necessary in connection to the hydraulic design itself. More precisely, a short discussion on slender element vibrations is given in the context of the dimensioning of the trash bars. The structures herein proposed are usually based on structures that are common in hydraulic construction practice, meaning that its structural design is *standard* and easily found in engineering manuals. On the other hand, these facilities are not *massive* hence the main challenges in the geotechnical design of the foundations is in the protection against piping and foot seepage, foot erosion and sedimentation, which don't need discussion here.

Furthermore, the structures herein proposed are to be placed at the intakes of pumping stations, culverts, and other drainage facilities along the different navigable and non-navigable waterways across Flanders. The main purpose of these pumps is to redirect water from wetlands, tidal marshes, and other water bodies to channels or rivers, whenever needed. Given this scenario, these watercourses are expected to be in the late stage of depositional zones. This implies that the thrash rack facilities should not account for the trapping of coarse debris product, torrents, or flash-floods.

Figure 3 – Partially clogged trash racks at the combined in- and outlet construction of CRT Zennegat.

Finally, one cannot expect fully clean the trash racks via *backflushing* neither: the design of Archimedes pumps and overflow culverts in dikes may disallow the generation of pressure surges, and the downstream velocities may not be enough to jettison debris out of the trash racks.

Within the framework of the Sigmaplan, Controlled Reduced Tidal zones (CRT) are implemented in the river Scheldt and its tributaries. The water level in a CRT is regulated by an in- and outlet structures. Figure 3 presents an example for the trash rack of the combined in- and outlet culvert of the CRT area in Zennegat. The left picture presents the trash rack at CRT side, the right picture present the trash rack at river side. Note that for the trash rack at CRT side which experience flow in both directions the lower part is kept free while organic waste (twigs, reeds) is collected higher up the trash rack. For the trash racks at the inlet which only experience flow in normal direction lower part of the trash racks is blocked by twigs and reeds (see Figure 3). However, trash rack facilities should account for the trapping of large floating debris like wooden trunks and other large objects that may fall in the water course. On the other hand, flow across the intakes is entirely controlled by the operation of the pump station thus the approach velocities are known beforehand.

1.2 Overview

The report will be organized in 5 chapters. The first one, the introduction, will set up the framework over which the literature research will be conducted. This chapter will introduce the basic definitions and expectations for the design of debris collection facilities, and its challenges. The second chapter will describe the design considerations for the different approaches just discussed. This discussion may include lessons and outcomes from previously proposed structures. A third chapter may discuss a different approach in the design of trash facilities: flow diversion via bottom screens. The fourth chapter will give a brief discussion on fish migration and its relation with trash screens. Whenever possible general considerations will be drawn, and worked-out examples will be given. The last chapter will give closing arguments and a discussion over the present work.

1.3 A word of caution

As it should be clear by now, this text will not attempt to provide an ‘ultimate’ design proposal to the management of floating debris in channels, culverts, or intakes, using screens. In general, the final decision regarding the practicalities of setting a certain bar spacing, wetted area, location, and inclination, for a screen often respond to criteria other than the retention of debris itself, or even hydraulic considerations; instead, more importance is given into its maintenance, cleaning, fish migration, and cost-availability.

Rather, this text will show different design philosophies according to the way the designer d*ecides to manage floating debris*. Basically, one can either divert or collect floating debris using screens. The bar spacing will vary depending on which route to take. <u>Choosing which approach to follow is, as usual, left to the designer</u>. The author will not attempt to propose specific designs in the context of Flanders and deliberately will provide examples that, although pertinent to the context of Flanders, do not correspond to any particular location here.

A good design, it seems, would be one where maintenance and cleaning is reduced to a minimum. Therefore, given the difficulties present in the study of debris transport and other externalities, it is suggested not to use screens to trap floating debris unless it proves to be the only practical solution. One particular scenario where screens are typically designed for trapping debris is at the intakes of pumps and turbines. In this respect, for example, the author has made an effort to review lesser-known alternatives for debris diversion at intakes (see section 3.4).

2 Design Considerations: Practice and Theory

This chapter is organized as follows: first, different methodologies for determining the *debris load* that either the watercourse may transport or the trash screen may block will be described; second, basic structural and hydrodynamic considerations for certain trash rack configurations will be presented, which will allow the dimensioning of the rakes/bars composing trash screens; third, a discussion over the different trash screen locations and their implications in the dynamics of the flow will be made. Design contingencies for partially clogged screens will be deferred to Chapter 3.

2.1 Debris Load and Debris Blockage in Channels

As mentioned previously, whenever the maximum allowed debris size that can go through the trash screen is not known *a-priori*, different methods for determining the screen area and the bar spacings can be used. Such methods, given the complications inherent in the classification and study of *debris flows*, should be used with care, and the results obtained just *back-of-the-envelope* calculations. These may serve, however, to get an idea of the general dimensions needed for the trash facility.

2.1.1 Debris loads in a watercourse: Debris Amount Method

The Environmental Agency (J. Benn et al. 2019) has prepared a set of nomograms, based on hydrological considerations, where the yearly amount of debris per year is set against the length of the channel upstream, as shown in Figure 4. Notice that new terminology was introduced so, before going further, some short definitions are in place:

1. **Trash rack (or screen) area (A_{tr}):** It is understood as the total wetted area of the trash rack, in m^2, opposing the flow. If the trash rack is inclined, then the trash rack area is the projection perpendicular to the mean flow direction.
2. **Bar spacing:** The spacing, in mm, between the bars traversing the trash rack area.
3. **Annual Debris Amount (Q_{da}):** Hydrological quantity related to a debris unit hydrograph integrated over a year. The quantity is usually given in m^3/yr.
4. **Contributing Upstream Length:** In practice, is the total length of the perennial courses in the catchment. Theoretically, is the length of the courses appertaining areas in the catchment where debris is thought to be produced/dumped.
5. **Significant event (E):** The expected occurrence of hydrologically/hydraulically relevant surges on a year basis, that may contribute in the annual debris "budget", expressed in number of occurrences per year. An example is whenever there are bankfull events, that is, when the main water course floods wetlands or thalwegs during high storms. It is also assumed that each event washes the screen, or cleaning operations are conducted after such event. The precise definition of such is case dependent, and a precise definition may be needed for watercourses controlled by tides.
6. **Blinded depth factor (B_f):** A safety factor that corrects the number of significant events depending on the land use of the catchment.
7. **Slope correction Factor (S_{cf}):** Correction to the annual debris amount due to the channels' slope.

Notice that you may apply the *superposition principle* where you can divide the catchment into areas with different land uses and then assigning said areas to different reaches along the water course. The total resulting debris amount (DA, in short) will be the cumulative sum of each of the reaches' annual debris amount contribution. The aforementioned manual doesn't specify how to assign reaches to the areas with different land uses within the catchment.

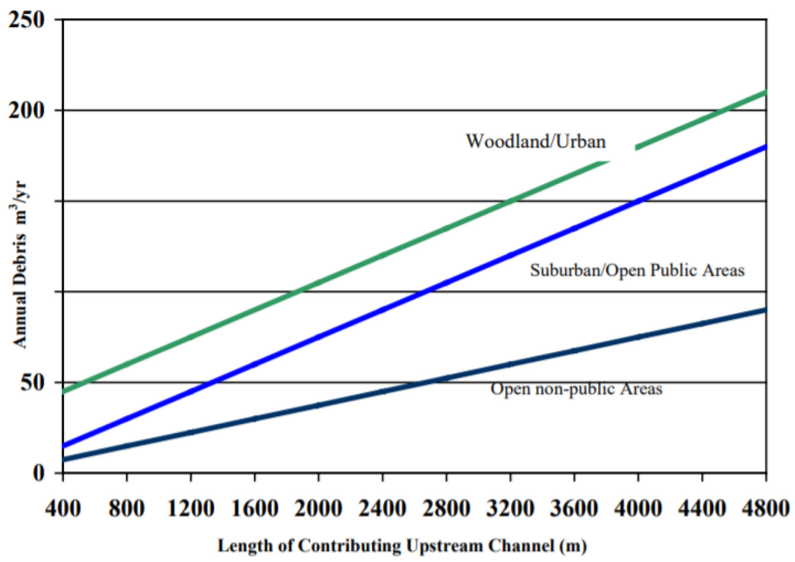


Figure 4 – Expected Debris Amount to Catchment type and main channel length.

Once the total amount of debris per year is known, calculations for the trash rack (or trash screen) area can be performed. Typically, the total annual debris amount should be multiplied by a correction factor according to the mean slope of the primary watercourse, as suggested in Table 1.

Table 1 – Annual Debris Amount correction factor for slope.

CHANNEL SLOPE (M/M)	CORRECTION FACTOR (S_{CF})
GREATER THAN 1/250	1
UP TO 1/500	0.75
UP TO 1/1000	0.50
LESS THAN 1/1000	0.25

Furthermore, the so-called blinded depth factor can be determined for different land uses in a catchment, as it is shown in Table 2. Notice that the differences between catchment types may be subtle, hence the differences in the blinded factors are also rather similar.

Finally, the trash screen area is calculated as follows:

$$A_{tr} = s_{cf} \frac{Q_{da}}{E \cdot B_f} \tag{2.1}$$

Notice that the area of the trash screen corresponds to the wetted area being traversed by the flow in the most critical of events. It is also important to note that the equation assumes that the trash rack is cleaned after each significant event. The trash screen area must satisfy the minima suggested in Table 3 which, instead, may be used as a "rule of thumb" method for the dimensioning of the trash rack screen. One could use the suggestions placed there, whenever measurements of the annual debris amount are available or the former method is deemed unreliable. Notice the classification there is rather coarse: it is not clear what "large" debris means, for example.

Table 2 – Blinded depth factor.

CATCHMENT TYPE	BLINDED DEPTH FACTOR (B_F)
WOODLAND	0.63
URBAN	0.23
SUBURBAN	0.20
OPEN PUBLIC AREAS	0.37
OPEN NON-PUBLIC AREAS	0.32

Table 3 – Empirical (or "rule of thumb") sizing of screens.

Debris size	Q_{da} (m^3/yr)	A_{tr}
Large	Greater than 60	12 m^2 or 9 times the wetted area of the intake
Medium	Greater than 30	9 m^2 or 7 times the wetted area of the intake
Small	Less than 30	6 m^2 or 3 times the wetted area of the intake

2.1.2 Dimensioning of bar spacings

The separation between bars responds to several factors not only related to the blockage of debris but also to others, including: fish migration/exclusion, safety concerns, maintenance, equipment protection, etc. In this section a discussion over bar separation as function of debris blockage on the screen, and as function of equipment protection will be held. Which method to use are discretional to the designer: the methods herein presented should be understood as guidelines, of empirical nature.

Empirical bar spacing dimensioning for culverts in waterways: Blockage efficiency

In an effort to define empirical relations for debris blockage, bar spacing, and different flow parameters, scale experiments were conducted for different flow conditions and trash racks under commission of UK's Environmental Agency (Blanc, Janice 2013). Such experiments assume the debris to be buoyant and slender, thus resembling floating logs and other organic material. An analysis of trends for the various variables considered (debris blockage, bar spacing, discharge, and trash rack angle) were prepared, and then lumped together in the following expressions:

$$\log\frac{D}{100-D} = 1.635 - 16.136S + 0.012\theta - 0.975P_v \tag{2.2}$$

where D, S, θ, and P_v are the debris blockage (%), bar spacing (m), trash screen inclination angle (degrees), and the ratio of surface velocity to approach velocity, respectively. The variable P_v is somewhat cumbersome when used for trash rack design: the surface velocity is a value one rarely computes in desktop calculations, and difficult to extract from typical field measurements. Nowadays it is more common to use LSPIV techniques for determining surface flow velocities, but it is seldom the case when suchs velocities are measured for the exact discharge the trash rack is being designed to operate. However, one may write the surface velocity as a function of the mean velocity of the flow if one assumes Prantdl's one-seventh law as valid near the trash rack, that is $V_{top} = 1.2245\ V_{mean}$. Furthermore, the approach velocity in mild channels may be assumed to be the *normal velocity*, assuming Mannings' formula is applicable. With these assumptions in place, one may propose the following equation:

$$\log\frac{D}{100-D} = 1.635 - 16.136S + 0.012\theta - 1.194V_v \tag{2.3},$$

where V_v is the ratio of mean velocity just before the trashscreen to the mean normal velocity of the approaching flow.

Working directly with Equation 2.3 may present its difficulties, since it is more common (and simpler) to measure water depths rather than velocities in a waterway. One can re-write the Mannings' equation for wide, or rectangular, channels assuming the Mannings' coefficient to be function of the mean roughness height of the bed:

$$\frac{V_n}{\sqrt{S_0}} = \frac{5\sqrt{g}\ h_n^{7/12}}{d_s^{1/6}} \tag{2.4}$$

where V_n, S_0, g, h_n, and d_s are the normal velocity, channel mean slope, gravity, water depth, and mean roughness height in the channel bed (or mean grain diameter in gravel beds), respectively. A graphical representation of the equation may prove useful for fast calculation (see Figure 6).

Further manipulations of equations 2.3 and 2.4 may allow for a direct method for calculating the bar spacing, once the ratio of the water depth at the trash rack and the water depth upstream, h/h_n, is determined. The resulting equation is presented in the form of a nomograph, in Figure 7. Notice that once the normal depth of the approaching flow is known, and the angle of the trash rack and the expected blockage already defined, the bar spacing is easily determined.

The CIRIA manual (J. Benn et al. 2019) for the design of culverts offers further recommendations regarding bar spacings for fish exclusion and security. Notice that these spacings might be *mutually exclusive*, that is, the design procedures for a trash screen may give too wide bar spacings for fish exclusion (more on this in Chapter 4), or too close for security screens. In such case one may place several screens for each purpose: fish exclusion, security, and debris trapping. There, a maximum bar spacing of 150 mm is suggested for security screens, and a minimum of 100 mm is suggested for fish migration.

Bar spacing dimensioning for equipment protection

The Bureau of Reclamation (Bureau of Reclamation 2016) suggest that fish exclusion screens (more on Chapter 4) should have openings no greater than 5 cm; for Kaplan/Francis/Propeller turbines the bar spacings shouldn't exceed the minimum opening of the turbine's runner or the maximum opening of the wicket gates; for Pelton and other types of turbines the minimum debris size must be at most $1/6^{th}$ of the smallest flow opening/nozzle. On the other hand, PIANC's waterways commission (Benvegnu 2021) reported that bar spacings in trash racks placed across Europe and UK range from 120 mm for Archimedes screw pumps down to 50 mm for Kaplan turbines. However, it is common for such trash racks to be placed in a way to direct debris towards the fish passages.

Worked-out example 1: end-bearing trash screen for side intake in Arzbach river, DE

Let's say one is commissioned to place a trash rack in the reach shown in Figure 5. The thrash screen is supposed to serve a 5 m-wide broad-crested weir placed on one side of the bank at km 2.3 from the mouth, where a discharge of 10 m^3/s is sought. It is also assumed that the weir is placed incident to the flow direction, in order to avoid curvature in the flow's streamlines. The spillway connects with a grit trap, which filters for small suspended material. The number of bankfull events (dashed lines) per year equal 12, and the catchment is within a forest. The mean grain size of the bed is 4 mm.

Solution:

a) **Hydraulics**: From the graphical tool presented in Figure 6, one finds that the normal depth in the river is around 1.45 m. Since the channel is wide, the velocity can be calculated as follows:

$$\mathrm{V} = 2.5/1.45 = 1.72\ \mathrm{m/s}$$

Hence the specific energy at the entrance of the reach may be calculated:

$$E_0 = y_0 + \frac{V_0^2}{2g} = 1.45 + \frac{1.72^2}{2 \cdot 9.81} = 1.60m$$

Then, the height of the spillway's crest may be calculated as follows:

$$z_0 = -(3/2)y_c + E_0 = 1.60 - (3/2)\sqrt[3]{2^2/9.81} \cong 0.50\mathrm{m}$$

$$y_c = \sqrt[3]{q^2/g} \therefore y_c = 0.7415\ \mathrm{m}$$

The velocity at the spillway's crest is V_c = 2 / 0.7415 m = 2.70 m/s.

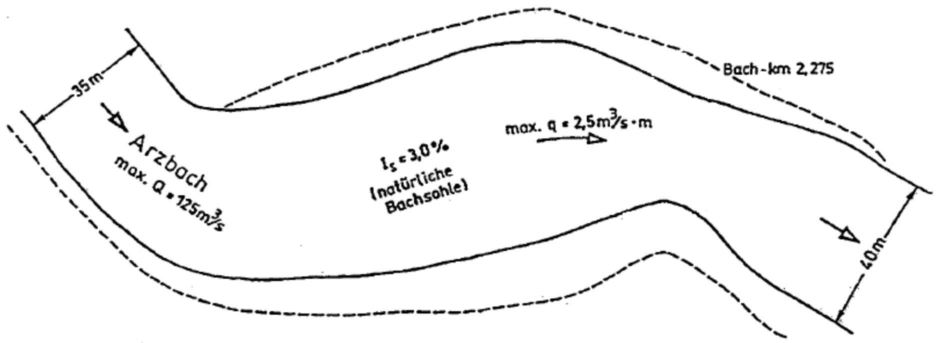


Figure 5 – Example reach in the Arzbach river, Germany. I_s is the slope of the channel.

b) **Bar Spacing:** Notice that the trash rack will be located upstream from the spillway, so the ratio of depths can be calculated as follows:

$$\frac{h}{h_n} = \frac{0.7415/0.715 + 0.50}{1.45} = 1.06$$

Notice the water depth at the crest was corrected, according to Chow (1959). Since the trash screen is supposed to be cleaned manually, then an angle of 60° of inclination seems prudent. If one takes a bar spacing of 5 cm, using Figure 7 one may assume that at most 55% of floating debris of the same size as the bar spacing or greater will be retained. In other words, there is a risk of 45% that floating debris of size 5 cm will go through the screen. However, it is not possible to guarantee a blockage percentage higher than around 60% with the current flow parameters.

c) **Trash screen area**: from Figure 4, the annual debris amount rounds 120 m^3/year. The trash screen area is equal to:

$$A_{tr} = 1 \cdot \frac{120}{0.63 \cdot 12} = 15.9\ m^2$$

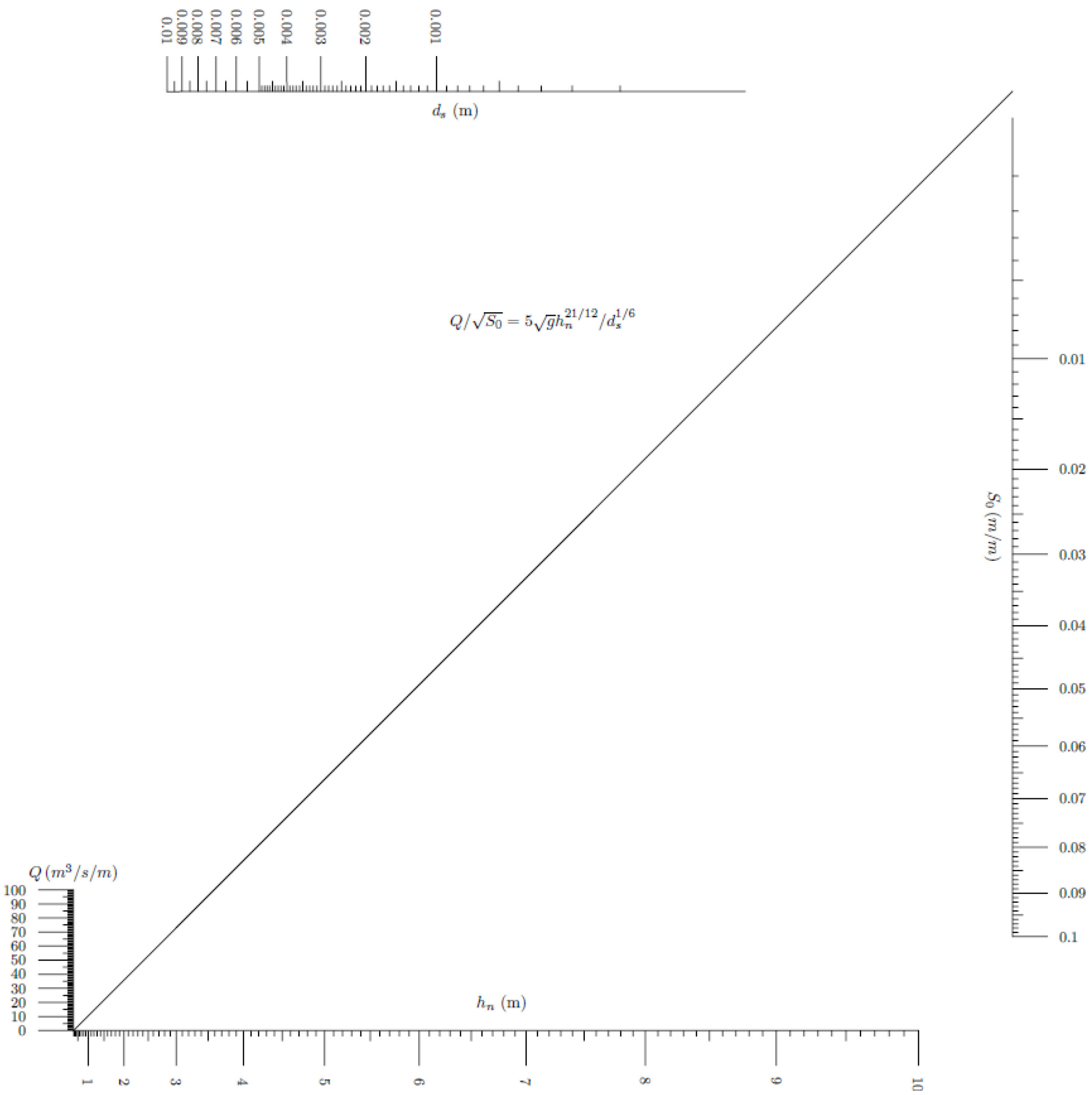
The water depth near the weir is around 1.54 m, then the trash screen height should be equal to 1.54/cos(60°) = 3.1 m. The length of the trash screen is then 15.9 m^2/3.1 m = 5.15 m, which roughly corresponds to the width of the weir.

Worked-out example 2: end-bearing trash screen diversion in Arzbach river, DE

Now, assume the weir is supposed to encompass the width of the channel and must serve as a control for a pumping station downstream. Assume the width of the weir to be of 40 m. All the river flow will be diverted towards the pump. Propose a trash screen.

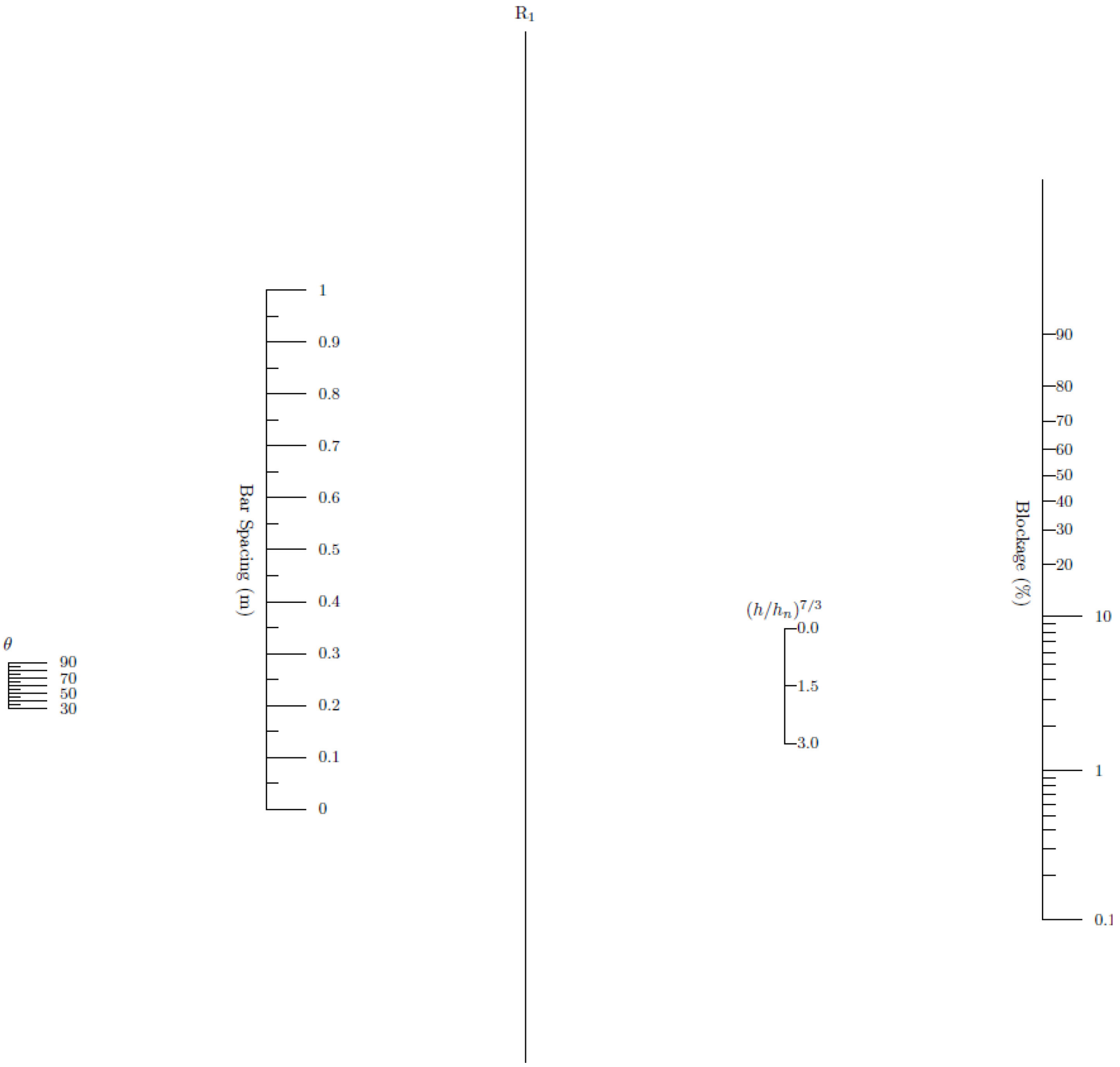
Solution:

Notice that the calculations made up to point (c) are relative to the mean width of the river; in other words, one needs only to re-assess the trash screen area for the hydraulic control (the weir). The calculations for the trash screen area, however, are not valid anymore. Notice that the total wetted area at the weir's crest is equal to A_{weir} = 40*0.7415 = 29.66 m^2. According to Table 3, A_{tr} = 9*A_{weir}=270 m^2. This leads to a trash screen of around 86 m long and 3.1 m high, inclined at an angle of 60° with respect to the vertical.



Straight lines connecting values in opposing axes may be drawn, with the condition that such lines intersect the diagonal line at a single point. The value in one axis can be determined by drawing crossing lines.

Figure 6 – Nomogram for normal depth calculations in wide channels (Q is unit discharge).



Its use is simple: draw two lines passing through three known values at the axes, with the condition that the lines intersect R1 at the same point. The resulting value will be given by the fourth axis.

Figure 7 – Nomogram for the calculation of bar spacing in trash screens.

2.2 Basic considerations in Trash rack design: Positioning & Bar loads

In previous sections, focus on the functional aspects of certain types of trash screens were used to present a semi-empirical method for their dimensioning. Nothing was said about how these screens should be positioned across the water course, except for its inclination angle, nor which should be the shape or dimensions of the bars composing the trash rack.

2.2.1 Spatial arrangement of trash racks and debris booms

The spatial arrangement of the trash rack depends greatly on whether it is side-bearing, integral, or end-bearing. Clearly the first two arrangements are predetermined by the size of the intake and the inclination of the rakes, so there is not much to add there. On the other hand, end-bearing rakes may be co-located in ways that ease debris collection or reduce energy losses. On the latter aspect, experiments conducted in US and Germany shown that the arrangement that least impact has in hydrodynamics is a v-shape arrangement, where the tip points downstream (Watterstein, N. Thorne, C. R. Abt, S. R. 1997). Such an arrangement can be complimented with an end weir and a stilling basin, for further efficiency (see Figure 8). You may, in addition, place a trash screen or debris boom upstream of the weir to collect floating debris.

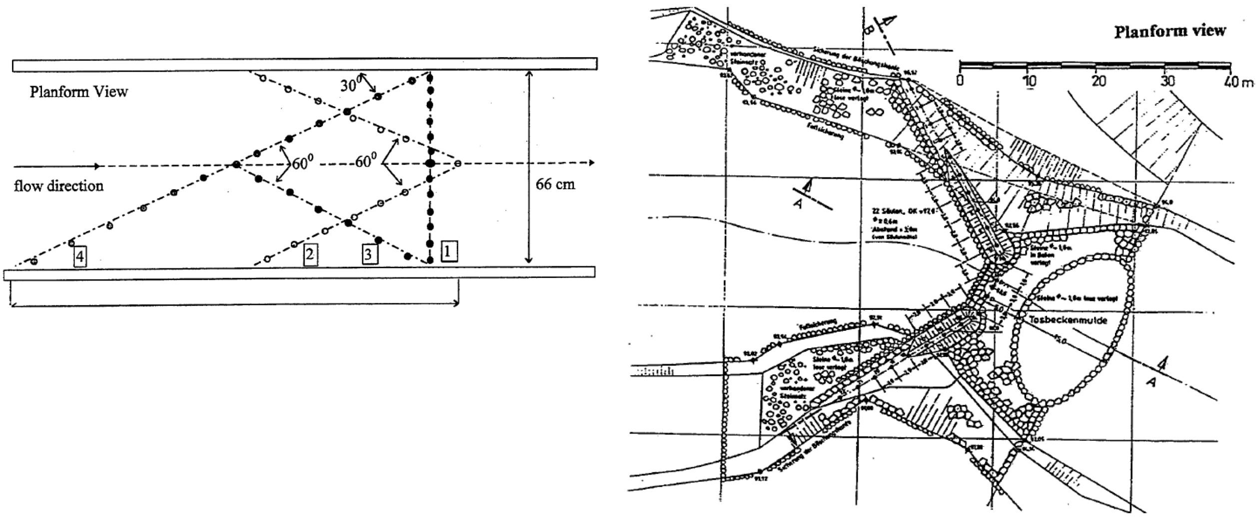


Figure 8 – Arrangement of end-bearing trash racks (Watterstein, N. Thorne, C. R. Abt, S. R. 1997).
Left: Different arrangements studied in a flume, where No. 2 was proven the most efficient.
Right: a v-shaped debris control facility with an end weir and a stilling basin.

Notice that the arrangement of the debris collection facility proposed in Figure 8 assumes that all debris is to be collected either behind the weir or at the dissipation pit. The structure therein shown is supposed to trap floating debris at the rakes and trash screen located at the weirs and the wall contractions, while collecting non-floating debris (product of high flows, floods, or surges) in the dissipation pit. Instead of the dissipation pit, one can trap the debris crossing the weir using either a net or a floating storage device (see Figure 9). Cleaning operation may require the use of heavy machinery during low flow periods.

One may prefer to contend with the increased form losses and backwater if that allows for an easier cleaning operation. In that case, arrangements No. 3 & 4 in Figure 8(left) may be more useful. Both arrangements collect floating debris at either bank of the channel, where it can be collected.

Figure 9 – Alternatives to trapping pits. **LEFT**: flow net, **RIGHT**: litter trap. [source: google.com]

Nowadays there are several companies that offer floating debris booms that can be placed in a channel, and may be held in position by anchors (Benvegnu 2021). Such structures may be used for the arrangements proposed in Figure 8 in place of the side rakes, as shown also in Figure 9. Design criteria for those is not well established given that the design of the plates and cables comprising the structure itself are vendor-specific. From a hydraulic point of view, the energy losses have to be evaluated in-situ, or calibrated using one-dimensional gradually-varied flow models.

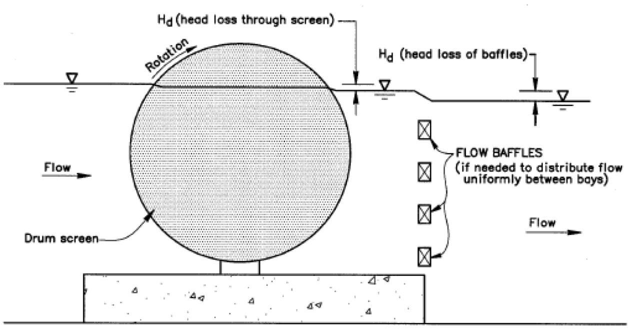


Figure 10 **– LEFT:** Sketch of a drum screen. **RIGHT**: in-situ placement of drum screens. (Bureau of Reclamation 2016).

2.2.2 Debris Booms (or drums) for floating debris collection

Drum screens are often used in dams and diversions as a mechanism for guaranteeing fish migration and debris collection. It typically consist of partially submerged cylindrical drums covered in woven wire (or rubber) placed horizontally across a channel (see Figure 10) that rotate from upstream to downstream, after which a flume or horizontal screen may be placed to collect the debris. It is suggested for the drums to be 65-85% submerged, and the speed of rotation to be such to not produce any additional accelerations in the surface flows (Bureau of Reclamation 2016). The advantage of such structure is its self-cleaning properties. The structure, however, may be more complicated to build.

2.2.3 Dimensioning of trash rack bars

The dimensioning of the bars is directly linked to the stability of the trash rack against vibrations. This implies that bar profiles with higher moments of inertia are preferred in order to increase the natural frequency of the bar. Such profiles tend to have shapes that are not convenient from a hydrodynamic point of view: these produce higher form losses. In the end, it is a game of optimization: the highest possible inertia that causes the minimum possible form loss. But, in practice, is a game of availability and price: which are the available bar profiles that one may use for a reasonable price. It will be clear later that, from a purely structural, cost and maintenance point of view, the most effective cross section for a bar would be a square, however, these may pose great form losses compared to a more prolate element (such as a rectangular profile).

Typically, the design of the bars themselves is not paid too much attention as these usually come as part of a prefabricated trash rack and, sometimes, the supplier provides use specifications wich includes limits on the maximum flow velocity that may go through the screen without causing "too much vibrations". Additionally, the Bureau of Reclamation (Bureau of Reclamation 2016) suggests that velocities exceeding 1.2 m/s produce too high vibrations, and velocities higher than 0.6 m/s makes it dangerous for personnel to inspect/clean the trash rack.

A rational approach to the design of the bars first requires determining the natural frequency of each individual bar. Shedding vortices from cylinders and other blunt objects fully immersed in a current tend to have a *Strouhal number* (St) between 0.2-0.4, depending on the Reynolds number (Re). The St number is the ratio between the natural frequency of the shedding vortices and the minimum frequency that can be generated by the passing flow. The St number can be expressed as:

$$St = \frac{fL}{U} \tag{2.5}$$

where f, L, and U is the frequency of the shedding vortices (natural frequency), a characteristic length, and a characteristic velocity, respectively. In the case of flow around bars, the characteristic length L would be the largest linear dimension in the cross section perpendicular to the flow direction. The characteristic velocity is taken to be the mean velocity approaching the screen.

The second step is to determine the dimensions that may cause resonance of the bar with the shedding vortices, given some cross-section shape. The theory of strength of materials proposes the following approach for determining the natural frequency of vibration f in slender elements:

$$f = \frac{\alpha}{2\pi}\sqrt{\frac{E\,I\,g}{wl}} \tag{2.6}$$

Where E, I, w, l, and α, are the Young's modulus of elasticity, the moment of inertia, the weight of the bar plus the weight of fluid on top of the bar, the bar's length, and a coefficient, respectively. The coefficient α varies from π^2, for a cantilever, to $4\pi^2 / 3^{1/2}$ for an element fixed at both ends. Notice that for cross sections of unitary area, the most convenient of engineering bar profiles is the I profile, followed by the rectangular, the square, and the circle. The I profile however may prove cumbersome to clean and impractical for small dimensions.

By combining equations 2.5 and 2.6 one may come up with a methodology for determining the dimension(s) that may produce resonance in the bars:

$$St\frac{U}{L} = \frac{\alpha}{2\pi}\sqrt{\frac{E\,I\,g}{wl}} \tag{2.7}$$

Notice that the dimensions obtained with this formula do not represent a threshold, that is, neither a minimum nor a maximum, or even a design value. In other words, equation 2.7 tells which linear dimension(s) <u>not to use</u> in order to avoid resonance, given a certain cross section shape for the bar. Additional criteria such as bending moments and impact forces must be considered in order to come up with such minima or design value. The latter is out of the scope of this work.

Worked-out example: revisiting the end-bearing trash screen diversion in Arzbach river, DE

Continuing with the example given in previous sections, no spatial arrangement was given. A v-shape arrangement where the tip points opposite to the flow direction is preferred, since it makes cleaning operations more convenient. An arrangement similar to case No.3 in Figure 8, where the angle of the screen incident to the flow is 60°, is chosen. Notice the length of the trash screen (L_{tr}) when placed in such a manner is equal to:

$$\frac{L_{tr}}{2} = \frac{w/2}{sin(\alpha/2)} = \frac{40\,m/2}{sin(60°/2)} = 40m \therefore L_{tr} = 80m$$

which roughly corresponds to the L_{tr} predicted using the "rule of thumb" method. A sketch of the proposed design is shown in Figure 11. The bar spacing in the trash rack may remain the same as the one calculated previously. As it will be shown in Chapter 4, the current bar spacing design (5 cm) may exclude fish and small mammals from swimming across the screen.

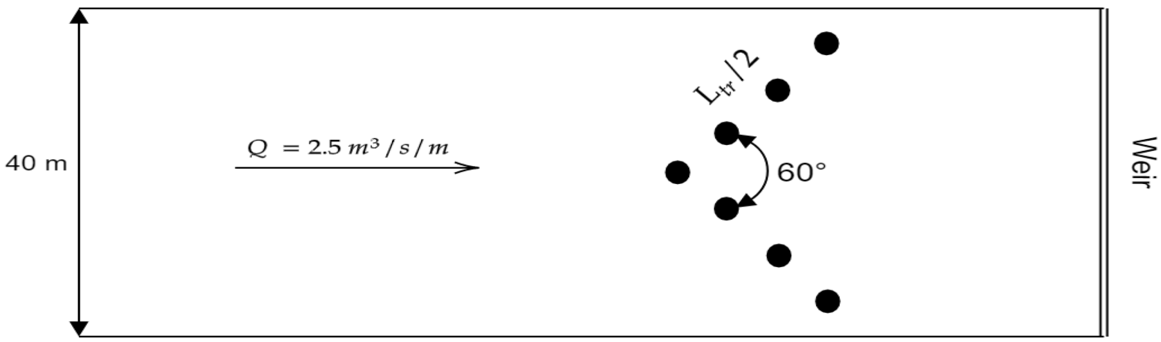


Figure 11 – Trash rack upstream from a weir in Arzbach, DE.

The dimensions that <u>may not</u> be used for the bars, in order to avoid resonance, can be calculated assuming a square cross-section of side b. It will be further assumed that the bars will be fixed only at the bottom of the channel, and the bars are made of steel. The calculation is as follows:

$$0.4\frac{1.72}{b} = \frac{\pi^2}{2\pi}\sqrt{\frac{210\cdot 10^9\,(b^4/12)\,9.81}{8050\cdot 1.54^2 b^2}} \therefore\ b\ = 0.012\,m$$

Notice that one can manipulate the resonance frequency of the element by *shortening* its wavelength, that is, by setting traverse beams (side-bearing trash racks). The end conditions are changed and now the length of the element is measured between the end conditions. It can be easily shown that the length of the square resonant bar is proportional to the area cross section, that is:

$$l \propto b^2$$

2.2.4 Trash screen inclination

The inclination of trash racks with respect to the direction of gravity responds mainly to safety measures during cleaning and, to a lesser extent, reducing the chance of debris lodging in the screen. On the former, several agencies and authors (Bureau of Reclamation 2016; J. Benn et al. 2019) suggest inclination angles that vary between 45° and 60°; such angles ease manual raking by putting part of the debris' weight onto the screen while picking it up.

The problem of putting the screen in an inclined angle is that it may increase the chance of partially submerged debris lodging onto the screen, due to the friction force acting between the screen and the debris balancing the screen-parallel *apparent* weight of the debris patch, and the incoming flow momentum force acting on the patch. Such debris patch might dislodge if the friction force (which is function of the apparent weight of the patch) becomes lower than the apparent weight component. This relation, however, becomes complex as it depends on the porosity of the debris and the screen itself. Experiments conducted by the USACE (Watterstein, N. Thorne, C. R. Abt, S. R. 1997) suggest to place trash racks with inclinations no higher than 1:3 (h:v) in order to avoid floating debris to lodge in the screen. Such inclination may prove difficult for manual cleaning operations, as discussed previously.

2.3 Head losses across trash racks

The backwater effect caused by setting a trash screen in the water course may be easily detemined using classical tools in hydraulics. Imagine two sections, one before and one after the trash rack, for convenience denominated as 1 and 2. Using Bernoulli's equation one can determine the water depth upstream of the trash rack in the following way:

$$h_1 + \alpha_1 \frac{U_1^2}{2g} = h_2 + \alpha_2 \frac{U_2^2}{2g} + \Delta h \tag{2.8}$$

where h, α, and Δh are the water depth, energy correction factor, and height drop due to the trash rack and other sources, respectively. The energy correction factor is usually ignored in most calculations, as these are assumed negligible compared to either the friction or lumped with the form/local losses along a channel. Sometimes, however, given the proximity between sections (sufficiently close to ignore friction losses), α needs to be calculated. For the flow approaching the trash rack, one can assume $\alpha_1 = 1.05$ as it is common for normal subcritical flows. For the flow downstream from the trash screen one may calculate the energy coefficient in the following manner:

$$\alpha = \frac{1}{U^3 A}\int u^3 \; dA \approx \frac{1}{U^3 A}\sum u^3 \Delta A \cong \left(\frac{A_{tot}}{A_{eff}}\right)^2 \tag{2.9}$$

where u, A_{tot}, and A_{eff} are the local velocities, the total wetted area of the channel section where the trashrack is placed, and the total area sum of the bar openings in the screen, respectively. The A_{eff} is taken perpendicular to the mean flow direction. Notice that whenever the energy correction coefficients are used, one should assume the form losses due to the trash rack equal to zero, because there are implicitely assumed in α. It does not make sense to correct the kinetic head and then add form losses for the same local perturbation in the flow streamlines.

On the other hand, whenever the downstream section is sufficiently far away from the trash rack one may calculate the head drop caused by the trash rack, and set $\alpha_2 = 1.05$, in the following manner (Bureau of Reclamation 2016):

$$\Delta h = \left[1.45 - 0.45\left(\frac{A_{eff}}{A_{tot}}\right) - \left(\frac{A_{eff}}{A_{tot}}\right)^2\right]\frac{U^2}{2g} \tag{2.10}$$

Notice the resemblance of the coefficients in equations 2.9 and 2.10: the latter equation corrects (reduces) the coefficient that corresponds (roughly) to the energy loss across a weir (1.5 E_0) which, at the same time, represents an extreme case for trash rack energy losses; the former corrects for the acceleration due to the flow constriction of the flow, without considering the flow may also spill from the top. Given the theoretical consistency of the aforementioned equations, the author suggests their use. Nonetheless, the author has done an exhaustive review of the different semi-empirical equations proposed for the calculation of form losses due to trash racks, and found equation 2.10 to be the simplest and most conceptually sound.

This method can be extended in order to consider clogging, by just pre-multiplying the ratio A_{eff}/A_{tot} by the blockage ratio D presented in Chapter 2. A visual representation of the method is presented in Figure 12. One may estimate the energy losses of partially clogged screens if one admits the methodology condensed in Figure 7 valid for measuring clogging: the blockage ratio can be understood as percentual reduction on the effective screen area due to clogging caused by floating debris. It must be stressed that the methodology for the calculation of debris blockage (Figure 6) was calculated in terms of *probabilities*, that is, a blockage of 55% means that there is a 45% chance that slender elements of length of at most 5cm (see previous examples) would not pass. In that sense, it is not strictly correct to use the blockage ratio as a percentual reduction of the effective area due to clogging.

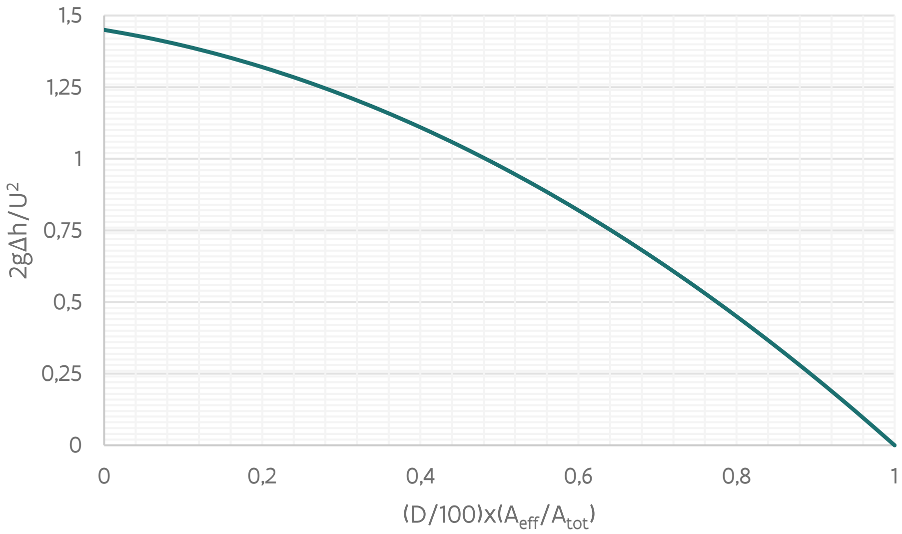


Figure 12 – Dimensionless head drop as function of clogging and area ratio, following equation 2.10.

Worked-out example: local losses at end-bearing trash screen intake in Arzbach river, DE

The calculation of the local losses produced by the screen may follow either from equation 2.9 or equation 2.10, depending which energy grade line one decides to follow (to go along the river or to go through the intake). Assume one needs an estimation of the water drop just after the trash rack. The unit discharge passing through is 2.5 m^3/s/m and the depth just before the screen can be set at 1.53 m. The dimensions of the trash rack bars is taken as 5 cm, and the spacing was determined to be 5cm as well. The effective area of the screen is equal to:

$$A_{eff}/A_{tot} = 2(1.53\, m \times\ (40\, m\ \times\ 0.5 \sin 30°))/(1.53 \times 40) = 0.5$$

And the head drop caused by the clean screen is:

$$\Delta h = (1.45 - 0.45 \cdot 0.5 - 0.25)\ \ 2.5^2/(2 \cdot 9.81 \cdot 1.53^2) \cong\ 0.133\, m$$

The effective area of the screen when partially clogged by floating debris (55%, calculated earlier) becomes:

$$\left(A_{eff}/A_{tot}\right)_{clogged} = (D/100) \times \left(A_{eff}/A_{tot}\right)_{clogged}\ = 0.55 \times 0.5\ =\ 0.275$$

then the head drop caused by the (partially) clogged trash rack is equal to:

$$\Delta h = (1.45 - 0.45 \cdot 0.275 - 0.076)\ \ 2.5^2/(2 \cdot 9.81 \cdot 1.53^2) \cong\ 0.150\, m.$$

3 Flow diversion as mechanism for trash exclusion

Up until this point, the design paradigm for trash collection facilities herein proposed has been for (some) debris to be trapped, or diverted, and then collected/cleaned later. The methodologies that have been presented until now show that such paradigm is filled with uncertainties and this reflects at every step of the design process, particularly in the quantification of the debris amount and bar spacing, all based upon “statistically-adjacent” hydrological arguments. One may argue whether the calculation of such quantities is pertinent at all, and whether one can propose a different approach to the problem without resorting to such methodologies or, at least, not directly depend on them. One may propose a design solution that *diverts the flow* needed to operate the intake instead of diverting/trapping debris, that is, to separate both flows. Notice that such *trash exclusion facilities* may either drain part of the total flow of the canal, or may transbase the whole flow from it. Examples for both scenarios will be given later on.

Notice that the quantification of the debris amount used in the aforementioned methods work under the assumption that such debris will *accumulate* at the trash screen, and then cleaned on a regular basis. If the debris flow is separated in a way different from percolation one may dispense of the debris amount as a quantity needed for the design.

This chapter will explore different methodologies based on the idea of *flows diversion* (or trash/fish exclusion): this implies that one considers possible to separate useful water from debris flow (water plus debris runoff) just by using gravity and the flows’ own inertia, and to exclude fish. Such assumption is not new: is often used in sanitation engineering for separating wastewater from “clean” water, and in mining operations to separate ore from washing by-products. Notice this notion doesn’t exclude the diversion of a whole watercourse or flow, either.

3.1 Side screens

Unknowingly, the worked-out example in Section 2.1.1 can be designed directly as a side weir – see Chow (1959) for details – if one aligns the entrance with either channel’s bank, and then place a standard trash rack comprising the opening according to the the criteria for dimensioning the trash rack given in the Introduction. Notice that side intakes and weirs have low chance of catching debris, so long the attraction currents towards the intake, or spatial accelerations towards them, are not too high. In Chapter 4, details on the approach flow velocities suggested for fish passage and exclusion will be discussed in further detail.

The problem is that the approach velocities in wide rivers and channels are too low (or during dry seasons) compared to the attraction currents produced by the side intake, hence debris attraction is very likely. In those cases it might be necessary to set debris booms or rakes surrounding the entrance.

3.2 Bottom Screens

If one admits that all debris passing the intake is buoyant, then one can avoid trapping debris just by placing the intake at the bottom of the channel. Furthermore, if the flow past the bottom screen is supercritical the debris flow may have enough momentum to escape the attraction flow produced by the bottom drainage. Notice that the method assumes the discharge downstream from the screen is greater than zero. A sketch of a bottom drainage is shown in Figure 13. Spatially varied flow, such as the one being discussed, may be modelled using the following relation (Chow, 1959):

$$\frac{dy}{dx} = \frac{S_0 - (Q/gA^2)(dQ/dx)}{1 - Fr^2} \tag{3.1}$$

where S_0, and **Fr** are the channel's slope, and the Froude Number, respectively. Notice that the openings on bottom intakes hamper the formation of a boundary layer, hence it is safe to neglect friction losses in such calculations. This means the specific energy remains *unchanged* across the bottom screen. An outflow relation for the flow exiting the screen may be determined using Torricelli's formula:

$$-\frac{dQ}{dx} = \varepsilon C_r b\sqrt{2gE} \tag{3.2}$$

Where b, C_r, and ε are the channel's width, the screen's loss coefficient, and the *porosity* of the bottom plate, respectively. The porosity may be measured as the ratio of the opening area to the total area. Combining equations 3.1 and 3.2, neglecting the slope, and by integrating (up to a constant) the resulting equation one gets the following:

$$x = cte - \frac{y}{\varepsilon C_r}\sqrt{1 - \frac{y}{E}} \tag{3.3}$$

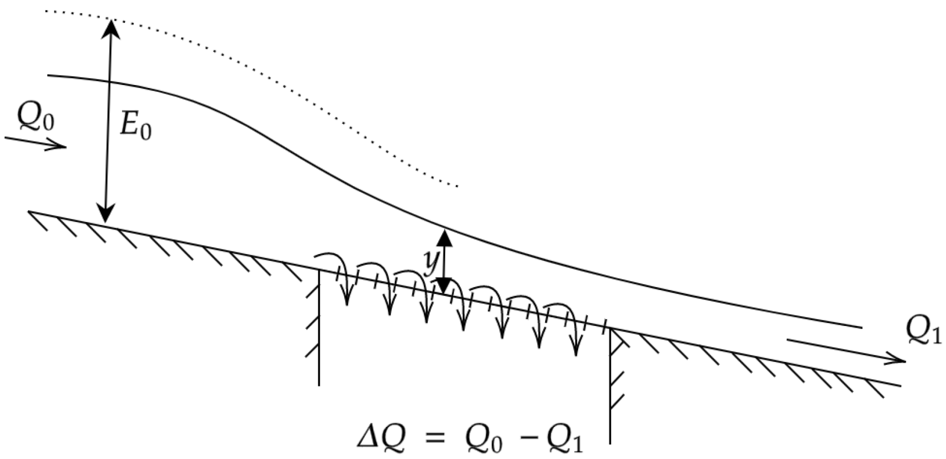


Figure 13 – Flow through a bottom screen.
Floating debris is expected to be washed away by the flow in the channel. Q is discharge and E is specific energy.

If the hydraulic control is upstreams from the bottom screen, then determining the constant in equation 3.3 is straightforward. Otherwise a trial-and-error approach must be followed to determine the constant. Notice Q_1 is not directly obtained from the method, instead one has to resort to the specific energy (which remains unchanged) and the depth downstreams from the bottom screen to determine it.

Worked-out example: bottom screen in Arzbach river, DE

One may propose of using a broad-crested weir, instead of a trash screen, to separate debris flow from the flow needed at the intake. Suppose that one has to guarantee a minimum of 2 m^3/s of ecological discharge to flow in any channel diversion. This implies that the weir proposed in Section 2.1.2 must be widened to (12 m^3/s / 2 m^3/s/m =) 6 m. The flow needed for the intake is still 10 m^3/s. Calculate the length of the bottom screen needed to be placed on the floor of the weir in order to supply the intake, assuming a porosity of 0.05 and a form coefficient C_r = 0.35.

Solution:

First, find the constant in equation 3.3:

d) Specific Energy at the weir's crest E = (3/2) 0.7415 m = 1.112 m, then the constant is equal to:

$$cte = \frac{y_c}{\varepsilon C_r}\sqrt{1-\frac{y_c}{E}} = 24.463$$

e) Since the energy is kept equal across the channel, then the depth downstream from the bottom channel is:

$$E = y + \frac{Q^2}{2gb^2y^2} \therefore\ y \cong\ 0.073\,m$$

f) The length of the bottom screen may be calculated using equation 3.3:

$$x(y = 0.073)\ =\ 24.463\ - \frac{y}{\varepsilon C_r}\sqrt{1-\frac{y}{E}} \approx\ 20.50\,m$$

The screen must be 10-by-20.5 meter. The total opening length must be equal to 205 x 0.05/10 = 1.025 m, which accounts for a total of around 195 square bars of side 10 cm traversing, spaced 5 mm from each other. The velocities on the floor of the weir range between 2.7-4.5 m/s, corresponding to the critical water depth before the screen and the depth at the end of the screen. More precisely, the minimum *slot Reynolds Number* is (U d / v = 2.7 * 0.005 / 1e-6) = 13500; a minimum of 1000 is required for self-cleaning. A sketch of the intake is presented in Figure 14.

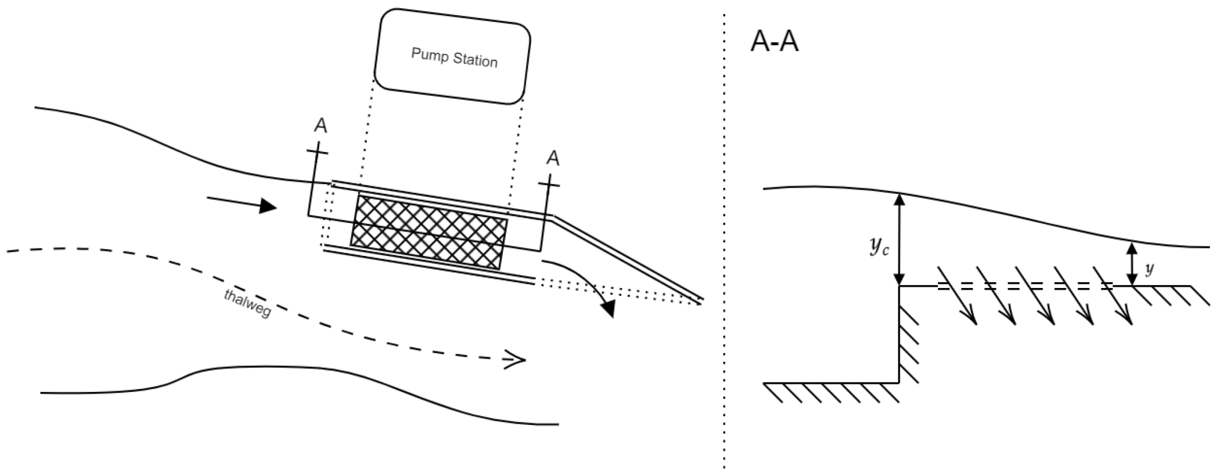


Figure 14 – Design sketch of a broad-crested weir placed in Arzbach river.
Notice that along the weir a bottom screen is placed in order to divert 10 m³/s of flow towards the pump station. A security screen is needed upstream from the weir's entrance to ward off vessels and other very large objects that may pass through it.

A more efficient form of separation would be setting a bottom screen on a sloped channel which will then reduce the chances of debris clogging the bottom screen even further. The calculation of spatially varied flows in steep channels may require the numerical integration of equations 3.1 and 3.2 simultaneously, since now it is required to set S_0. A simple finite-difference algorithm may be proposed for this problem. As the channel becomes steeper, one may need to slightly tilt the screen bars in order to force the flow's diversion across the screen, since too high velocities may produce the flow to *skim* along the screen. Such tilting will add differential discharge proportional to the tilted area projected onto the plane orthogonal to the flow direction.

3.3 Interlude: contingencies for clogged trash racks

Part of the discussion on the design of trash collection facilities in Chapter 2 was put on hold, in particular the design of contingencies for clogged trash racks, until the basics of flow across bottom screens were presented. The methodology for bottom screens will serve as a basis for the dimensioning of contingencies for clogged trash racks. The suggestions herein presented follow, at least partially, Benn et al. (2019); however, the are some fundamental differences. This is the reason why the discussion was held until this point.

The screen area, calculated using equation 2.1, assumes the trash screen is supposed to be cleaned after each *significant event* (E) during a yearly-period. If the screen area is completely clogged while still blocking the intake, flooding is very likely to happen. It is also possible that under heavy rains a water surge will form along the channel while carrying all kinds of debris which may lodge on the trash screen, and block it. At this point it is clear that such scenario must be avoided, and contingencies have to be put in place whenever is not possible to guarantee flow passage through the intake. Benn et al. (2019) proposed to set part of the trash screen area horizontally, in order to avoid flow choking in case the frontal screens clog. The hydraulic assessment of such scenario assumes the horizontal part of the trash rack will work as an *orifice* which, by definition, assumes the approach velocity to be equal to zero (or the trash rack to be fully submerged). Notice that under such conditions the flow regime of the conduit downstreams will be forced to be that of an outfall, with its inlet *fully submerged*, causing the flow in the culvert to be partially (or fully) pressurized. The author opinion is that such scenario is better avoided and one should seek reducing backwater effects, or water level rises upstream due to clogging.

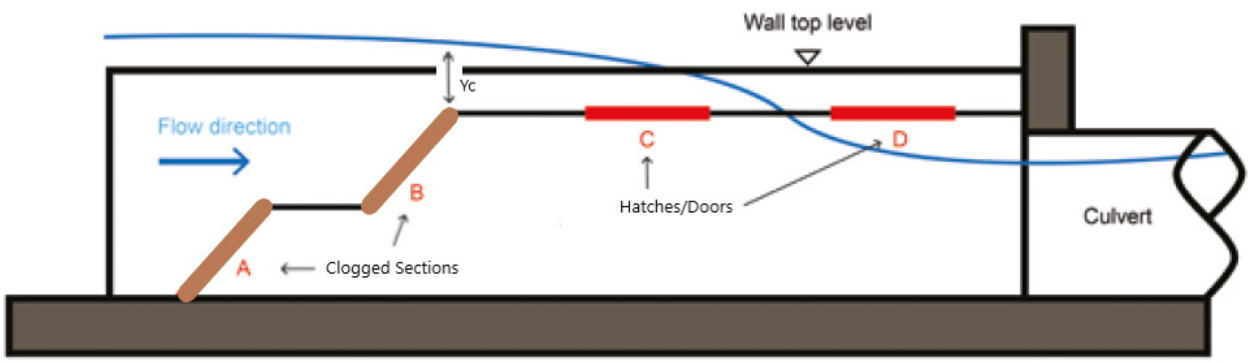


Figure 15 – An integral trash rack for the intake of a culvert (J. Benn et al. 2019).
The inclined screens are assumed fully clogged, and water passes only across the horizontal screens.
Screens A and B are calculated using equation 2.1, the top horizontal screen is dimensioned using equation 3.3.

Given the high uncertainty of the *Debris Load Method* (J. Benn et al. 2019; Blanc, Janice 2013) described in Chapter 2 and the suggestions just given, the author proposes a different methodology to dimension the horizontal sections of the trash rack assuming these may eventually have to drain the bulk of the flow in case the vertical trash screens become clogged.

During the discussion about energy losses, it was mentioned that an extreme scenario of trash rack operation is when the bar spacing is reduced to an infimum, that is, the trash rack works as if it were a weir. One may assume the latter as a surrogate for trash screen clogging, that is, for the screen to work as a weir when debris is not removed in a timely manner. A very similar scenario was, incidentally, just presented in the last worked-out example (see Figure 14). There, a superelevation was proposed and a revited bottom screen suggested, from where part of the discharge will be taken. Similarly, one could then propose a horizontal screen below the free-surface (unclogged), forming a *cage* (or integral trash rack). The length of the horizontal screen may be found using equation 3.3, assuming that the vertical trash rack is fully blocked, a hydraulic control is formed in the edge between the horizontal and vertical/inclined screen, and all discharge is assumed to go through the horizontal screen. The total screen area, calculated using equation 2.1, may be distributed amongst the horizontal and vertical/inclined screens.

A sketch for integral trash racks in culverts considering overflows, or clogging, is presented in Figure 15. Notice the techniques for dimensioning the horizontal proposed herein differs from the one discussed in (J. Benn et al. 2019): there an orifice/weir equation is proposed to determine the discharge that goes through the horizontal screens given certain degrees of blockage (which translate in energy losses) in the vertical/inclined screens. Such assumption is valid whenever the culvert's inlet is fully submerged which, whenever possible, should be avoided. Here, a *worst scenario approach* is chosen, where all flow must go through the horizontal screen in case of full clogging, and the flow in the culvert is never (neither partially nor fully) pressurized.

3.4 Coandă Effect Screens

One could go one step further and propose short ogee-crested spillway: this creates a hydraulic control upstream from the bottom screen, which makes calculations easier for the reasons explained earlier, and by further setting a concave tailrace one can take advantage of the Coandă effect so to guarantee flow attachment towards the screen, and further acceleration to the debris flow. One additional advantage of setting an ogee-crested weir is that it blocks sediment and bedload to go through the screen. By setting rakes upstream from the weir, one may further trap very large trunks and garbage that may travel downstream. Furthermore, it is suggested that the *bar opening Reynolds number* (=Ud/ν, d: bar opening) be greater than 1000 to guarantee self-cleaning (Wahl and Einhellig 2000).

The Bureau of Reclamation (Wahl 2001; Wahl and Einhellig 2000) has extensively studied the problem of flow diversion through Coandă screens (see Figure 16). They have prepared a freely-available software (HERE) for the dimensioning of such screens, using a simplification of the theory of spatially varied flows and equation 3.2. Details on the approach proposed by Wahl (2001) will not be discussed here thoroughly. However, for the sake of completeness, it's worth mentioning that Wahl (2001) have conducted a detailed experimental study on the determination of the discharge coefficient C_r, which is shown in Figure 17. Notice that the orifice coefficient is function of the form of the bars, the openings, the tilting of the bars, the incident velocities towards the bars, and centripetal force. Furthermore, this coefficient lumps together the contributions arising from the bar tilting and of the bar openings. In case one decides not to tilt the bars, then this coefficient is too large and must be corrected. In the following chapter, a complete example of a Coandă-type screen will be given.

The methodology can be made mathematically rigurous, by simply changing to a polar coordinate system when deriving the energy equation for spatially varied flows:

$$\frac{d\,E_\alpha}{d\,s} \equiv \frac{d\,E_\alpha}{d\,\theta}\frac{d\,\theta}{d\,s} = \frac{1}{r}\frac{d\,E_\alpha}{d\,\theta} = 0, E_\alpha = y\,cos\,\theta + \alpha\frac{V^2}{2g} + G_0 + \frac{V^2 y}{rg}$$

where s, r, and G_0 are the linear dimension along the bottom of the channel, the radius of curvature, and the height of the bottom, respectively. Notice the energy equation considers curvature. A full derivation is out of the scope of this work.

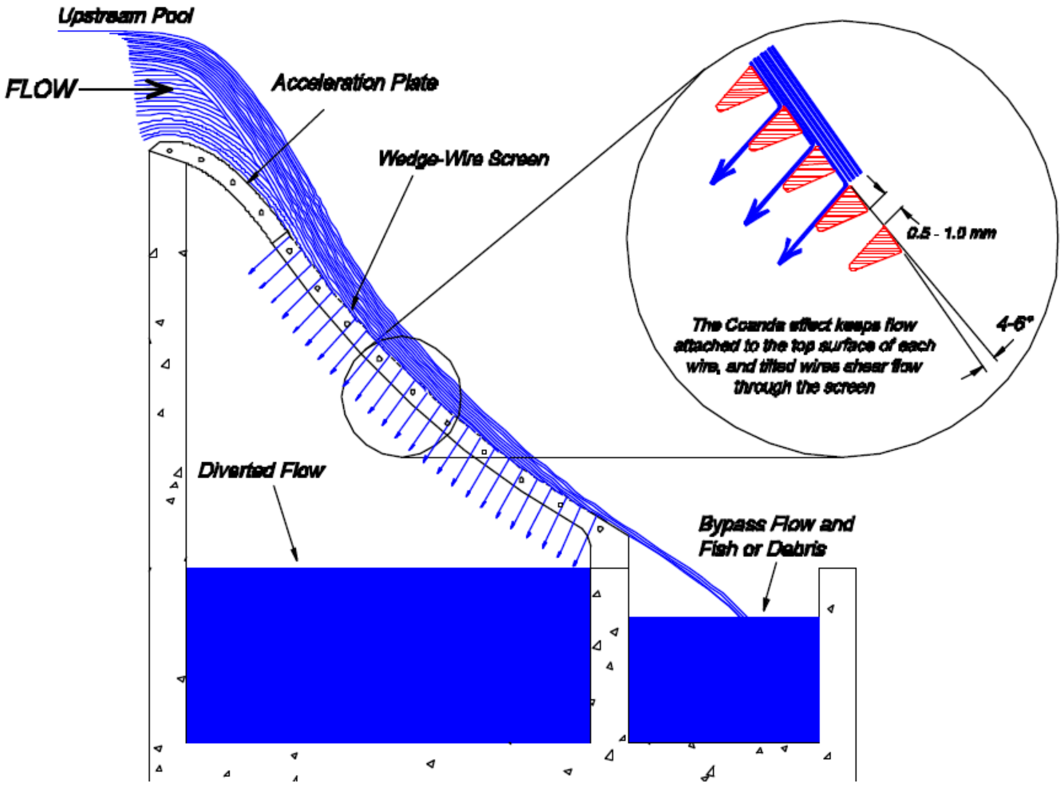


Figure 16 – A Coandă-type screen schematic mounted on an ogee-crested spillway.
Notice how the screen bars are slightly tilted in order to avoid the flow to skim through the screen.

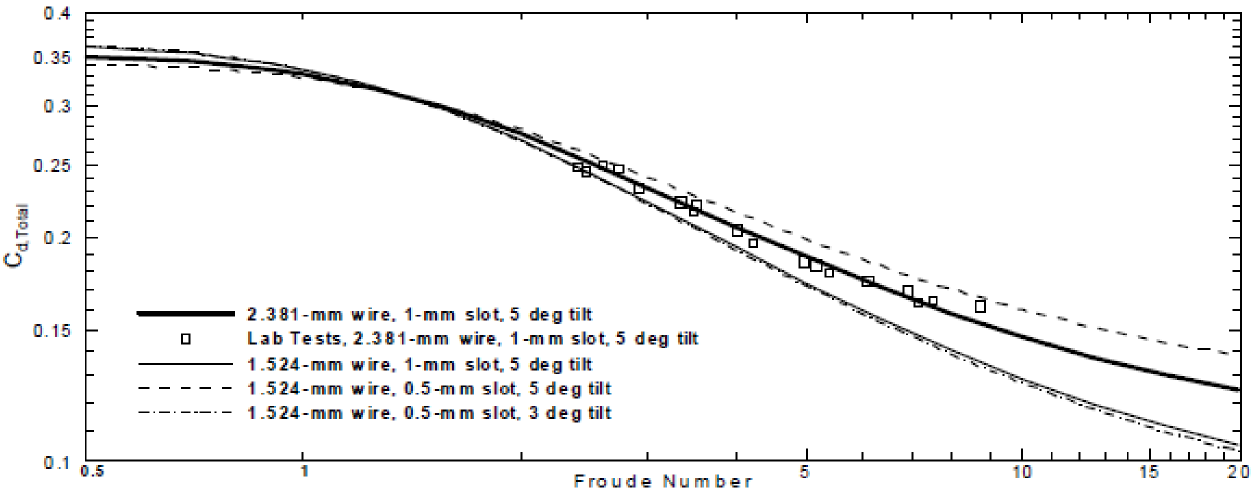


Figure 17 – Orifice Coefficient for Coandă-type screens.

4 Fish Migration

Fish migration is considered a behavioural process mediated by so-called genetic tyranny: that is, fish migration patterns, timing, speed, distance, and destination are phenotypical expression of their genotypical traits. On the other hand, fish deterrence/exclusion and diversion represent anthropogenic attempts to affect the volition of fish to take a certain path by either deterring it to go through said path or by generating favourable conditions for its passage.

The requirements for diversion/deterrence of adult fish, eel and juveniles through anthropogenic passages along their migration path are dependent on the species present in a watercourse, their age, and their rheotaxis. However, requirements for different species may contradict with each other and force to retrofit an existing structure into excluding certain species while letting others pass. Thus a first fundamental part on the design of "fish-friendly" structures, in particular intakes for pumps and culverts, is to make an inventory (a taxonomy) of the species that are present in the water course. With this inventory, an assessment on whether a fish passage (or collection) facility is required can be conducted. A distinction needs to be made: it is common that flow through culverts allow for the passage of fish, whereas it is not as usual to let fish go through mechanical equipment, such as pumps or turbines; in the latter case one may give some allowance to adults (at low stator speeds) and juveniles (smolts and fries) to go through turbines, for example. As it will be presented later, some pump stations in Flanders have opted to convey all fish migration through the pump stations.

Some suggestions for fish/mammal exclusion screens were given earlier. First a description on fish volition and favorable flow characteristics for different types of structures is given. Then, a discussion over different types of screens is presented along with worked-out examples.

4.1 Fish volition and Flow Characteristics that affect Migration

Different aquatic species base their rheotaxis (swimming patterns) on different mechanisms. These mechanisms induce a behavioral response to certain flow patterns, and environmental stressors. Without loss of generality, current velocities can be taken as the primary criterion for the study of fish volition and, by consequence, used as a threshold for the design of man-made structures affecting natural migration paths.

The work of Coenen et al. (2013) relates the maximum current velocities against which a fish can swim against with the design of fish passages. There, the basic criterion is that the flow velocity must not exceed the maximum escape velocity of the fish, or the top speed at which a fish can swim. With this criterion in mind, a classification of the type of flows present and its effect on the fish's endurance while passing through it is presented in Table 4.

The maximum escape velocity varies between fish species, and some are suggested for in Flanders (Kroes et al. 2005; Coenen et al. 2013). In particular for fish passage design in Belgium and the Netherlands maximum sprint speeds between 1 to 1,5 m/s are suggested. For normal speed both works recommend no more than 0.5 m/s.

Table 4 – Flow velocity classification according to fish volition/endurance. (Coenen et al. 2013)

Type	Description	Durance
Top speed	Reached with intense effort, leads to exhaustion, not favorable for fish pass design.	Very brief (< 1 sec.)
Sprint speed	To surpass obstacles, for a brief period of time. value for design of weirs, slots and orifices.	Brief (< 15 sec.)
Increased speed	Can be maintained for some time, for instance to pass a more difficult route.	Short (> 15 sec.)
Normal speed	Endurable over longer distances without exhaustion.	Long (> 200 min.)

Notice that fish 'endurance' and 'volition' are different in meaning: one refers to an imposed stressor while the other can be thought of as a 'choice' or a response to environmental or genetic factors guided by self-preservation.

Other parameters may affect fish 'volition', and should be consulted to the corresponding fisheries entities and stakeholders. For example, aquatic species like European Eels and Salmons are quite sensitive to illumination (or lack thereof), and the channel's wetted perimeter "smoothness". Salmons tend to avoid dark areas, and Eels being near-bed swimmers avoid swimming over smooth surfaces (concrete, for instance). Additional measures for these species may be needed.

4.1.1 Fish volition through Screens

As a rule of thumb, three basic criteria have to be taken into account when designing screens: (1) minimum ecological water depth and discharge, and (2) maximum velocities in the watercourse, (3) and bar spacings of trash racks and fish barriers. On the first, such values must be consulted with the corresponding environmental agency. On the second aspect, the maximum velocities/accelerations in the flow are needed to determine the deterrence that the flow may impose to the fish. In some cases one may want to deter swimmers to take certain paths; in other cases, however, one may need to generate strong enough currents to attract, or guide, swimmers towards a certain path. Environmental regulators in France suggest to keep velocities no higher than 0.3 m/s when approaching to a fish barrier, to avoid injuries in salmon smolts and fries (Benvegnu 2021). In general, these aspects require first a hydrological assessment of the watercourse, involving the discharges with flow exceedance of 30%, 90%, and 95% (J. Benn et al. 2019). However, such percentages are determined by the admissible risk of failure of the fish passage, that is, the percentage of time that the environmental authorities allow for the fish collection facility to not operate (Bureau of Reclamation 2006). On the third and last aspect, bar spacings in trash racks for fish exclusion (barriers) are dependent on the direction where migration is expected, and the type of fish. For salmon smolts minimum spacings can be as low as 12 mm, and for the European eels up to 3 mm have been proposed (Benvegnu 2021). The Bureau of Reclamation (Bureau of Reclamation 2006) suggest that fish exclusion screens should have openings no greater than 5 cm.

4.1.2 Fish volition through Culverts

The Environmental Agency (J. Benn et al. 2019) has prepared some rules on the flow patterns based on the swimmer's resistance to follow a certain current/path within a culvert. Table 5 gives an overview of general recommendations from Benn et al., 2019 for flows within culverts that may allow swimmers to pass (upstream/downstream migration). Notice for Belgium and the Netherlands target species are mostly in the first two categories (low land river systems). Usually four types of flow velocities are taken into account for each of the target species, see Table 4.

Table 5 – Maximum mean-flow velocities within culverts that may allow fish to pass through (J. Benn et al. 2019).

CULVERT'S/FISH PASSAGE'S LENGTH (M)	COARSE FISH ROACH, CHUB, ETC; SMALLER THAN 25 CM (M/S)	BROWN TROUT AND COARSE FISH UP TO 25 CM AND LARGE COARSE FISH UP TO 50 CM (M/S)	SEA TROUT AND BROWN TROUT UP TO 25 CM AND LARGE COARSE FISH LARGER THAN 50 CM (M/S)	SALMON AND LARGE SEA TROUT LARGER THAN 50 CM (M/S)
< 20	1.1	1.25	1.6	2.5
20 – 30	0.8	1.0	1.5	2.0
>30	0.5	0.8	1.25	1.75

4.1.3 Fish volition and pump station in Flanders

Research on the upstream/downstream migration patterns of different aquatic species (Silver Eel, in particular) on some watercourses in Flanders have shown that standard Archimedes-type pump stations form an effective barrier to their migration, and 'fish-friendly' pumps are needed to guarantee a high survival rate (Buysse, Coeck, and Mouton 2014). Since the purpose of such pump stations is to transbase the whole water course to another, the installation has to guarantee fish migration along the system as well. The option that has been common in Flanders has been to allow fish to go through the pump station, hence any trash rack installed at the intake of the structure must allow fish to go through it. The minimum bar spacing for fish migration through trash racks are shown in Table 6.

Table 6 – Minimum screen bar spacing for upstream/downstream migration of fish.

SOURCE	COARSE FISH ROACH, CHUB, ETC; SMALLER THAN 25 CM (CM)	BROWN TROUT AND COARSE FISH UP TO 25 CM AND LARGE COARSE FISH UP TO 50 CM (CM)	SEA TROUT AND BROWN TROUT UP TO 25 CM AND LARGE COARSE FISH LARGER THAN 50 CM (CM)	SALMON AND LARGE SEA TROUT LARGER THAN 50 CM (CM)
(J. BENN ET AL. 2019)	10	10 to 15 (coarse fish)	15	20
(BUYSSE, COECK, AND MOUTON 2014)	8 to 10			

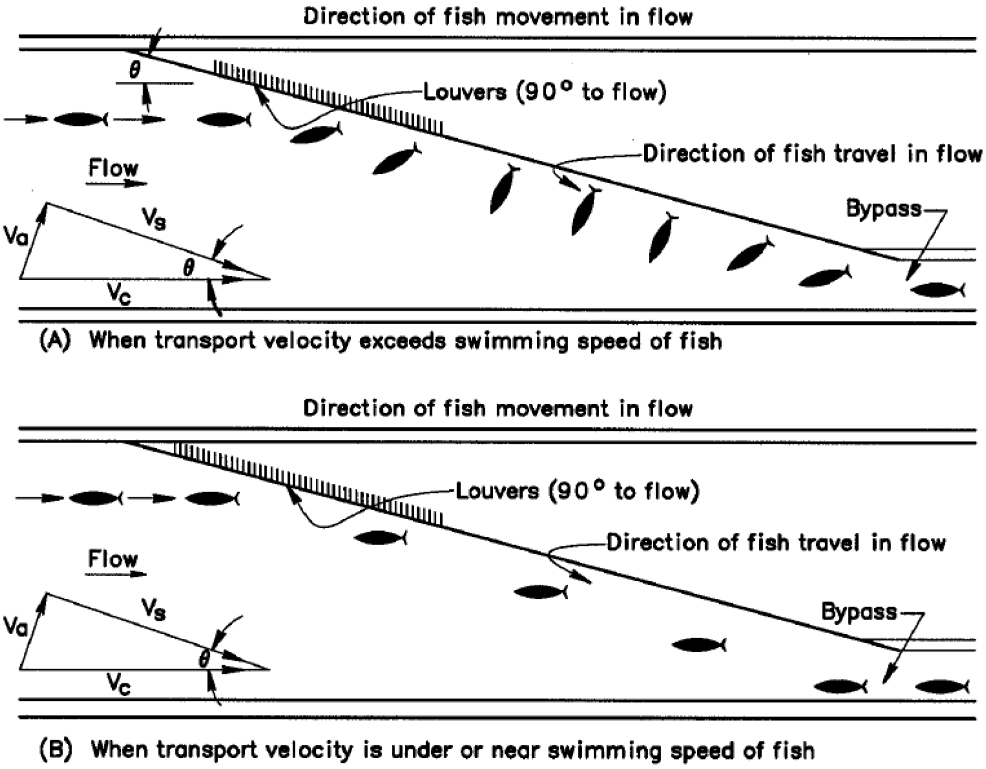


Figure 18 – Diagram illustrating reaction of swimmers to louvers under different flow conditions.

Figure 19 – Flat v-plates, including mechanized screen cleaners (not necessary).

4.2 Fish deterrence and diversion structures

Given the great variability in the requirements for the different fish species, there exist a myriad of fish exclusion/guidance structures that may be proposed, and different methodologies are suggested in the literature. A rather complete treatise on fish diversion facilities is given by the Bureau of Reclamation (Bureau of Reclamation 2006), including design examples and post-construction assessments for many kinds of structures. The author will not attempt to reproduce their work here; instead, some general notions will be given. There, a general classification of fish exclusion structures is given as follows:

1. **Behavioral:** A behavioral barrier requires the volitional action on the part of the swimmer to avoid entrainment. In other words, such barrier generates a deterrence for the fish to avoid a path. This barrier may include the use of passive (non-hydrodynamics related) deterrence techniques, such as bubbly walls, electricity, sound, illumination, and chemical agents (Noatch and Suski 2012).
2. **Positive:** A positive barrier physically prevents the swimmer from being entrained at the intake.

Rather, some examples for each type of structure proposed there will be discussed here given the relation these have with some of the techniques already discussed in this work. The following fish diversion screens may be considered:

a. **In-channel louvers:** a type of behavioral barrier, somewhat similar to a vertical trash rack, that produces fish deterrence by inducing turbulence. Increased turbulence is generated by arranging the louver slats in a particular way. The louvers effectiveness varies as a function of fish species, fish life stage, fish size, and fish swimming strength.
b. **Bottom screens (including Coanda screens):** Type of positive, and sometimes behavioral, barriers in which the intake is placed at the channel's invert (see Figure 18). Chapter 3 discusses the technical details involving their design. An example will be given later.
c. **Flat v-plates**: Type of positive barriers where the channel is constricted via vertical fish screens, towards an inlet that funnels fish into a collection of passage facility (see Figure 19). The design of the flat panels follow the theory of "spatially varied flows" for lateral outlets.
d. **Vertical screen with bottom opening**: a combination of positive and behavioral barrier where a vertical screen (or trash rack) spanning the water column has a bottom opening where fish are allowed to go through. The bottom opening is usually set 30 cm high, from the bed of the channel.

Worked-out Example 1: end-bearing trash rack at intake in Arzbacht River, DE

In previous examples, a bar spacing of 5 cm was proposed for the trash screen at the intake (either side intake, or the full diversion). In the case of having only a side intake, fish exclusion is preferred, whereas for the river diversion through the weir fish migration must be allowed. According to Table 6, 5 cm is too small for fish migration, hence the bar spacing for the screen in the diversion has to be set to 10 cm, at least, but we may allow also small mammals to pass, hence a final bar spacing of 15 cm is chosen. According to Figure 7, the blockage ratio of the screen becomes around 20%.

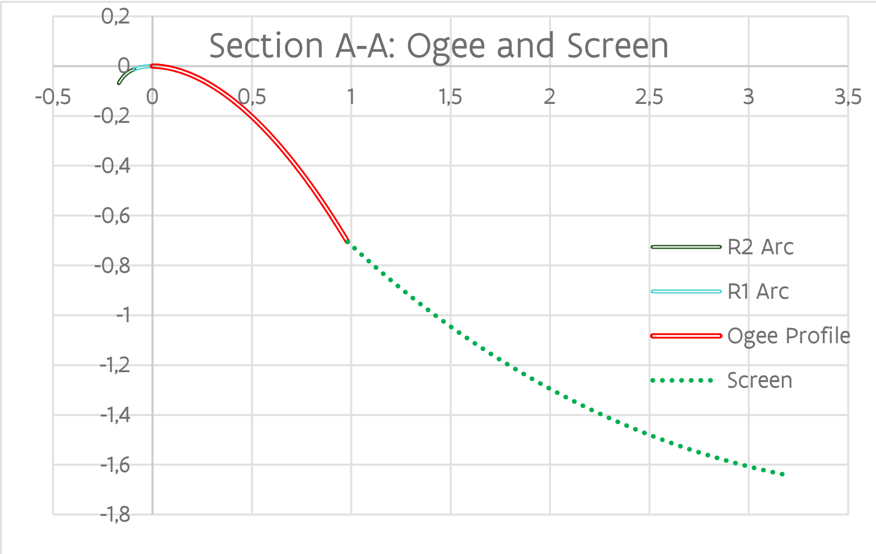
Worked-out Example 2: Coandă Screen and Fish Collection Facility for pump station

Suppose a pump station transbasing a channel to a higher level needs to meet environmental requirements regarding fish migration, but also has been presenting efficiency problems due to debris clogging. The channel is rectangular of 5 m width, and 1.455 m deep, carrying 8.5 m^3/s of water. Of the total discharge, around 500 lt/s are needed to feed the fish facility. Design the intake facility using Coandă-type screens, and draw a plan of the project considering debris and fish collection structures.

Solution:

Here, it is assumed that preserving the existing infrastructure is preferred (as opposed to changing all pumps) and that additional facilities for debris collection and fish passage are to be proposed. The fish collection facility (or passage) is left indicated: their detailed design is out of the scope of this work.

g) **Step 1:** An ogee-crested weir is to be placed transversally across the channel, at an angle of 45° with respect to the axis of the channel. The crest of the weir is to be placed at 0.8 m above the channel's bottom, so that 0.8 m + H_0=1.455 m, where H_0 is the design head of the weir. The design parameters and dimensions for the ogee-crested weir are given in Figure 20. Details on the methodology are given in any standard book on hydraulics and will not be repeated here.



Ogee Crest Design Details (See Chow, 1959)

- Design unit discharge = 1.143 m^3/s/m
- Weir height above approach channel invert, P = 0.800 m
- Design head, H_d = 0.655 m
- Discharge coefficient at design head, C_0 = 2.155 m^0.5/s
- Approach arcs
  R2 = 0.4499 m
  (R2 is centered at X=-0.1814, Y=-0.4762)
  R1 = 1.089 m
- Ogee profile equation: $y = -(0.51 \times 0.6551^{-0.848}) \cdot x^{1.848}$

Figure 20 – Profile of the Ogee-crested weir and Coandă screen. Notice that the frame of reference is at the crest of the weir.

- **Step 2:** The calculation of the discharge passing the Coandă screen is not a direct process, that is, one must calibrate the different parameters in order to obtain the desired discharge. Using the computer program described earlier, one can obtain the desired discharge by manipulating different parameters. The parameters used for dimensioning the Coandă screen are given in Table 7. There, the angle where the arc screen begins with respect to the horizontal is Θ_0; the arc's angle and radius are Θ_s and R, respectively; and W_0 is the width of the weir. Notice that the screen opening selected (5 mm) is supposed to retain most incoming debris. However, for the satisfactory operation of the screen, very large debris (greater than H_d) must be retained before entering weir.

Table 7 – Selected input dimensions for the positioning of the Coandă Screen, and the sizing of the bar spacing (s), the width of the bars (w), and the tilting of the bars (φ_{tilt}).

Screen Positioning and dimensions				Bar dimensions		
Θ_0	Θ_s	R (m)	W_0 (m)	s (mm)	w (mm)	Φ_{tilt}
53	25	5	7	5	15	5

In order to start with the calculations, it's necessary to determine the incoming energy to the Coandă screen. The total head at the crest of the ogee is equal to:

$$H_0 = 0.8 + 0.89 \times 0.655 \approx 1.38\, m,$$

which corresponds to the input energy for the calculation of the discharge for the Coandă Screen. With the aforementioned input data, calculations can be performed and the results obtained are presented in Table 8. The vertical distance from the weir's crest to the upstream end of the screen is represented by H_a; the discharge coefficient and the inlet head are Cd and Hs, respectively; this data can be confirmed from Figure 20. The discharge going through the Coandă screen is *approximately* 7.5 m^3/s. The smallest *slot Reynolds number* through the screen is greater than 1000, so self-cleaning is expected. The screen is depicted in Figure 20.

Table 8 – Results obtained from Reclamation's Coandă screen calculator.

Ha (m)	Cd (m)	Hs (m)	Q_{Inflow} (m^3/s)	Q_{Thru} (m^3/s)	Q_{Bypass} (m^3/s)	Thru (%)	Bypass (%)	min Re_s (-)
0.704	2.154	1.38	8	7.4587	0.5413	0.9323	0.0677	23000

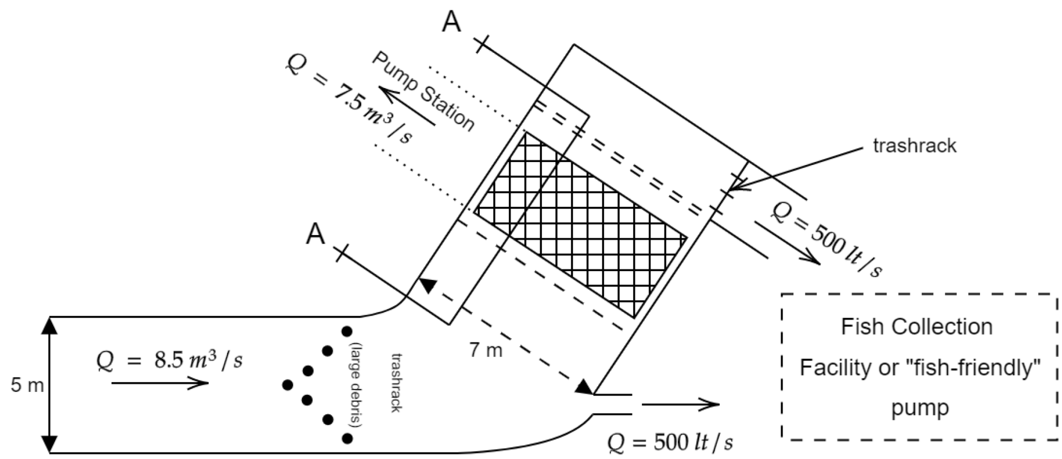


Figure 21 – Sketch of the proposed structure in the worked-out example.
Notice the inflow from the fish passage in the lower right side of the figure.
The black dots indicate the positioning of rakes or a floating screen, to avoid large debris from entering the channel.

- **Step 3:** a sketch of the proposed intake structure facility, with a fish passage entrance, one debris collection structure, and one debris diversion facility is shown in Figure 21**.** The rakes (or, eventually, debris booms) don't need any special hydraulic considerations since a hydraulic control is set downstreams. The spacing between rakes must be of order H_d in order to avoid the ogee weir to be blocked, but also be able to protect unsuspecting leisure vessels drifting in the channel. Here we can assume the rake spacing to be of 30 cm, which is roughly 1/6th the length of a one-person kayak, following the recommendations of the Bureau of Reclamation.

A back-up circuit may be built into the intake structure in case the Coandă screen clogs. In such case, one needs to simply dimension the channel downstream of the weir to carry 7.5 m^3/s, in case of an emergency, and then return it to the main channel, either through the fish collection facility's intake or using submerged diffusers. Another possibility is to place an arc gate, or a bulk gate, at the crest of the ogee, in order to close the weir completely or partially, whenever needed.

Fish are not expected to go through the Coandă screens given its rather small openings (only larvae may be able to pass), plus the flow approaching the intake is thought to be near critical to supercritical (and highly turbulent), thus producing a behavioral deterrent for smolts, fries, and juveniles that may choose to go through the weir (see Table 5). Notice the speed at the Ogee's crest is just above 2 m/s hence larger fish (sea trout and salmons) might go through the spillway. The spillway has a rather mild drop (1.6 m), so accelerations are not becoming too high; additionally, fish passing the spillway will be ported back to the fish collection facility (or pump) through the downstream channel. Hence, the structure may be considered both a behavioral and a positive fish barrier.

The entrance to a fish collection facility can be set upstream from the weir, with attraction velocities that do not exceed those suggested in Table 5 (or what is suggested by local environmental authorities). Notice that one of the reasons the weir sits at an angle of 45° with respect to the channel's axis was to be able to generate favorable currents towards the outer bank (due to centripetal forces) that may 'guide' swimmers towards the fish collection facility's intake. However, such an assessment is purely qualitative and is in no way guarantee that it will indeed attract fish. The efficiency of such structures depends greatly on the swimmer's species, and the local hydrodynamics. Thus, attempting to solve such questions require the use of high-resolution numerical studies (or physical experiments) and continuous interactions with biologists and the community.

5 Discussion

This work has dealt with a literature study regarding the design of debris diversion, and collection, facilities that may be used for pump stations intakes, particularly Archimedes pumps, and culverts in Flanders. As it was just implied, there are two main philosophies behind the design of such structures: (1) flow may be percolated through a screen and debris trapped, and later removed from the screen; and (2) debris flows may be diverted from the “useful” flow, while reducing cleaning operations. Both approaches have been discussed, and its features presented.

The study of debris flows as a hydrological parameter is, in the opinion of the author, statistically “inappropriate”, at least based on the categories that have been discussed in the introduction. One of the aspects that make the study of the water cycle amenable to be modelled using stochastics tools is the clear separation of the phenomena composing the cycle: precipitation, runoff, evaporation, etc, in the sense that these processes only act at the ‘boundaries’ of each other. For each item, well established models have been proposed, based on the other processes. That’s not the case for debris flows. That being said, one is better off if one avoids all the uncertainties associated in the determination of the debris amount (in hydrological terms, runoff discharge) when designing debris *protection* facilities.

Methodologies for the design of trash diversions and contingencies against clogging are neither devoid of uncertainties nor is deterministic. From the discussion in Chapter 3, it is clear that determining the form and orifice coefficients for Coanda and horizontal screens is far from simple. In fact, the author has deliberately avoided defining a range for C_r since it seems to be so much dependent on the particular configuration of the trash screen. Such argument also extends to the calculation of the energy losses in all types of screens.

Chapter 4 delves into the influence and interaction of trash racks and diversion/ exclusion screens on fish migration and makes a short account of the current literature pertaining design and worked-out examples. Notice that a complete discussion on fish rheotaxis and behavioral response to environmental stressors (pumps, fish passages) is beyond the scope of this work, and should be consulted with the corresponding environmental authority.

Finally the author proposes a workflow relating the design of trash racks in culverts and pump intakes, as shown in Figure 22. There, a visual summary of the discussion held in this text is organized in a way that may be useful for the design of trash racks.

5.1 Future Work

An effort in preparing a standard for the type and shape of trash screens must be made so to have uniform design guidelines regarding the bar spacing, screen size, inclination angle, and natural frequencies of vibrations produced by trash racks. Such endeavor may require physical experiments, particularly on inclination angles that would facilitate self-cleaning via raking.

Debris booms and drums present an interesting alternative for the collection of floating debris in channels. Their design and operation is ad-hoc, and more precise guidelines need to be prepared in case such alternatives are given a serious though. There is very little information detailing the design of such structures, except as-constructed experiences. Design guidelines may require to perform experiments.

A manual focusing specifically on the design of Coandă-type screens may be then prepared, including a rigorous approach to the study of the flow across the structure and the standards proposed in the experiments. An overall analysis of the costs (initial, Total Life Cycle) and an assessment of its impacts on fish migration must be conducted for a standard design, before committing to a full deployment of such alternative.

Lastly, and more importantly, an inventory of the trash screens currently operating in Flanders needs to be made. An analysis of their efficacy and state needs to be determined, in order to establish whether the current approach in placing those needs to be revised. Such inventory may serve as the basis for conducting a more complete study that may lead to a manual.

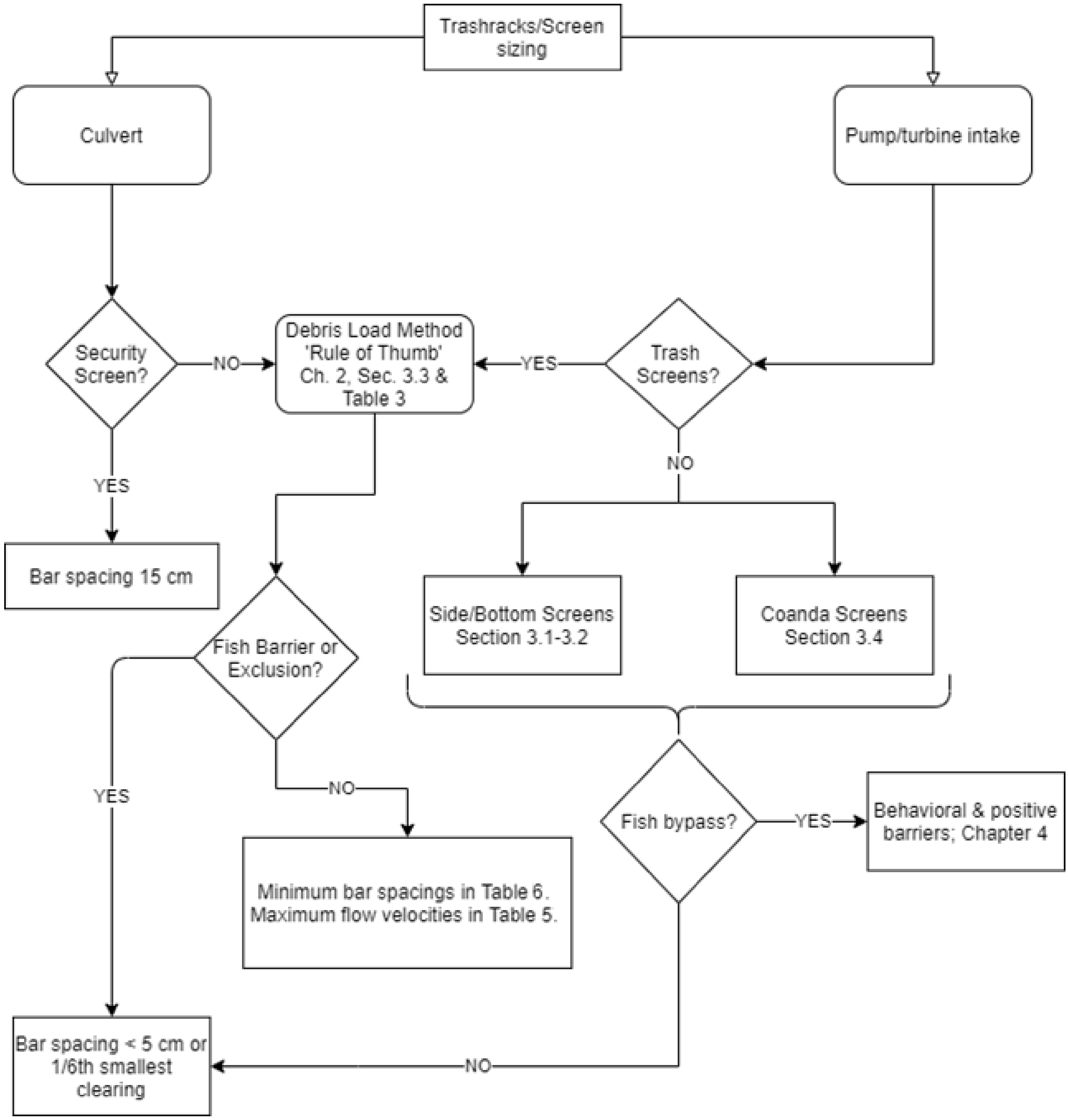


Figure 22 – Workflow regarding the design of trash racks in culverts and pump/turbines intakes.
This diagram is illustrative of the topics discussed herein.
This diagram disregards the suggestions made by CIRIA regarding the bar spacing for culverts where mammal crossings are expected: 30-45 cm spacings are meaningless for culverts with diameter less than 2 m.

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Appendix A: Use of Nomograms

Here, you'll find how the two nomograms shown in Chapter 2 should be used.

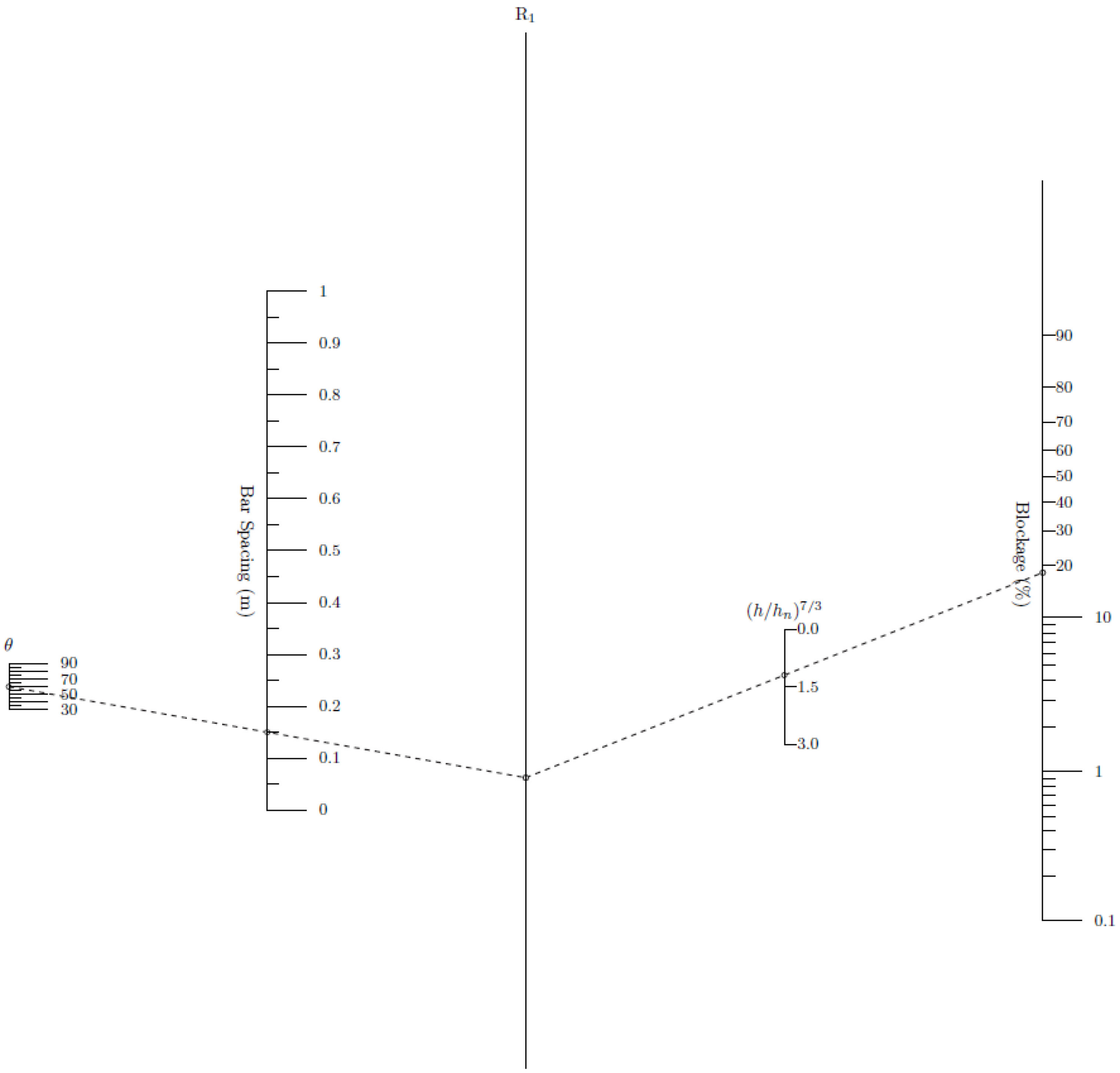

Figure 23 – Trash rack blockage estimator.
Example: For a trash rack inclined 60° in the vertical, a bar spacing of 15 cm, and h/h_n = 1.1, find the screen blockage. Solution: 19%.

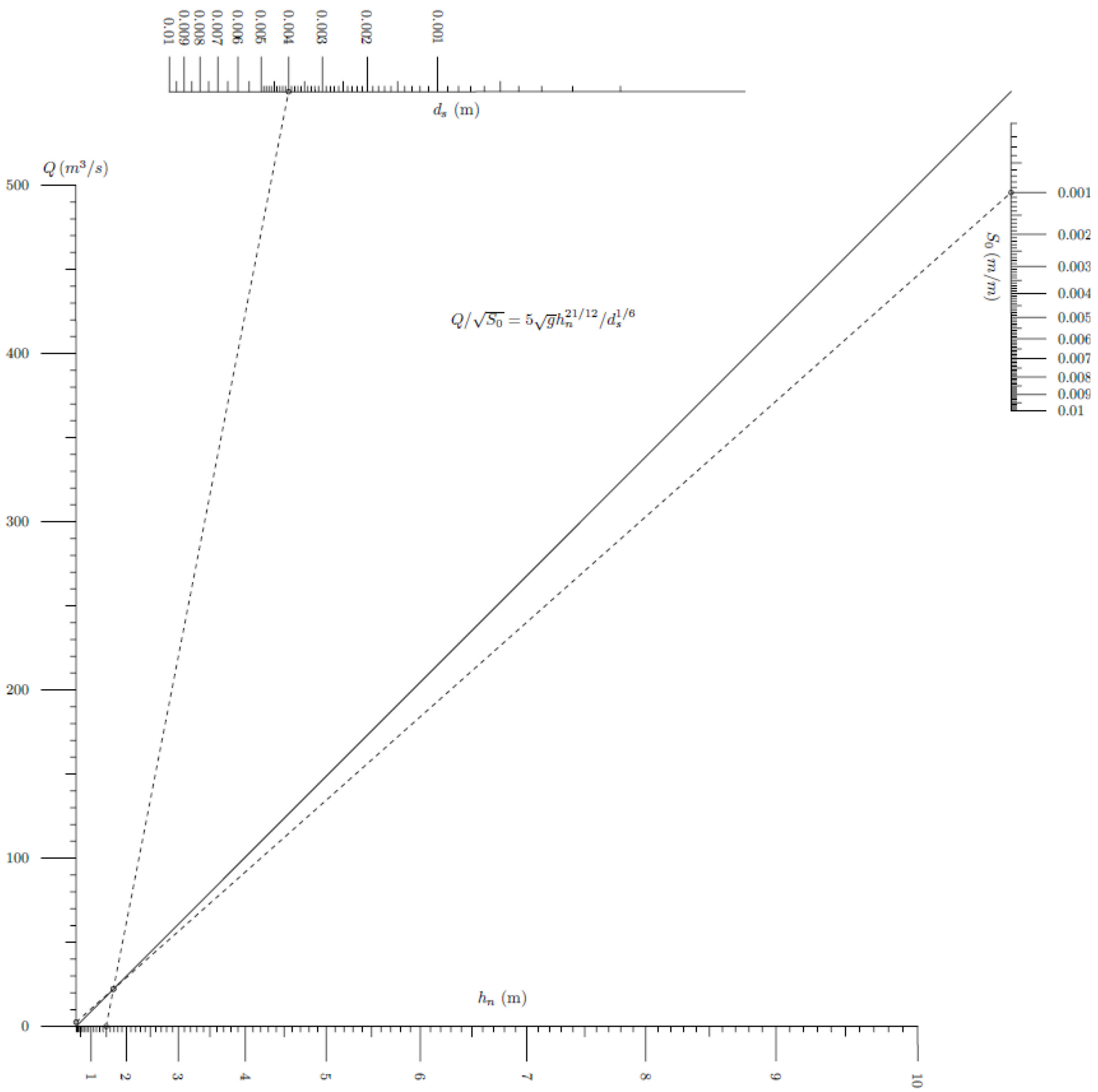

Figure 24 – Normal flow Nomogram.
Example: Calculate the unit discharge, if the normal flow depth (h_n) is 1.45 m, the slope of the channel is 1/1000, and the representative grain diameter of the bed is 4 mm. Solution: 2.5 m^2/s.

DEPARTMENT **MOBILITY & PUBLIC WORKS**
Flanders hydraulics Research

Berchemlei 115, 2140 Antwerp
T +32 (0)3 224 60 35
F +32 (0)3 224 60 36
waterbouwkundiglabo@vlaanderen.be
www.flandershydraulicsresearch.be