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Manning's roughness coefficient in small scale nature-like fish passages

Field study and evaluation

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Abstract

Fishway construction remains a crucial measure in environmental adaption of flow barriers. A well-functioning fishway should be able to pass all naturally occurring species of fish and other aquatic fauna. A common approach when designing and dimensioning a nature-like fishway is to calculate flows with Manning's equation but the selection and impact of Manning's roughness coefficient lacks a robust scientific background. In this study, field-data from four different nature-like fishway passages are collected to evaluate roughness coefficients for 19 different cross-sections. The average roughness coefficient was M = 10.5, spanning from M = 3.7 to M = 20.7. The method of field measurement was compared to two other ways of estimating roughness coefficients from (Cowan, 1956) and (DVWK, 2002). Limitations included measurement difficulties and assumptions of uniform flow for easier application of Manning's equation. Based on the results, Manning's roughness coefficient should be lowered from a typical design value of 15 to around 10 when designing small scale nature-like fishways or when estimating low-flow conditions in regular sized fishways. Future studies should seek to build data sets for greater varieties of fishways, evaluate the effect of varying flow within a fishway and thoroughly estimate the impact of perturbation rocks.

Popular Abstract

As demand for green energy, from hydropower among other sources, is ever increasing it is crucial that ecological and not only climate aspects are considered. For hydropower one of the most important measures is to ensure migration possibility for all naturally occurring species of fish. This is many times best obtained by installation of nature-like fish passages. One important step in fishway design is flow calculations and in this study roughness of small scale fishways has been evaluated to improve fishway design.

A fishway is a conduit that allows fish to pass obstructions in waterways, typically dam structures related to hydropower or irrigation. Historically, focus on species with higher economic interest such as salmon and trout and their upstream passage has led to inefficient passage for general migration of other fish species. Today, focus is put on nature-like fish passages that act like a small natural stream that is easier to pass for fish and that also creates important stream habitats.

When designing and dimensioning such fish passages, Manning's equation is commonly applied to calculate flows, but values for Manning's roughness coefficient and its relation do different design parameters is not well known. In this study, roughness coefficients were calculated based on data from fish passages to evaluate values currently applied in design. Methods for adjusting the roughness value based on parameters such as flow, channel geometry and perturbation rocks was also studied, along with two separate methods for roughness coefficient estimation.

It was found that for smaller fish passages, or low flow conditions, currently used roughness coefficients needs to be adjusted, for medium sized fish passages current values were verified by the study. Some of the other tested methods showed promise but need further evaluation before they can be applied. Generally, it was also noted that very precise roughness coefficient calculations are not necessarily the most efficient way of spending resources, with the many factor that affect a fish passage after installation monitoring also remains crucial in their prolonged usage.

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1 Introduction

Managing the flow of water courses has been a key for the evolution of society, from harnessing the power for mills and hydropower to storing water for irrigation of crops. These and other activities that are based around creating dam structures in watercourses have often greatly benefited mankind, and continues to do so, but they also have adverse effects on the surrounding ecosystems. Dams disrupt the migration patterns of aquatic species in the affected watercourse, they alter flow patterns and stops natural sediment transportation. Many species of fish and other aquatic flora and fauna are dependent on access to free migration during their life cycles to sustain healthy and resilient populations. As some species, such as salmon, trout, and eel, are also economically important species there have been solutions documented since the 1800s that aim to help migration of such fish. Today, however, fish migration has a more holistic approach where the goal is to pass all existing species as well as invertebrates and plants for a given watercourse. This is hard to accomplish in practice, with many very technical solutions to fish passage such as steep-passes, pool and weir fishways etc. fails in different way to create passage opportunities for a broad variety of fauna with differing mobility capabilities. One solution, that's currently considered best practice, is nature-like fishway passages. These are designed to mimic the surrounding environment to create a stream-like passage that should be able to pass all naturally occurring species. When designing a nature-like fishway passage, one great challenge is to make it functional over the range of common flows, and durable for extreme flows. A common approach for flow calculations is Manning's formula:

$$Q = A\frac{1}{n}R^{2/3}S_0^{1/2} \quad (1)$$

Where:
Q = flow, $[{}^{m^3}/_{s}]$
A = waterway cross sectional area, $[m^2]$
n = Manning's roughness coefficient, $[{}^{s}/_{m^{1/3}}]$
R = hydraulic radius, $[m]$
S_0 = water surface slope, $[{}^{m}/_{m}]$

Important to note is the two different ways to express the roughness coefficient: M and n, where M = 1/n. In this study, M will be most commonly used but n-values will sometimes be shown to give a comparison and easy reference.

All parameters are typically adjusted during the design process to obtain a fishway passage that fits the specific requirements of that passage. The parameter M, Manning's roughness coefficient, is typically chosen a rigid base value and used throughout the design process. The coefficient should however vary with many different parameters, and a deeper understanding of how to use it would improve the accuracy of the design process and would thus increase the functionality of fishway passages. The objective of this study is to perform field measurements of flow and geometry of fishways to determine Manning's roughness coefficient and compare this with current values used in design and alternative methods of roughness coefficient estimation.

In this study, field studies of water flows in existing nature-like passages are carried out to calculate their Manning's roughness values. These values are evaluated regarding factors for each specific passage to evaluate the most significant factors and how they can be utilized in a design process. The values are compared to similar studies done in natural small streams and compared to other ways of calculating Manning's roughness coefficient.

2.1 Fish and Aquatic Fauna Migration

2.1.1 Flow barriers

The reason behind dam construction is almost always to store water in a flowing system to be able to use it as needed at times when demand calls for it. Water mills have been used in Sweden and over Europe since the Middle Ages. Some of these dams were later modernized by installation of electrical generators that allowed the current to be used at greater distances, while others simply went out of time. After the installation of the first hydropower plant in Sweden in 1882 (Perers, Lundin, & Leijon, 2007) hydropower expansion quickly increased in Sweden. The expansion began mainly in south Sweden, were most of the demand was, and still is, located. After the 1930s expansion began to move north as most sources in the south were already exploited. Transmission lines were installed allowing for power transfer over the 1000 km that divides the larger hydropower resources and the centers of demand. Hydropower expansion in Sweden peaked around the -50s and -60s after which it declined. The decline was a result of several factors, but mainly due to political and popular pushback due to the ecological impact of hydropower, the fact that most large resources were already exploited and the introduction of nuclear power in the Swedish energy mix meant that the hydropower was not the final solution to energy production. Currently, around 2100 hydropower stations exist in Sweden (Calles, et al., 2013) and the expansion of Swedish hydro power mainly lies in modernization and maintenance of existing power stations. (Östberg, 2020)

The typical flow barrier that is discussed in this paper is some type of relatively small weir-structure, positioned over the water course, either straight or at an angle. Specially for older dam structures that has been built for water mills or smaller hydropower stations, these are rather simple in their construction and does usually not require very large fishway passages. Very largescale hydropower stations or regulation dams located on large rivers will require fishways of greater capacity. The general approach of this study will be applicable, but the direct results will likely not transfer very well to a greater scale.

2.1.2 Migration patterns

Migration is a natural and vital part for many species of fish and aquatic fauna (DVWK, 2002) (Katopodis C. , 1992). Habitats that are optimal for growth of juvenile and adult fish are often not the same, and habitat for reproduction or specific periods such as winter might also differ (Näslund, Degerman, Calles, & Wickström, 2013). It thus becomes a natural part of the life cycle of fish to migrate between these areas. It is important to note that this is not only the case for the most well-known species of migratory fish, that are typically anadromous or catadromous, such as salmon, trout, eel and lamprey. Also, common freshwater species such as perch, pike, roach, and many more undertake extensive migration during their life cycle (DVWK, 2002). In fish way passages in Sweden, Poland, and the Czech Republic, 32 common freshwater species have been found (Näslund, Degerman, Calles, & Wickström, 2013). If the possibility for fish and aquatic fauna to migrate is disrupted they will typically do their best to use the areas that are available to them, but this will likely result in less efficient spawns and less diversity in the gene pool leading to lowered resilience of the populations. A very wide definition of fish migration was put forth by (Baras & Lucas, 2001) and is good to have in mind when thinking about fish migration disrupted by artificial structures:

” A strategy of adaptive value, involving movement of part or all of a population in time, between discrete sites existing in an n-dimensional hypervolume of biotic and abiotic factors, usually but not necessarily involving predictability or synchronicity in time, since interindividual variation is a fundamental component of populations”. (Baras & Lucas, 2001)

From this quote it is important to notice that specific weight is placed on the possible nature of fish migration, that it is not always predictable in time or in space. It is therefore evident the importance of fish passages being always functional.

Other factors aside from the typically mentioned more large scale and life-stage driven migration such as spawning and transition from juvenile to adult areas or seasonal areas are daily movement patterns of fish that feed during darker hours in certain areas and take cover during light hours in other parts.

Also short-term, short-range transitions between areas with higher oxygen content, more favorable temperatures or brief very high concentration of insects can occur. (Waters, 1972)

Other aquatic fauna that are impacted by flow disruptions and impermeable barriers are mainly different invertebrates such as crayfish, mussels, and insects. Similarly, to fish these also have migration tendencies and will suffer from a lack of diversity in their gene-pools. Some species of mussels, such as Freshwater Pearl Mussel (*Margaritifera margaritifera*) are also dependent on the migration of their larvae host species, trout (Havs- och vattenmyndigheten, 2020). When constructing a fish passage, it should be designed to accommodate an as wide mixture of species as possible.

2.1.3 Fish passes and fish biomechanics

Naturally, since a fishway should be designed to pass a wide variety of fish species and other aquatic fauna, proper knowledge of the capabilities and preferences of target species must be known. The basic premise of a fishway is that the fish should be able to overcome the resistance and force of the water, if this basic criterion is not met then no other factor matters. The swimming and jumping capacity vary widely between species, between life stages within a single species and between individuals. Fish swimming capacity can be divided into three categories: sustained speed, prolonged speed and burst speed. The sustained speed is defined as the speed at which the species can travel for a longer period of time, at least for 200 minutes. The prolonged speed is faster than the sustained speed and should be able to be withheld between 20 seconds to 200 minutes. Finally, the burst speed can only be withheld for 15-20 seconds (Katopodis C. , 1992) (Calles, et al., 2013). The velocity where a species is no longer able to pass is defined as the critical velocity. For some of the weakest swimmers this begins already at 0.3-0.4 m/s (Calles, et al., 2013), for juvenile fish it can be as low as 0.1 m/s. It is suggested that fish will only very rarely use their max capacity burst speed to pass obstacles, it is rather used to hunt or avoid predators (Bell, 1990). The use of burst speed will very quickly build up critical levels of lactic acid which requires longer resting times for the fish.

The passage ability is further affected by external factors such as temperature and oxygen content. At low temperatures, the fish become more rigid, and at temperatures of 6-7 degrees Celsius even strong swimmers will have trouble passing technical fishways (Gee, 1980) (Cowx & Welcomme, 1998). At very high temperatures the oxygen content will be low, this will instead increase lactic acid build up and prolong the resting time between bursts.

Like swimming capability, jumping capabilities also vary to a great extent and typically species that are poor swimmers will also be poor jumpers. For any species to be able to jump, the depth must be sufficient for acceleration, and a depth of 1.25 times the height of the barriers is seen as optimal. (Ovidio & Philippart, 2011) Many species can be expected to jump 2-3 times their body length, but some species can't be expected to jump at all, for example bream and burbot (Calles, et al., 2013). It is always optimal to design for fishways that do not require jumping.

2.1.4 Solutions to aquatic fauna migration

The history of fish passages is considerably shorter than that of dam building (DVWK, 2002). In Swedish history, mitigation practices for dam structures were not commonly enforced by law before 1918, when a majority of the dams that exist today were already constructed, and in those cases it almost exclusively was to facilitate migration of Atlantic salmon (Salmo Salar), brown trout (Salmo Trutta) and European eel (Anguilla Anguilla) (Calles, et al., 2013). In the late 1800s such measures included Denil fishways, pool and weir fishways, eel fry conductors, stocking with farmed fish and pure economic compensation to damaged fisheries or authorities. Realization that solutions for downstream passage were also needed came later, with introductions of behavioural devices, bar racks and screens (Calles & Greenberg, 2009). In recent years, the best practice is the natural fish passage, a solution that mimics the specific site and is tailored to have a functional flow that should always allow passage of all naturally existing species, at least in the best case scenario (Katopodis & Williams, 2012) (DVWK, 2002) (Calles, et al., 2013). The following chapter will summarize the most common fishway passages, with an emphasis on nature-like fish passage design.

2.1.5 General requirements for fish passage

Regardless of the type of fish passage, there are some universal design criteria. Depending on specific site and barrier conditions, target species and available funds, these are evaluated to create the specific solution. These criteria can be summarized according to the list below:

- Appropriate fishway flow velocity
- Flow characteristics
- Possibility for fish to pass both ways
- Location of fishway entry
- Location of fishway exit
- Bottom material
- Ability to handle varying upstream water levels

As earlier stated, if the velocity is too high then effective passage will not occur. Almost all fish passages will have instalments to create energy dissipation, the most obvious example being baffle fishways, but also nature-like fishways will usually feature rocks in the stream that fill the same purpose. Too much turbulence will however discourage fish from passing and energy dissipation should not exceed 200 W/m^3 (M, 1992). Velocities in the fishway should match species that occur in the water course, but a general rule of thumb is to have velocities of 0.2-0.3 m/s close to the bottom and sides to allow weaker swimmers and crawling invertebrates (Calles, et al., 2013) and never velocities greater than 2 m/s at crucial points where cross sectional area is reduced and fish must pass, for example orifices or slots (DVWK, 2002).

For fish passage to work the flow velocity and characteristics must be fit for all occurring species to pass. The flow velocity must be below critical velocity, as discussed in section about fish biomechanics, for fish to be able to pass. If the passage is expected to be difficult for some species, resting pools or flow obstructions can be incorporated to allow passing fish to overcome one section at a time. For fish to find the entrance and view it as a viable option for migration the flow must be sufficient and must be able to compete with attraction from turbine jets or excess water from spillways. This can be solved by either locating the entrance close to such parts of the structure that will by themselves attract migrating fish, or by construction of water conductors that end at the fishway entrance, without adding to its actual

flow. When migration can be expected to increase due to spawning, flow can also be redirected to the fishway to increase attraction, called “klunkningar” (gulps). For some locations, especially at hydropower sites where the turbines are located apart from the original riverbed, or where a wide range of species with varying swimming capabilities should be able to pass, a multitude of fish passages could be the only solution for effective passage and remediation of river longitudinal connectivity. This can also help if fish and aquatic fauna that prefer one installment when moving downstream and another when moving upstream, or if flow conditions for different parts of the barrier vary with upstream water level. Since passage must be able to occur both upstream and downstream, this must be accounted for. Many traditional fishway passages such as denil fishways and pool and weir fishways are focused on upstream migration (Calles & Greenberg, 2009). At such sites, it becomes very important that care is taken to ensure safe downstream migration by diverting fish from passing through the turbines. This is naturally also important at sites with nature-like fishways as downstream migrating fish in many cases will tend to move towards the turbine intakes, but the nature-like fishway at least provides an alternative.
The upstream exit of the fishway should not be located too close to the spillways or the turbine intakes as this might cause fatigued fish to be swept away. If the dam is large with low velocities close to the exit an increased risk of predation occurs which should be avoided, if possible, by extending the fishway (DVWK, 2002).

The bottom should be made up of a rough coarse substrate that would naturally occur in the watercourse at higher water velocities. This will allow resting space for smaller species of fish and invertebrates that will have a very hard time crawling on concrete or other smooth materials.
Finally, the ability to handle a range of upstream water levels is very important. Naturally, the water level of the dam will vary throughout seasons and as discussed, fish migration is hard to predict and should be always manageable for all species. A nature-like fishway is typically constructed with an upstream inlet that decides the fishway flow depending on the upstream water level, with a double staircase design that ensures a minimum flow without overfilling at higher flow levels.

3 Types and design of fishway passages

Fishway passages are meant, as the name suggests, to allow for passage of fish and other aquatic fauna. As previously discussed, and as engineering typically works, the solution put forth is targeted at the problem statement. Historically with the main species of interest being salmonids and their upstream migration to spawn the solutions have focused on solving that problem in a as cost efficient matter as possible. What these solutions often fail to achieve is ways for species with lower swimming- and jumping capacity that will not be able to use the passage. Even the species that the passage is meant for may have difficulties passing and will often lose a lot of time as they hesitate around the object. Furthermore, downstream solutions have been historically overlooked (Calles & Greenberg, 2009). This is still as vital as upstream passage, as juvenile anadromous fish must be able to safely travel downstream to reach the sea, adult catadromous fish must be able to pass downstream in order to reach their spawning grounds and all other species that also have different migration patterns must also be able to move in both stream directions for optimal strength of the population. This chapter will briefly discuss some different solutions to the disruption of river flows by man-made structures, but focus will be on nature-like fishway passages.

3.1.1 Denil fishways

The Denil fishway was introduced by G. Denil as a solution to failed fishway in 1907 on the river Ourthe in Belgium (Larinier, 2002) (Katopodis & Williams, 2012). A Denil fishway is based around energy dissipation created by baffles inside a rectangular channel at a rather steep incline, typically between 15 – 25%. Passages with slopes as high as 40% have successfully passed species (Katopodis & Williams, 2012). The flow is often very turbulent and energy dissipation is high due to the high momentum transfer (Larinier, 2002). The relatively long history of the Denil fishway has allowed for many tests of different configurations and designs. The main properties that can be differentiated are the positioning of the baffles, normal to the sides or the floor, baffle angle, opening width and fishway slope.

The Denil fishway have been popular in both the US and in Europe with a wide range of species known for using them, including American shad (*Alosa sapidissima*), Sockeye salmon (Oncorhynchus nerka), northern pikeminnow (*Ptychocheilus oregonensis*), steelhead (*Oncorhyncus mykiss*), Chinook

(Oncorhynchus tshawytscha), suckers (*Catostomus* spp.), Pacific lamprey (Entosphenus tridentatus) and Dolly Varden (*Salvelinus malma*) (Katopodis C. , 1992). The age of the Denil fishway has allowed rigorous testing of hydraulic properties such as discharge, velocity distributions and water depth through physical hydraulic modelling and both laboratory and field testing (Katopodis C. , 1992). Denil fishways have been successfully installed for fish to overcome dams with hydraulic head differences up 15 m, with lengths reaching over 200 m (Katopodis & Williams, 2012). The effectivity of such installations is however seen as unreliable. The Denil fishway can be relatively simple to construct and can be very space efficient. Negative aspects is that it can be difficult to obtain a fishway that both works over a range of possible upstream water levels while maintaining fish passaging conditions. Wider gaps between baffles allow greater flexibility of flow levels but will also weaken the flow and thus impair the fish attraction at the bottom of the fish passage. This is often counteracted by locating the downstream entry close to spillway exits to increase turbulence and add attraction at the entrance.

Figure 1. Denil fishway, Gillmitzer mill, Brandenburg, Germany (DVWK, 2002)

3.1.2 Pool and weir fishways

Pool and weir fishways have been popular in Scandinavia, often called "laxtrappor" which directly translates to "salmon stairs". The design is based on a rectangular channel sectioned of into pools by weirs, often constructed in concrete or sometimes blasted directly into the rock. Pool and weir fishways are heavily designed for salmonids, especially salmon (*Salmo Salar*), brown trout (*Salmo Trutta*), and Arctic Char (*Salvelinus Alpinus*). The water level in the pools is most often lower than the upstream weir level, making some sort of jumping action performed by the fish necessary. This will limit many species from effective passage (Katopodis C. , 1992). By introducing orifices at the bottom of the weir this can be counteracted. (Larinier, 2002)

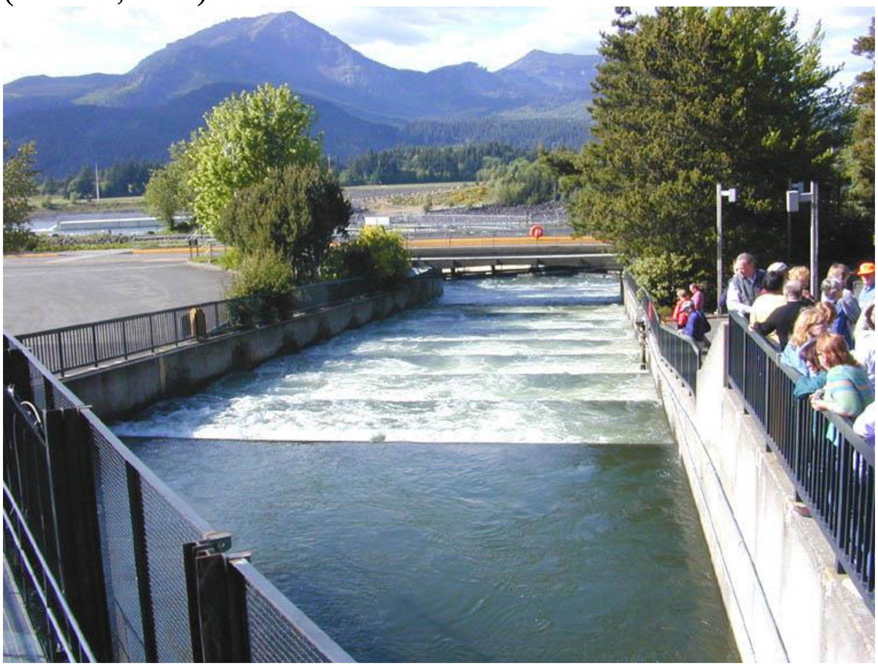

Figure 2. Pool and weir fishway at Bonneville dam on the Columbia River, USA.

3.1.3 Fish elevators and fish locks

An uncommon method that has been used at some very tall dams were space is limited and initial costs of fishway construction would be high are fish elevators or locks. These have been shown to pass fish but are ineffective. They also require more manual labour and control during operation and will not be considered further in this report. (Calles, et al., 2013)

3.1.4 Nature-like fishway passages

The nature-like fishway is designed to mimic the surrounding area and morphology of the site. Typically, some sort of flow determining structure such as a weir or gate is located at the uppermost part of the passage that ensures the flow levels in the fishway in relation to flow in the actual stream. Within the fishway different structures are placed to dissipate the energy of the water and create resting spaces, such as rocks. The fishway can also be given a meandering shape to further enhance its fish passaging function and recreational value. Below are several different configurations of nature-like fishway passages pictured.

Nature-like fishways can look relatively different and be separated into four different categories.

1. Rocky ramp (Swedish: Upptröskling)
2. Bypass through the dam (inlöp)
3. Bypass (omlöp)
4. Nature-like ramp (naturlik bassängtrappa)

The rocky ramp is generally used to generate a higher water surface level and neutralizing steep slopes in the stream. This can allow previous obstacles that were protruding above the water, forcing fish to jump to pass it, to become submerged and thus much easier to use. It is typically combined with rocks added to the stream to further dissipate the energy and create resting places and improve the general ecological characteristics of the fishway passage, creating a habitat suitable for stream species at all times.

A bypass through the ramp is created by partially removing the dam structure to lower the level of the obstacle. This can be done together with a rocky ramp to facilitate easier passage. Since the fishway is located in the main stream it is generally easy to find for species and also favours downstream plant and invertebrate migration. This method is suitable when the banks are steep or space on the side of the stream or space is limited due to buildings or other structures. By creating a structure that can be flooded it is also resilient to flow variations.

A regular bypass is located at the side of the dam. When space is available for this, it has the advantage of not altering the dam structure, which can be hard either due to cultural historical values or from a technical standpoint. By not having to necessarily having to “lift” the fish over the same height as the dam structures lip the stretch of the passage can also be made shorter. Similar to a bypass through the dam, the side of the bypass can be constructed so that it can be flooded to aid at high water levels.

Nature-like ramps are built on a similar principle to the pool and weir fishway, but without the sharpness and often cascading design of a concrete fishway. Natural pools are constructed with stone weirs, but with openings that allow for passage both ways and for fish species that are not prone to jump. Each pool allows resting space and creates a stream like habitat suitable for some species of fish and macro-invertebrates.

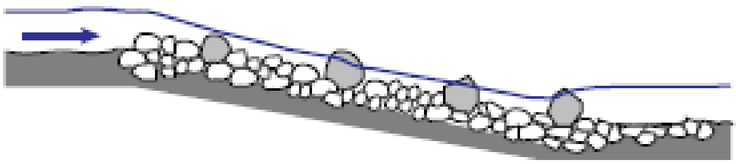

Figure 3. Illustration of rocky ramp fishway (DVWK, 2002)

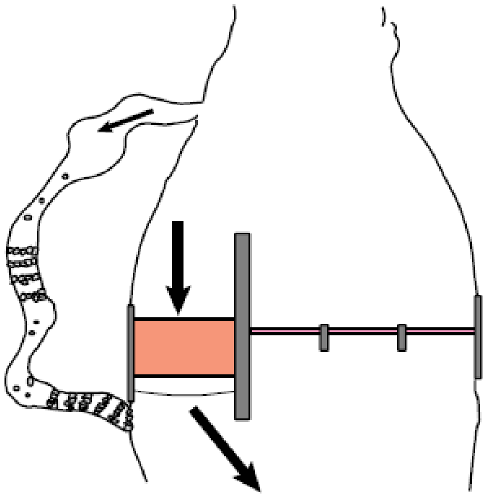

Figure 4. Illustration of a bypass fishway (DVWK, 2002)

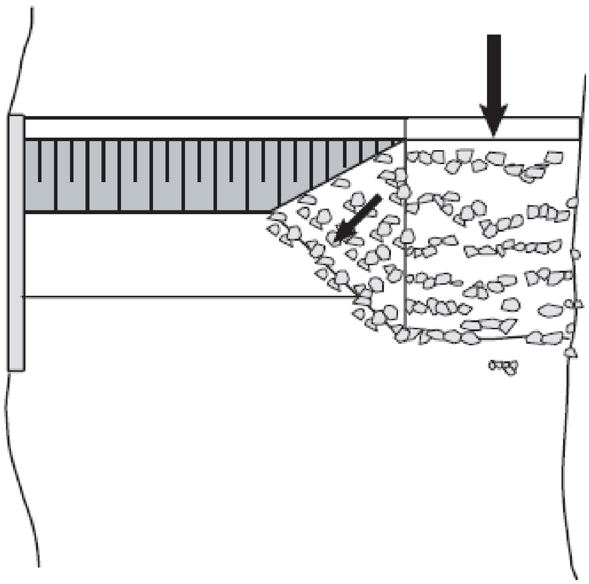

Figure 5. Illustration of nature-like ramp (DVWK, 2002)

3.2 Design of nature-like fishway passages

In a typical design scenario of a nature-like fishway, the needs of the specific site and species, and the constraints that exists are weighted to reach a functioning design.
Constraints often include:

- Slope lower than 2.5 % for optimal fish passage conditions (Calles, et al., 2013)
- Maximum depth of at least 30 cm at MLQ flows (DVWK, 2002)
- Ability to not flood at a design flooding event, often chosen as the 100-year flow event
- Cost-efficiency
- Minimal intrusion on existing built structures
- Lack of space

All of these constraining factors are affected by the flow and the resulting water level. Thus, the need for proper estimation of Manning's roughness factor becomes important in the design process.

4 Darcy-Weisbachs equation and resistance from perturbation rocks

In the exhaustive report regarding fishway design and dimension of fishways by *Deutscher Verband für Wasserwirtschaft und Kulturbau* (DVWK, 2002); a chapter is spent on flow formulae and roughness coefficient calculations based on rock size and placement. In this report, the Darcy-Weisbach equation is used for flow calculations according to

$$Q = A * V_m = \frac{1}{\sqrt{\lambda}} \sqrt{8 * g * R_h * S_0} \quad (2)$$

where

$$1/\sqrt{\lambda} = -2 \log(\frac{k_s/R_h}{14.84}) \quad (3)$$

k_s is the equivalent sand roughness diameter. This can be replaced by either the average rock diameter, d_s, if the bottom is made by rockfill, or the average grain size diameter, d_{90}, in the case of mixed bottom substrate.
A method for calculation of an overall friction coefficient to apply in Eq. (3) is also proposed, based on (Pasche & Rouvé, 1985).

$$\lambda_{tot} = \frac{\lambda_s + \lambda_o(1-\varepsilon_0)}{(1-\varepsilon_v)} \quad (4)$$

In which

$$\varepsilon_v = \frac{\sum V_s}{V_{tot}} = \frac{immersed\ area\ of\ perturbation\ boulders}{total\ volum\ A*I} \quad (5)$$

$$\varepsilon_0 = \frac{\sum A_{o,s}}{A_{o,tot}} = \frac{surface\ area\ of\ perturbation\ boulders}{total\ basal\ area\ I_u*I} \quad (6)$$

$$\lambda_s = 4c_w * \frac{\sum A_s}{A_{o,tot}} \quad (7)$$

I = length of studied section
I_u = wetted perimeter
$c_w \approx 1.5$ form drag coefficient
$A_s = d_s h^*$ wetted area of perturbation boulders
$h^* = h_m$ if water flow < boulder height, h_m = average water depth
$h^* = h_s$ if boulders are completely immersed, $h_s =$ boulder height

The bottom roughness coefficient, λ_0, can be approximated with Eq. (4) and the total roughness coefficient can be applied in Eq. (2) for flow calculation.

5 Open Channel Flow

All fishway passages (except for fish cannons and elevators) are open channels and share the characteristics of open channel flow. Open channel flow occurs in conduits with a free surface and is gravity driven, not pressure driven. As such, flow will only occur over surfaces that slope, where a control volume of the water will have a force vector acting along the plane that the water is flowing over. Surface pressure is constant at each point at the surface and will, for the applications in this paper, be atmospheric. In a not-full pipe the flow is also regarded as open channel flow and share the same characteristics. Open channel flow can be divided by three characteristics that will be important to understand for the coming discussion of Manning's roughness coefficient determination. To first understand these, a short discussion of relevant hydraulic parameters will be presented.

5.1 Flow parameters

5.1.1 Velocity (V)

In open channel flow there is a velocity profile within a cross section where the velocity is zero at the channel boundary and reaches it maximum close to the surface, see figure. In this study, velocity refers to the mean velocity at a cross section. (Hamilles, 2011)

5.1.2 Top Width (B_S)

Top width of the watercourse from bank to bank perpendicular to the flow. (Charlotte-Mecklenburg, 2014)

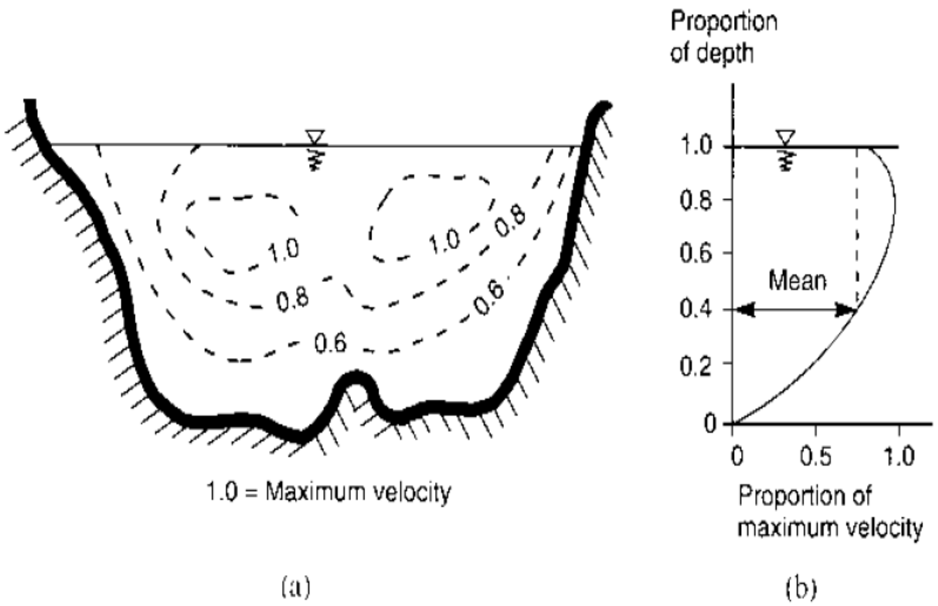

Figure 6. Velocity profile within a cross-section (Hamilles, 2011)

5.1.3 Slope (S)

The slope must also be clarified as it is not always obvious what is meant. Typically, the slope is the general slope of the water surface along the water course. For specific flow characteristics the slope of the water surface is parallel with the bottom of the watercourse but that is not necessarily always the case. The slope could also be regarding the energy line of the water which for non-uniform flow will substitute the slope of the water surface. (Hamilles, 2011)

5.1.4 Cross sectional area (A)

The cross-sectional area of the water course is the flat area between two points of the side of the water course orthogonal to the flow. (Hamilles, 2011)

5.1.5 Wetted perimeter (P)

The wetted perimeter is defined as the surface of the bottom and sides of the channel in contact with the flow. (Hamilles, 2011)

5.1.6 Hydraulic radius (R)

The hydraulic radius is the ratio of cross-sectional area to wetted parameter. (Hamilles, 2011)

$R = A/P$

5.1.7 Normal depth (D_N)

Flow through a section of a channel with uniform flow. (Hamilles, 2011)

5.1.8 Hydraulic mean depth (D_M)

The hydraulic mean depth $D_M = {}^{A}/_{B_S}$ is an attempt to define the mean depth for the more regular conditions in natural channels with irregular geometry and varying depth. Typically used in equations such as the one calculating Froude number. (Hamilles, 2011)

5.2 Flow Classifications

Open channel flow can be classified in a few different ways that are important to consider for functional fishway design.

5.2.1 Steady – unsteady flow

Parameters such as depth and velocity change over time the flow is unsteady. If it is constant, then it is steady. Of course, flow will vary over time but typically, the rate of change in fishway passages is slow enough for it to be considered as steady. (Hamilles, 2011)

5.2.2 Uniform and non-uniform flow

If the flow parameters, depth, and velocity, instead change over the length of the flow the flow is classified as non-uniform. If they do not change over space the flow is classified as uniform. (Hamilles, 2011)

5.2.3 Gradually varying flow

A specific case of flow that is steady but non-uniform where the change of flow is not abrupt, but rather happens gradually over a range of the watercourse. An example is a gradual change of water depth. (Hamilles, 2011)

5.2.4 Subcritical and supercritical flow

One of the important ways of defining flow is if it is subcritical or supercritical. Subcritical flow typically occurs in deeper parts of a water course with a flow that seems to flow “calmer”. A common metaphor is subsonic and supersonic airplanes. If a rock is thrown into a stream where subcritical flow is occurring, the resulting waves will propagate in all directions, whereas for supercritical flow they will be carried downstream. (Hamilles, 2011)

5.3 Basic derivation of flow equations for uniform open channel flow

As stated, open channel flow is gravity driven where one of the force components acting on a control volume is acting parallel to the plane over which the water is flowing. This can be remembered by many as a simple sloping plane problem from their introductory physics course. If one thinks about it, it also seems intuitive that the control volume is in many cases not accelerating. If that was the case, then continuity would give that the cross-sectional area of a water course would be decreasing, either from becoming narrower, or by decreasing depth. As this is often not the case, there must be some equal counteracting force on the control volume, resulting in a net 0 force and thus a constant velocity of the control volume, see Figure 7.

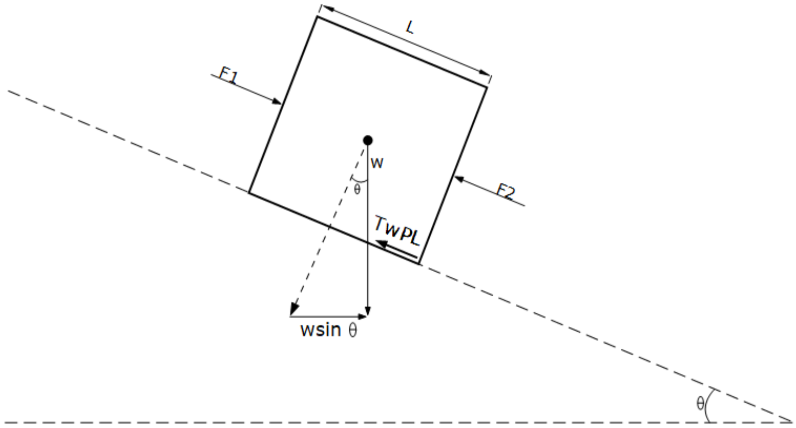

Figure 7. Forces acting on a control volume assuming uniform flow

The forces F_1 and F_2 are equal but opposite as hydrostatic conditions are assumed to be constant.
The force acting parallel to the plane in the flow direction is a component of the gravity acting on the control volume. It can be expressed as:

$$\omega * \sin(\theta) \quad (8)$$

Where ω is the weight of the control volume and θ is the angle to the horizontal plane.
The equal and opposite force is the shear force of friction that can be expressed as:

$$\tau_{\omega} * P * L \quad (9)$$

The forces F_1 and F_2 are equal but opposite as hydrostatic conditions are assumed to be constant. Thus, a force balance can be written as

$$\omega * \sin(\theta) + F_1 = \tau_{\omega} * P * L + F_2 \quad (10)$$

This can be rewritten to a simpler from according to Eq. (12)

$$Wsin(S_o) = KA_pV^N \qquad (11)$$

Where
W = Weight of water in control volume
S_o = bottom slope
K = roughness coiefficient
A_p = Contact area between water and channel conduit
V = mean velocity
N = exponent, typical value 2 for turbulent flow
By further rearrangement, Chezy's formula can be stated as:

$$V = C\sqrt{R_hS_0} \Leftrightarrow C = {V}/{\sqrt{RS_0}} \qquad (12)$$

Where
C = Chezy's roughness coefficient, $\frac{\sqrt{m}}{s}$
R_h = hydraulic radius

Chezy's friction coefficient is a function of both Reynolds number and the friction of the channel. The two coefficients share a relationship according to Eq. (14)

$$C = {R_h^{1/6}}/{n} \qquad (13)$$

n = Manning's friction coefficient, s/m$^{1/3}$

By substitution with Eq. (13) this can be formulated as the commonly known form of Manning's Equation

$$V = \frac{1}{n}R^{\frac{2}{3}}S_0^{\frac{1}{2}} \qquad (14)$$

According to the continuity formula

$$Q = AV \qquad (15)$$

Where
Q = flow

A = cross-sectional area
V = mean velocity

Manning's formula can be rewritten for flow, not velocity, which is the more usual approach.

$$Q = A\frac{1}{n}R^{2/3}S_0^{1/2} \qquad (16)$$

It is also commonly used to solve for other parameters when the flow is known. By rearrangement this study will solve for the roughness coefficient given measured geometric values of a watercourse and the measured flow.

$$n = \frac{A}{Q}R^{\frac{2}{3}}S_0^{\frac{1}{2}} \qquad (17)$$

5.3.1 Manning's equation for non-uniform flow

As shown the above derivation of Manning's equation stems from Chezys equation which in turn is formulated on the assumption on uniform flow. This is however seldom the case for flow occurring in many natural water courses, especially the smaller streams that nature-like fishways are. This flow is more often characterized by non-uniformity as both the geometry, the slope and the flow are variable. For such applications, the slope of the water surface, S_0, is exchanged for the slope of the energy line of the water, S_f, with regards to the energy loss of the water:

$$S_f = {}^{h_f}/_{L} \qquad (18)$$

h_f = frictional energy losses
L = length of stretch

$$h_f = \Delta h + \Delta h_v - k(\Delta h_v) \qquad (19)$$

Where
Δh = height difference between sections
Δh_v = velocity head difference between sections

k = dimensionless energy loss coefficient for local losses, typically 0 for contraction sections and 0.5 for expanding sections.

6 Summary of previous studies on Manning's roughness coefficient

Since the formulation of Manning's Equation and its gain of popularity in civil engineering applications a wide range of studies have been carried out to develop methods for accurate estimation. Such work has ranged from roughness coefficient determinations of large-scale rivers where projects such as bridge construction and flood mitigation are main topics, but many studies have also focused on mid-range and smaller streams, focusing on applications such as culvert design and smaller bridges. In later years, more studies on Manning's roughness coefficient in both technical and nature-like fishways have been put forth. Approaches include those similar to this study, where flow measurements are made to utilize Manning's equation "backwards". Other approaches include formulation of equations based on bottom material sizes, compound Manning's n values methods and hydraulic simulations (Shahabi, Ahdiyan, Narimousa, Ghomeshi, & Azizi Nadian, 2022) (Tran, Chorda, Laurens, & Cassan, 2016). Following is a summary of the most important sources for this study.

6.1 USGS: Guide for selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains 1989

The report "Guide for selecting Manning's Roughness Coefficient for Natural Channels and Flood Plains" (1989) was written by George J. Arcement, JR, and Verne R. Schneider. The report aims to verify n-values for natural streams, especially ones with vegetation, to fill in an existing knowledge gap and aid in future evaluations of Manning's roughness coefficient in engineering applications. For background they refer to earlier published work regarding n in natural channels by Chow, Streeter and Barnes. In the study, longitudinal subsections with associated cross sections were measured and characterized based on geometry, slope, vegetation, and bottom material. The composite Manning's roughness method is discussed. Both the base value and the modifications are discussed. They present a table for approximate values to use for the modifications when extracting a composite n value. The same approach is then applied to flood plains. A distinction between stable and unstable channels are made, where unstable channels are defined as channels where the bottom composition primarily consists of sand that will move at higher flows, giving the stream a variable geometry compared to one made up of rocks or cobbles that will stay relatively constant regardless of flow.

The vegetation-density method is explained and coupled with photo examples of flood plains and selected Manning's n adjustment values.
The paper also presents a step-by-step guide to assigning n-values to channels and floodplains. The steps for assigning n for channels can be summarized as:

1. Determine longitudinal reach where factor will apply.
2. Determine if factor is uniform over cross section.
3. Determine stability of channel.
4. Determine important roughness factors.
5. If non-uniform cross section, decide segments according to roughness.
6. Determine bed material and median size.
7. Determine base n value.
8. If non-uniform section, add adjustments factors to individual segments.
9. If non-uniform section, select basis for weighting n for channel segments.
10. If non-uniform section, estimate wetted perimeter and assign weighting factor.
11. Select adjustments factor that effect entire cross section.
12. Cross-check result to photos to evaluate validity.
13. If sand channel, check flow regime.

A similar method is presented for flood plains and an example applying the methods is made.

6.2 USGS: Estimation of Roughness Coefficients for Natural Stream Channels with Vegetated Banks 1998

The study both summarizes previous similar studies and work to determine Manning's roughness coefficient and presents work done to determine the roughness coefficient for 21 streams in New York, USA. It discusses common influential factors for the roughness coefficient with emphasis on vegetation but also including flow depth, energy gradient, type-and size of bed material. The results of the study were compared to previously discussed methods of theoretically calculating Manning's n and limitations were evaluated. Lastly it presents a method to assign Manning's n value theoretically to an unstudied river.

The study presents tables from previous, mainly American, studies as one of the ways to determine Manning's n without direct flow measurement. The second method includes comparisons of photography's and hydraulic factors. Lastly, equation that have been formulated are presented. Equations included in the study is by Limerinos, 1970; Bray, 1979; Jarret, 1984; Sauer, 1990; Strickler, 1923 and D.C. Froehlich, 1978. Almost all equations are based on particle size of bed material in the stream and not directly including energy losses contributed by other factors such as vegetation, meandering, obstructions et.c. This is indirectly accounted for in how the equation is formulated and as such, the equations are limited in their ability to give proper estimations for streams that are not like the streams they are based on. Coon therefore discusses the method put forward by Cowan, 1956. This method utilizes a base value for a straight, uniform, and smooth channel with the natural material for the streambed and the bank. Modifying values for further factors that affect the flow are then added to create the total Manning's coefficient.

$$n = (n_0 + n_1 + n_2 + n_3 + n_4) * m$$

Where
$n =$ total coefficient value
$n_0 =$ base value for straight uniform channel
$n_1 =$ cross section irregularity
$n_2 =$ variations in size and shape of the channel
$n_3 =$ effect of obstructions
$n_4 =$ effect of vegetation
$m =$ degree of meandering

Coon discusses the limitations of this approach and the risk of overestimation by including affecting factors multiple times. He further discusses previous studies with specific scope of estimating the effect of streambank vegetation.

The need for adjusting Manning's formula for non-uniform flow is further established and the method from Barnes, 1967 is explained and adopted. To calculate Manning's roughness coefficient the method from Barnes, 1967 and Jarret and Petsch, 1985, is used according to

$$n = \frac{1.486}{Q}\left[\frac{(h+h_v)_1-(h+h_v)_m-[(k\Delta h_v)_{1,2}+(k\Delta h_v)_{2,3}+\cdots+(k\Delta h_v)_{(m-1),m}]}{\left(\frac{L_{1,2}}{Z_1Z_2}\right)+\left(\frac{L_{2,3}}{Z_2Z_3}\right)+\cdots+\left(\frac{L_{(m-1),m}}{Z_{m-1}Z_m}\right)}\right]^{1/2} \quad (20)$$

This formula is based for measurements of multiple cross-sections along a reach of the stream, where denotation 1 marks the most upstream cross-section and m denotes the cross-section farthest down-stream.

$$Z = AR^{2/3} \quad (21)$$

The sites selected for the study were sought to have as little flow obstruction as possible, with relatively well-known stage discharge relationship curves. Care was also taken to select sites with very little or no overbank flow.

Data collection included water-surface profiles, stream discharges, photography, channel geography, streambed particle size and stream vegetation.

After calculating n-values for the over 300 water-surface profiles measured, a correlation matrix was used to identify the factor that had most significant impact on Manning's roughness coefficient. These included hydraulic radius, slope, stream-bed particle size and relative smoothness. It was found that for larger channels, with a width of 100 ft (~30.5 m) and low-gradient slope, the roughness coefficient only varied about 0.005 between lowest and highest measured flow. For smaller streams, with a lower relative smoothness ($R/d_{50} < 5$) it was found that the roughness coefficient was highly affected by flow depth. Lower flow depth resulted in higher roughness values and with increasing flow depth the value asymptotically approached a set value for the location. Between low-flow and bank full conditions n-values varied as much as 0.068 in the most extreme cases with a general interval of 0.015 to 0.030.
The factor with highest correlation to n-values was energy gradient (friction slope) and water-surface slope, 0.86 and 0.83 respectively. This is in line with previous cited research: (Riggs & Va., 1976), (Barnes, 1967) (Jarret, 1984) and (Bray, 1979), that suggests that slope is a better indicator of n value than bed material size.

The study also evaluates the effect of stream bank vegetation, this is however not a factor that is generally affecting fishway passages as they are constructed to be relatively void of vegetation.

Furthermore, Coon discusses that no single roughness equation can cover all type of streams and flow conditions. Previous work (Bathurst, 1978) suggests that for very large roughness vales ($R/d_{50} < 2$), is best described by drag on individual roughness elements, whereas for small roughness values, boundary-layer theory is more fitting.

Twelve different equations for calculation of n-values were assessed on their ability to match the computed n values in the study. The main finding was that no equation managed to properly estimate the roughness value at all stages for all locations. The equation that best estimated is from (Bray, 1979) with least mean absolute error at 0.002. Coon credits this to the similarity between the sites and flow conditions of the two studies rather than the equation being superior to others tested. Among the equations tested, only one were based on high-gradient conditions, similar to these prevalent for fish passages. That equation is by Jarret, 1984 and produced a mean absolute error of 0.008 for the 40 n-value calculation based on sites with gradient exceeding 0.002.

6.3 Estimation and calibration of Manning's roughness coefficients for ungauged watersheds on coastal floodplains

In the report "Estimation and calibration of Manning's roughness coefficients for ungauged watershed on coastal floodplains" (Boulomytis, Zuffo, Folho, & Imteaz, 2017) the objectives was to obtain stage-discharge relationships over sections of the river Juqueriquere in Brazil, use the method by Cowan, 1956 to estimate Manning's roughness values and calibrate estimated values from data.

Data was collected with acoustic dopplers and current meters. Slopes were calculated by reformulation of Manning's formula and the estimated roughness values. Based on this data a HEC-RAS model was implemented to study three river cross-sections. The model cross sections were then compared to calculated stages using rating techniques in an iterative manner.

The stage-discharge rating was determined satisfactory even though some sediment transport and scouring gave somewhat variable cross-sections. Coefficients of determination indicated proper fits with values over 90%.
Manning's n was determined according to Cowan, 1956. Base value was chosen as 0.024 for sections with bed material ranging between 4 and 8 mm in diameter, and 0.020 for sections with firm dirt bottom material. Adjustments for surface irregularities was chosen as 0.02 for one section with scalloped banks and 0.005 for other sections with slightly eroded banks. Values were collected from table 3 in Coon, 1998. Cross-section shape and size variation were chosen as either 0.015 or 0.005 depending on the cross-section as they had different degrees of variability. Degree of obstruction was chosen between 0.000 and 0.030 depending on cross-sections. Vegetation adjustment was chosen between 0.010 and 0.025. Finally, degree of meandering, *m*, was chosen as 1.0 for two of the sections and 1.15 for the third, according to Coon, 1998.

The results of the estimated and calibrated roughness values were presented in tabular format. Three key takeaways were also presented:

1. The base n_0 value itself overestimated the roughness compared to the later calibrated value indicating and overestimation of the tabulated values used from Cowan, 1956.
2. One section had double the maximum discharge compared to the others, which the authors pointed out as an possible correlation to the lower roughness of that section.
3. A combination of high flow and low biomass in spring led to a roughness coefficient minimum, also observed by (Song, Schmalz, & Fohrer, 2014)

Mean absolute deviation between estimated and calibrated n values was 0.008, 0.008 and 0.004. The best estimation was correlated to easier estimation process due to homogenous vegetation, less sedimentation and lower flows which allowed better profile overview.

6.4 Roughness coefficient and its uncertainty in gravel-bed river

In the paper "Roughness Coefficient and its Uncertainty in Gravel-bed River" (KIM, LEE, KIM, & KIM, 2010) the objective was to evaluate the two approaches to get a roughness coefficient value: direct measurements of flow and geometry or indirect methods based on evaluation of roughness factors or proxy equations. In the introduction the possible importance of accurate n-values is discussed referring to works by (Fread, 1988) and (Kim, Kim, & Woo, 1995) who got widely varying results when evaluating uncertainty in n-values on flood events.

Measurements were carried out on the Dalcheon River in South Korea, with a bed material mainly consisting of coarse gravels and cobbles with an alternating riffle and pool character and a 50-year flood of 1750 m^3/s. Bubbler gauges with continuous logging were used to obtain water level. River cross-section geometry was measured at 50-meter intervals. Bed material was sampled at 12 points according to the grid-by-number method (ISO 1992). Water surface slopes were measured at all cross-sections. Using NCALC software, roughness coefficients were calculated for 32 cases with discharges varying between 37 m^3/s and 1237 m^3/s.

Roughness coefficients were calculated for 32 cases by three methods: direct application of Manning's Equation, NCALC roughness calculation and NCALC weighted friction head loss calculation. The results are displayed in table that shows a correlation between lower flows and greater spatial variability in the roughness coefficient.

One finding was that the difference between using weighted values for friction head loss only had a significant effect on flow under 600 m^3/s. All three calculation methods showed a similar trend over the measured range of flows. The final chosen n value for the river for flows over 600 m^3/s according to NCALC- method 1.

The method by (Cowan, 1956), based on the sum of roughness elements, was also tested. Eleven different formulas were also evaluated. The value estimated by Cowan's method was 0.039. Values by Strickler based formulas, using bottom material diameter as proxy variable, gave results between 0.028 and 0.042. Power and semi-logarithmic formulas, amongst them formula, which use the Darcy-Weisbach friction factor and not Manning's roughness coefficient, gave generally somewhat lower results at flow over 400 m^3/s. For flows under 400 m^3/s they gave significantly lower values, down to about half of the values derived from measured data. This was explained by the increasing effect of the rivers irregularity as the flow is reduced.

The uncertainty of calculation of hydraulic roughness values were tested by comparing the flood level of the 50-year design flow with the roughness value calculated from the study and the official roughness value by the Basic River Plan (BRP), at 0.33, which is 20% less than that of the study for the design flow. HEC-RAS was used to simulate seven different flow conditions ranging from 37 m^3/s to 1750 m^3/s. The results gave and average 7% increase of water depth and 8% decrease of velocity with the 20% increase in roughness coefficient. The maximum difference was 15 % increase in water level corresponding to a 0.7-meter increase at a specific cross section. An analysis on the uncertainty of the roughness coefficient based on either a 5% or 10% uncertainty level in flow measurements showed that uncertainty of n varied from 9.9% to 6.2 % for a 5% measurement error at 37 m^3/s and 1000 m^3/s respectively. For a 10 % uncertainty level in flow measurement, the uncertainty in n varied from 14% at 37 m^3/s to 11.3 % at 1000 m^3/s.
The authors concluded that

1) Values calculated with the NCALC model decreased with increasing flow and spatial variation followed the same trend.
2) The method proposed by Cowan (1956) can give an approximative value but requires expertise and subjective judgement. Of the formulas evaluated, Limerinos formula performed the closest values to field measurements at discharges over 400 m^3/s.
3) The roughness values calculated in the study and official values deviated, resulting in a 7 % increase in water depth on average compared to water depths given by the official value.
4) A 10 % error of discharge measurements can lead to a *n*-value error of up to 14%, the resulting uncertainty in water level and velocity is however reduced to about 5 %. As such, roughness coefficients estimated by field measurements can be deemed as appropriate to estimate hydraulic variables.

7 Factors affecting Manning’s roughness coefficient

Several factors affect Manning’s roughness coefficient but to different degrees. The most important factors are:

- Type and size of bank and bottom material
- Channel geometry

Since the friction occurs mainly between the water and the flow boundary, the composition of bottom and banks will have a crucial effect on the roughness value. In technical situations such as pipe flow of or open channel flow through man-made channels constructed of concrete or similar material the values are commonly simply tabulated. In natural systems where a much greater variety of the bottom composition is the standard case such tables are not plausible to make. Still, it stands that a channel with a more even shape due to homogeneity of bottom material, generally in smaller diameters, will result in less resistance to the flow. In nature-like fishway passages, the bottom is typically rather varying, with coarse gravel as a base material used when constructed but with larger rocks being added for stabilization and to create pools and stream refuge. A natural shift of material will occur by recurrent high-and low flows that will displace lower diameter material and possibly also larger rocks.

The channel geometry both has its own effect and interacts with other factors such as bottom material composition. The longitudinal geometry has an impact as meanderings or full turns will greatly affect the flow compared to straight stretches of flow. A straight longitudinal section will allow the flow to gain momentum and have a greater flow compared to a meandering section where the water will face greater resistance. The cross-sectional geometry also has a great impact as a broad and shallow channel will have a lower hydraulic radius, meaning that a greater percentage of the flow will be affected by the flow boundary. Looking at two cross sections with the same cross section area, slope and n, the resulting flow as calculated by the formula will vary greatly due to the difference in hydraulic radius.

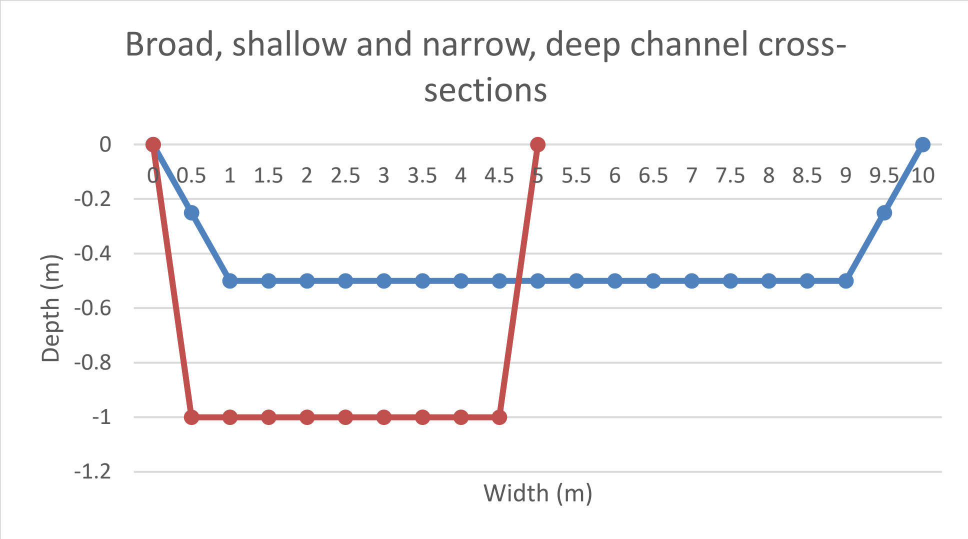

Figure 8. Illustration of two cross-sections with same area but different hydraulic radius.

Table 1. Illustrating impact of hydraulic radius on flow according to Manning's Equation, corresponding to Figure 8.

$S_{1,2}$ (m/m)	0.01
$n_{1,2}$	0.067
$A_{1,2}$ (m^2)	5.0
$R_{h,1}$ (m)	0.49
$R_{h,2}$ (m)	0.80
Q_1 (m_3/s)	4.6
Q_2 (m_3/s)	6.4

8 Measurement Methods

To determine the roughness coefficient, the geometry, flow, and slope of sections of different nature-like fishway passages were measured. Aspects of the measurements are described in respective sub-heading below. Fishways were chosen based on their proximity and flow levels that allowed safe entry to perform measurements.

8.1.1 Evaluation of water velocity meter

Accuracy of the two-point measurement method and continuous section measurement method was performed at Höje å and Bråån, close to the flow measurement stations run by SMHI, (station 2768, TROLLEBERG 2; station 2126, ELLINGE). The measurement tool used throughout the project was a Global Water Flow Probe FP111.

8.1.2 Two-point method

The two-point method is a point-measurement method to calculate flows. It is Carried out over a cross section of the water course. The cross section is divided into trapezoids with an even base length. The water velocity is measured at 20% depth and 80% depth in each trapezoid. The average velocity of each trapezoid is calculated and multiplied with its area to obtain the flow through it. By adding the flow of all trapezoids, the flow of the entire cross section is obtained.

8.1.3 Continuous section method

The continuous method is based on the same trapezoid approach, but instead of measuring the flow at two depths for each trapezoid, it is instead measured by moving the flow-meter continuously from bottom to top two times. The Global Water device samples the velocity once per second and outputs the mean velocity for the measured duration.

8.1.4 Rock density

At each measured length section, the number of rocks were counted. This counting was performed based on approximation and with the irregular and submerged nature of the rocks the measurements are more of a guideline than an exact measure. Depending on the quantity of flow, the rocks that were seemingly affecting flow characteristics, such as creating turbulence or stream refuge were counted. Thus, they did not necessarily extend above the water surface to qualify for being accounted for.

8.1.5 Hydraulic radius measurement

The profile of each section according to field survey was drawn in Excel, from the wetted perimeter and cross-sectional area the hydraulic radius was calculated.

8.1.6 Measurement of water surface slope

The water surface slope was measured by laser. The laser was pointed at some object, typically a rock, just at the height of the water surface a few meters upstream and downstream the measured cross section. The laser used was a Leica Disto E7500I and it automatically gives the height difference between the two points with an accuracy of. 1.6 mm. The length difference was measured by either folding rule or laser.

8.1.7 Photo documentation

At each site a thorough documentation was carried out through photograph of the surroundings, the water course, and its characteristics to deepen the understanding of the roughness factor to stream parameters.

9 Field Measurements and cross-sections

9.1 Höje å, Trolleberg, Control measurement 1

Control measurements to practice field measurements were carried out at Trolleberg in Höje å where SMHI (Swedish Meteorological and Hydrological Institute) has a flow measurement station. The flow value from SMHI was used to validate the field measurements conducted to establish their accuracy. At the site of measurement, the river had almost uniform flow characteristics with a rather even shaped river bottom made up of gravel and sand. Both the two-point method and the continuous method were evaluated three times each to determine which method produced the best accuracy. The results are summarized in Table 2.

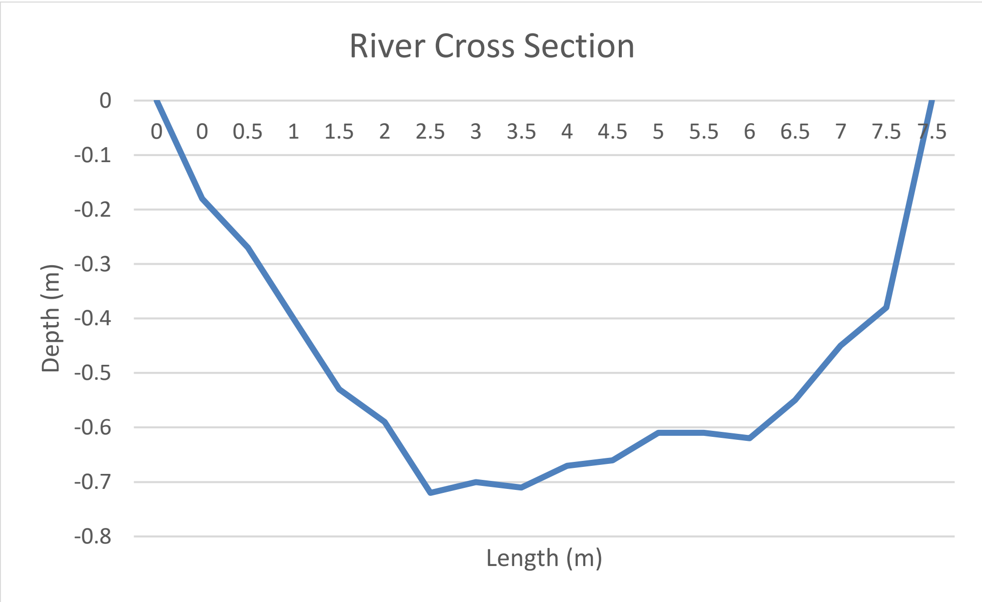

Figure 9. River Cross Section at control measurement site, Höje å.

Table 2. Results from both measurement methods and their mean value.

Method	**Test 1** *(m^3/s)*	**Test 2** *(m^3/s)*	**Test 3** *(m^3/s)*	**Mean** *(m^3/s)*
Two-point	1.71	1.64	1.60	1.65

method				
Continuous method	1.17	1.16	1.21	1.18

The flow according to the SMHI flow measurement station was 1.22 m^3/s. Thus, the mean value of the continuous method had the best accuracy.

9.2 Bråån, Ellinge, Control Measurement 2

Another flow measurement control was carried out in Bråån close to Ellinge where another SMHI flow measurement device was installed. Other parameters were also measured in order to determine Manning's roughness coefficient for the natural stream. SMHIs value for the flow of the day the measurement was conducted was 0.343 m^3/s.

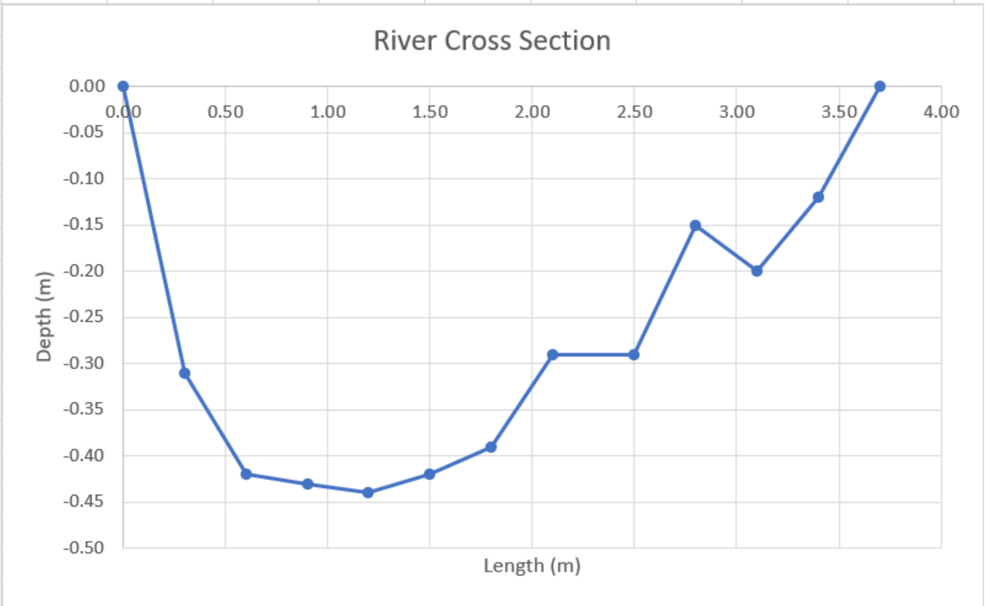

Figure 10. River Cross Section at control measurement site, Bråån.

Table 3. Results from both measurement methods and their mean value.

Method	Run 1 (m^3/s)	Run 2 (m^3/s)	Run 3 (m^3/s)	Mean (m^3/s)
2-point method	0.350	0.374	0.380	0.368
Continuous method	0.356	0.355	0.359	0.357

Again, the continuous method produced the most accurate results compared to SMHIs values, even though this sample size is very small. As the continuous method is more straight forward and faster it was chosen as the measurement method for the coming fishway visits.

9.2.1 Pictures of control measurement site, Bråån

Figure 1. Downstream view over measurement cross section


Figure 2. Upstream view over measurement cross section with folding rule marking exact cross section


Figure 3. Measurement cross section

9.2.2 Manning's roughness coefficient, Bråån, Ellinge

The cross-sectional profile and slope were measured at the control site to determine a Manning's roughness value for the river. The value of n was 0.069 and M was 14.4 for the measured section.

Table 4. Parameter for Bråån, Ellinge

L	8.8
dH	0.03
S_0	0.34%
A	1.067
P	3.94
R_h	0.27
Q	0.377
n	0.069
M	14.4

9.3 Silverforsen, Kävlingeån

9.3.1 General information and overview

River Kävlingeån is one of the larger rivers in Scania and runs from Vombsjön to its mouth nort of Bjärred. In the city of Kävlinge an old dam structure creates a migration barrier. A bypass has been constructed by making a breach in the dam wall. The upper part that was visited is formed as a single long curve. The flow is supercritical in its uppermost parts with an about 5% slope, and the rocky structure that has been created to form pools and stream refuge. As it curves the slope gradually decreases down to about 0.9 %, at the same time the rock density decreases. At the first visit no measurements could be made as the flow did not permit safe entry into the fishway, at the second visit only two cross sections could be measured as the flow in the upper half was still too strong. The total length and height difference could not be measured due to the bushy terrain surrounding the lower parts of the fishway. The following pictures gives an overview of the parts that were studied.

Figure 4. Upstream entry of the fishway, flow depth in pools is approximately 40-50 cm at the time of the visit.

Figure 5. Further downstream the slope is gradually decreasing

Figure 6. Further downstream before calm section

Figure 7. The fishway now changes character to deeper and less turbulent, less rocks. The surrounding bush becomes almost impenetrable.

9.3.2 Cross Section 1

The first cross section was measured at the end of the turbulent part of the fishway. The bottom was covered by rocks approximately 20-40 cm in diameter, number of flow obstructing rocks was 6. The n value for the section was 0.048 and M was 21.

Figure 8. First cross section measured at Silverforsen.

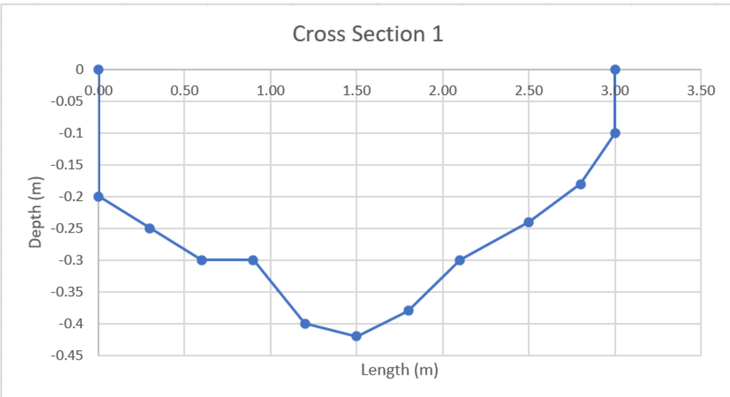

Figure 9. Cross section 1 measured at Silverforsen.

Table 5. General info section 1

L (m)	8
dH (m)	0.074
S_0	0.9%
A (m^2)	0.89
P (m)	3.36
R_h (m)	0.26
Q (m^3/s)	0.73
n	0.048
M	21

9.3.3 Cross Section 2

The second cross section was about 10 meters upstream from the first section, where the flow seemed more turbulent and with more rocks. The bottom was still covered by rocks approximately 20-40 cm in diameter. The n value for the section was 0.076 and M was 13.

Figure 10. Second cross section at Silverforsen.

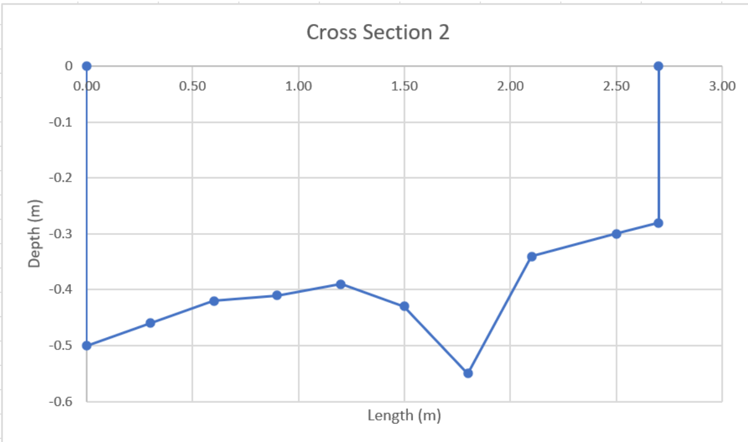

Figure 11. Cross section 2, Silverforsen.

Table 6. General info section 2

L (m)	7.5
dH (m)	0.09
S_0	1.2%
A (m^2)	1.11
P (m)	3.58
R_h (m)	0.31
Q (m^3/s)	0.73
n	0.076
M	13

9.4 Skarhult, Bråån

9.4.1 General information and overview

Bråån is one of the larger tributaries to Kävlingeån. It runs about 50 kilometers from northeastern Scania to Eslöv municipality, where it connects with Kävlingeån. At Skarhulp an old dam creates a migration barrier, and a bypass was constructed in 2003 with the main target to facilitate migration of sea trout and European eel. The bypass has a total length of 98 meters with a height difference of 1.68 m resulting in a mean slope of 1.68%. The bypass is constructed as a small natural stream with two almost full 180 degree turns. The slope is varying between sections with resulting higher and lower velocities. At the time of visit, the total flow in the bypass was 0.225 m^3/s as measured at the upper exit of the fishway. The width at the flow present during the measurements varied between 2 and 1.5 meter. Natural pools were formed by rock placement and loose rocks were scattered throughout the bypass to create refuge. The lowest slope was 0 % and the steepest was 5.8%.

9.4.2 Picture overwiev

Figure 11. Upstream exit in concrete and upper most part of fishway.


Figure 12. The upper straight section. Note the gradually calmer flow due to decreasing slope.


Figure 13. Calmer section with zero slope before rapids in the first turn.


Figure 14. Rapids in and between the two turns.


Figure 15. Final steep and narrow section just in front of the downstream exit.

9.4.3 Cross Section 1

The first cross section was measured just a few meters below the upstream exit. The flow characteristic was turbulent and non-uniform, the bottom covered with rocks of diameters ranging from 10 to 30 cm in diameter, number of stream affecting rocks was counted as 10. The calculated n-value was 0.065, translating to a M value of 15.

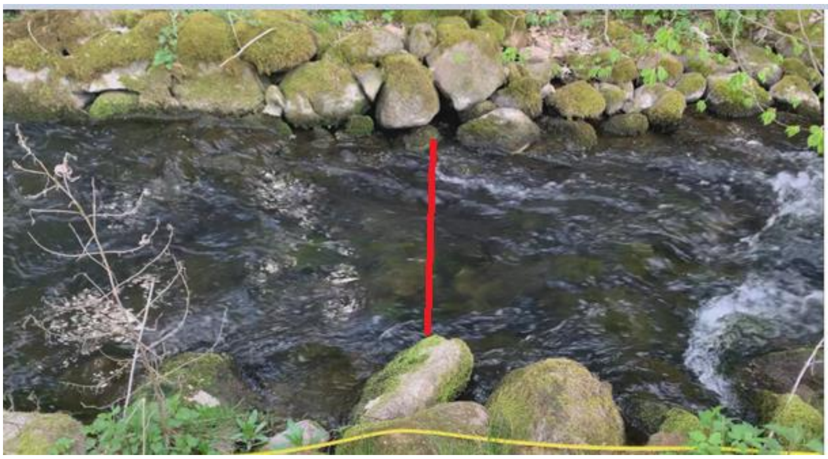

Figure 16. Section 1

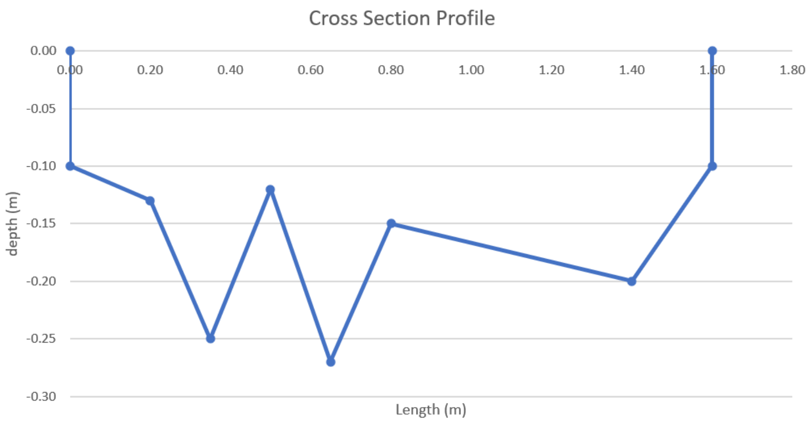

Figure 17. Cross section profile 1

Table 7.General info section 1

L (m)	10
dH (m)	0.40
S_0	4 %
A (m^2)	0.275
P (m)	2.02
R_h (m)	0.14
Q (m^3/s)	0.22
n	0.065
M	15

9.4.4 Section 2

The second section was measured about 7 meters downstream the first, where the flow was noticeably calmer, if still turbulent with standing waves. Bottom structure was a little less rocky compared to the first section, number of stream affecting rocks were counted as 7. The calculated n-value was 0.15, translating to a M value of 6.6.

Figure 12. Cross Section

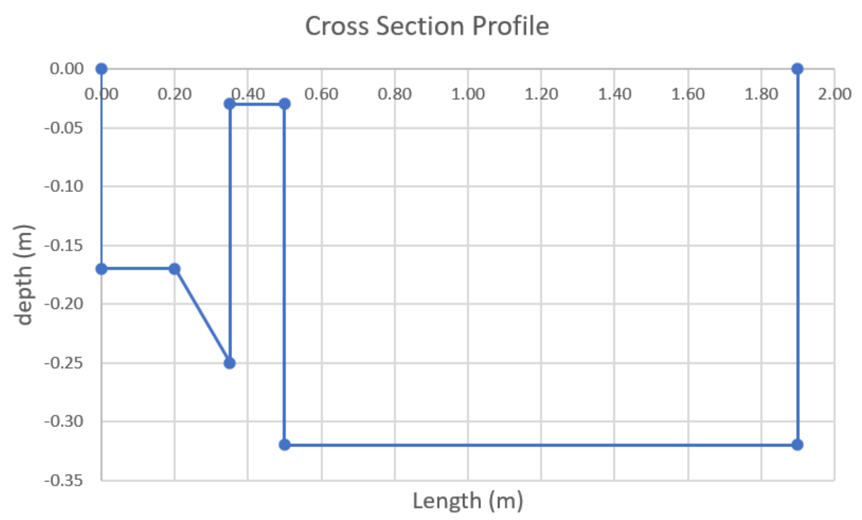

Figure 18. Cross section profile 2

Table 8. General info section 2

L (m)	10
dH (m)	0.40
S_0	4 %
A (m^2)	0.52
P (m)	2.76
R_h (m)	0.19
Q (m^3/s)	0.22
n	0.15
M	6.6

9.4.5 Cross Section 3

The third section was measured about 10 meters downstream the second, in a small pool created by the rock placement. In this section the bottom profile was relatively even due to the regular and small size of the rocks. Number of stream affecting rocks was calculated as 5. The calculated n-value was 0.12 with a resulting M-value of 8.6.

Figure 13. Cross section 3

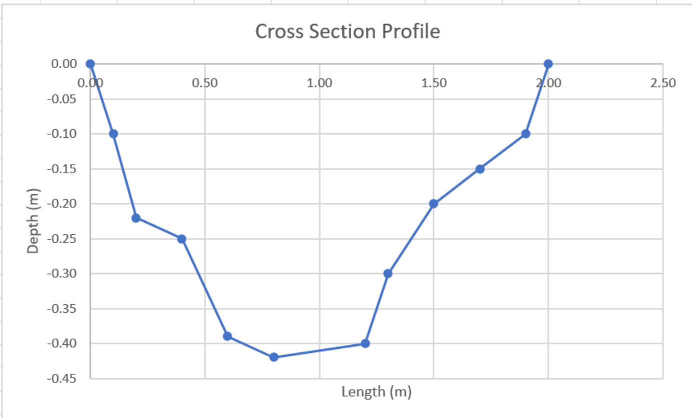

Figure 14. Cross section profile 3

Table 9. General info section 3

L (m)	10
dH (m)	0.17
S_0	1.7 %
A (m^2)	0.53
P (m)	2.27
R_h (m)	0.23
Q (m^3/s)	0.22
n	0.12
M	8.6

9.4.6 Cross section 4

The fourth section was measured at the beginning of the last pool of the first stretch of the fishway passage where the flow noticeably started to calm down. Some rocks on the bottom gave a rather uneven bottom profile. Stream affecting rocks were counted as 5. The calculated n-value was 0.09 with a resulting M-value of 11.

Figure 15. Cross Section 4

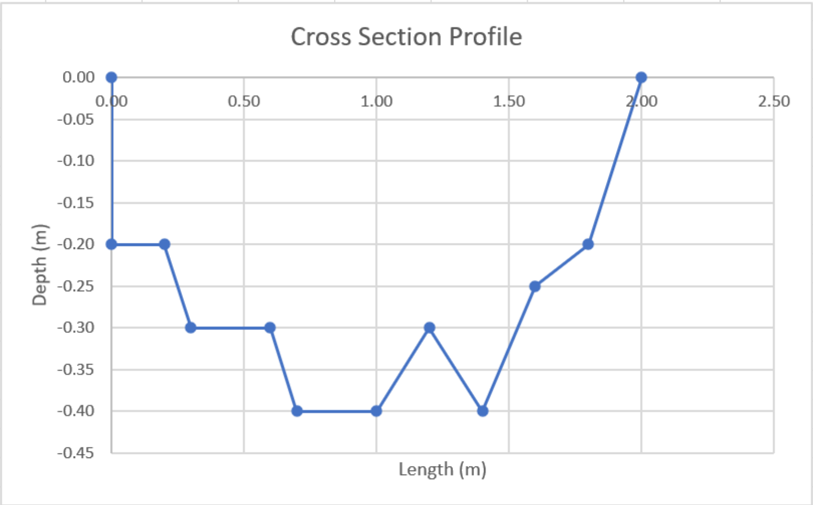

Figure 16. Cross section profile 4

Table 10. General info section 4

L (m)	10
dH (m)	0.05
S_0	0.5%
A (m^2)	0.68
P (m)	2.47
R_h (m)	0.28
Q (m^3/s)	0.22
n	0.09
M	11

9.4.7 Cross Section 5

The fifth section was measured at the calm pool before the first turn. In this section the flow looked almost uniform and without visible turbulence such as fluctuating water surface or standing waves. Number of stream affecting rocks were counted as 4. Since the section lacked a slope no n-value could be calculated.

Figure 17. Cross section 5

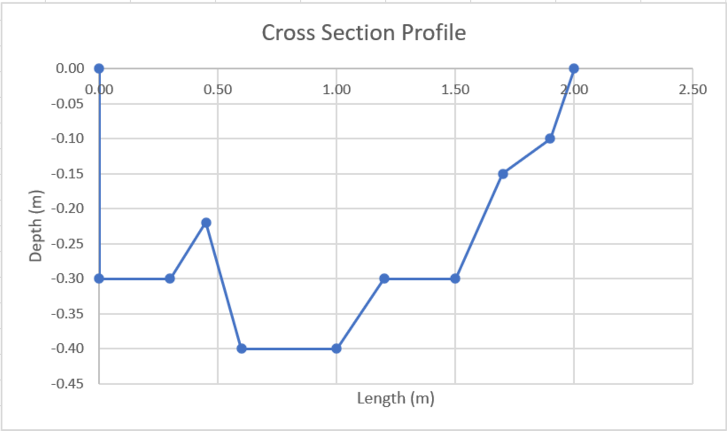

Figure 18. Cross section profile 5

Table 11.General info section 5

L (m)	5
dH (m)	0.0
S_0	0.0
A (m^2)	0.57
P (m)	2.53
R_h (m)	0.23
Q (m^3/s)	0.22
n	N/A

M	N/A

9.4.8 Cross Section 6

The last section was measured close to the downstream end of the fishway where the slope was significantly higher, and the fishway was more narrow. Small pools were created with rocks placed as sills. Rocks were counted as 6. The calculated n-value was 0.19, M-value was 5.2.

Figure 19. Section 6

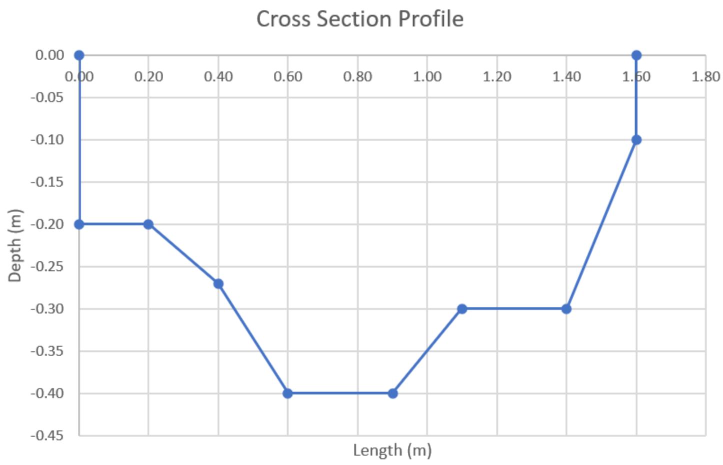

Figure 20. Cross section profile 6

Table 12. General info section 6

L (m)	8
dH (m)	0.46
S_0	5.8 %
A (m^2)	0.47
P (m)	2.01
R_h (m)	0.23
Q (m^3/s)	0.22
n	0.19
M	5.2

9.5 Skäralid, Skärån

Skärån at Skäralid in Södåsen national park is a smaller stream, where a dam has formed a small lake. A bypass was built in… in order to allow passage for sea trout and the native trout population. The upstream entry to the fishway is constructed as a natural lake outlet. The profile is rather wide and shallow, with a length varying between 2.8 to 3.2 meters and the depth was strictly less than 30 centimeters at the time of visit. The bypass had a varied slope between 0 to 6 %. Total length is 118 m and total height difference is 2.32 m.

9.5.1 Picture overview

Figure 21. Upstream natural lake outlet

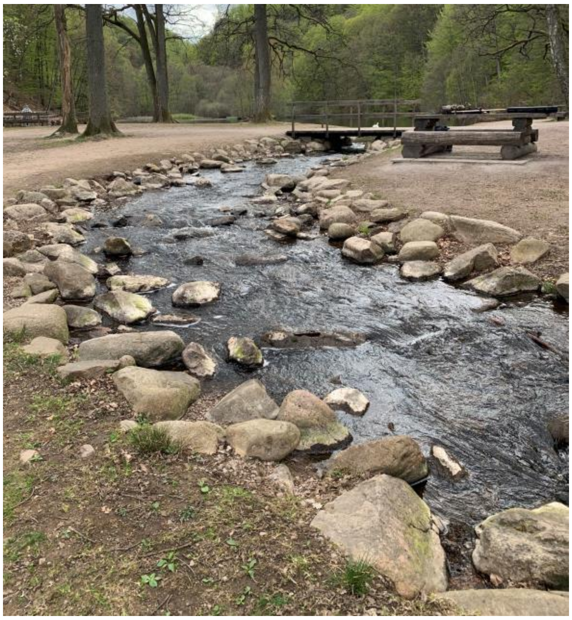
Figure 22. Rocky pool section downstream bridge


Figure 23. Entire meandering section before slow and wide pool with bridge

Figure 24. Second meandering section, with less rocks. Bridge pool is seen upstream

Figure 25. Turn before the last steep section


Figure 26. Steep section after last turn


Figure 27. Meandering steep section

9.5.2 Cross Section 1

The first measured cross section was between the natural lake outlet and the bridge, in a calm flowing shallow and broad section. The sides and bottom had scattered rocks in diameters up to 30 cm, rocks were counted as 7. This section was used to calculate flow as the relatively uniform flow should result in the best flow estimation as the fishway lacked any section with even concrete sides.

Figure 28. Cross section 1

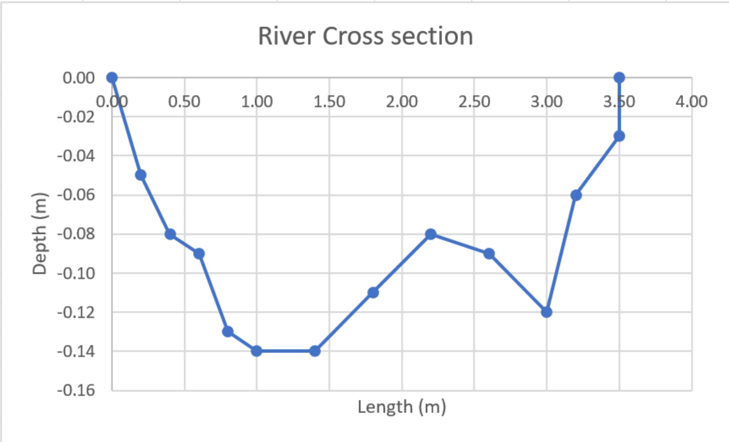

Figure 29. Cross section profile 1

Table 13. General info section 1

L (m)	6
dH (m)	0.015
S_0	0.25
A (m^2)	0.34
P (m)	3.56
R_h (m)	0.09
Q (m^3/s)	0.07
n	0.05
M	19

9.5.3 Cross Section 2

The second cross section was measured below the bridge, where the slope began to increase after the very calm first section. Rock placements on the created varying pools and small sills as well as an uneven bottom profile, rocks were counted as 12. The calculated n-value was 0.10 with an M-value of 10.

Figure 30. Cross section 2

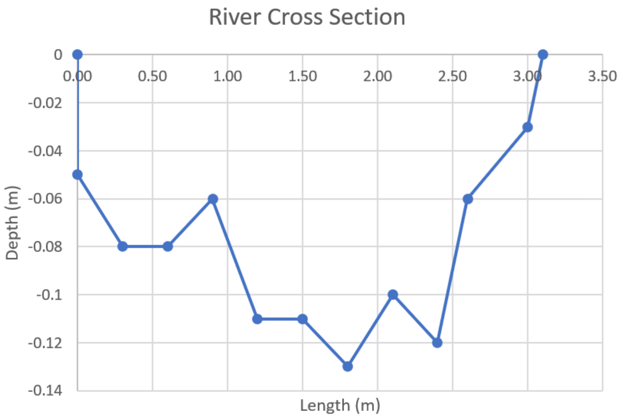

Figure 31. Cross section profile 2

Table 14.General info section 2

L (m)	6.5
dH (m)	0.11
S_0	0.016
A (m^2)	0.26
P (m)	3.17
R_h (m)	0.08
Q (m^3/s)	0.07
n	0.10
M	10

9.5.4 Cross Section 3

The third cross section was measured about 8 meters downstream of the second cross section. Rocks were counted as 25. Calculated n-value was 0.27, M was 3.7.

Figure 32. Cross section 3

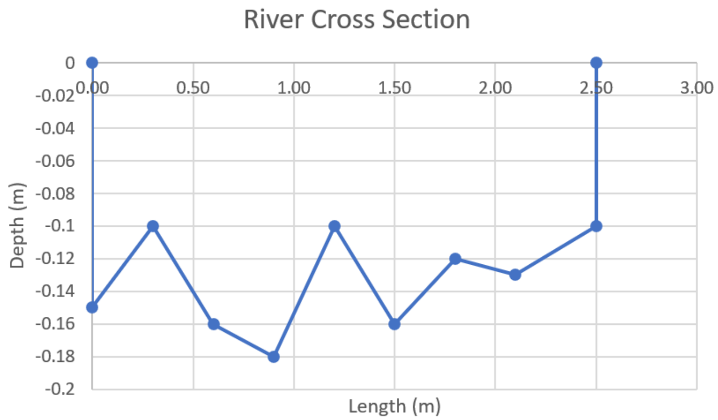

Figure 33. Cross section profile 3

Table 15. General info section 3

L (m)	9.6
dH (m)	0.38
S_0	0.040
A (m^2)	0.334
P (m)	2.78
R_h (m)	0.12
Q (m^3/s)	0.07
n	0.24
M	4.1

9.5.5 Cross Section 4

The fourth cross section was measured about 8 meters downstream of the second cross section. Rocks were counted as 10. Calculated n-value was 0.27, M was 3.7.

Figure 34. Cross section 4

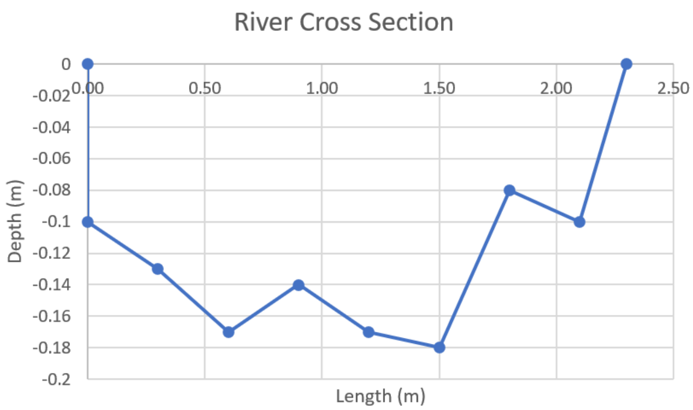

Figure 35. Cross section profile 4

Table 16. General info section 3

L (m)	6.2
dH (m)	0.031
S_0	0.5
A (m^2)	0.30
P (m)	2.45
R_h (m)	0.12
Q (m^3/s)	0.07

n	0.078
M	13

9.5.6 Cross Section 5

The fifth cross section was measured at the last relatively straight and steep stretch of the fishway. Rocks were counted as 12. Calculated n-value was 0.27, M was 3.7.

Figure 36. Cross section 5

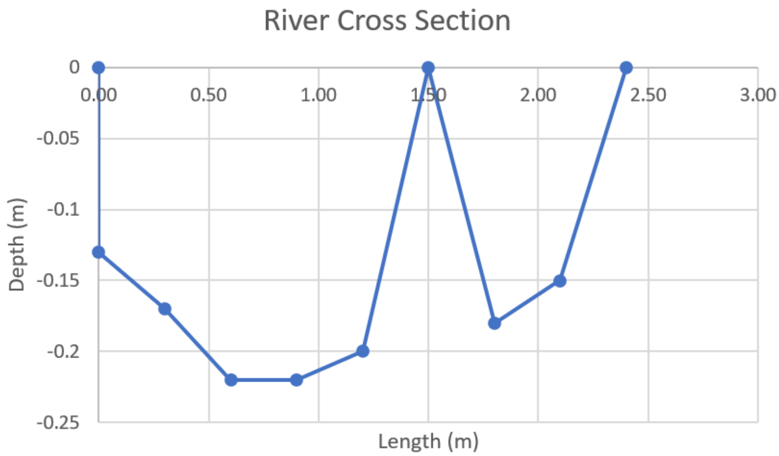

Figure 37. Cross section profile 5

Table 17.General info section 5

L (m)	10.2
dH (m)	0.351
S_0	3.4%
A (m^2)	0.36
P (m)	2.68
R_h (m)	0.13
Q (m^3/s)	0.07
n	0.26
M	3.8

9.5.7 Cross Section 6

The fifth cross section was measured at the last relatively straight and steep stretch of the fishway. Rocks were counted as 10. Calculated n-value was 0.27, M was 3.7.

Figure 38. Cross section 6

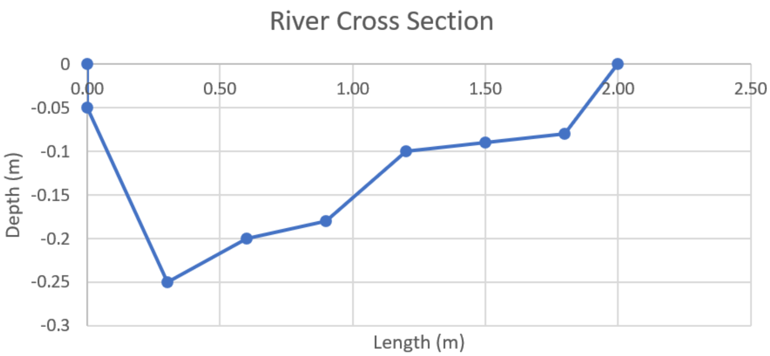

Figure 39. Cross section profile 6

Table 18. General info section 6

L (m)	8.1
dH (m)	0.11
S_0	0.016
A (m^2)	0.27
P (m)	2.14

R_h (m)	0.13
Q (m^3/s)	0.07
n	0.22
M	4.6

9.6 Haväng, Verkeån

Verkeån is a small river on Österlen in south-eastern Scania Only about 700 meters from the mouth of the river is a fishway constructed to create a workaround for an old fish trap. The width varies between 5 and 2.5 meters, with a total length of 63 meters, height difference is 0.88 meters which results in a mean slope of 1.4 %. The slope varies between about 0.13 to 2.7.

9.6.1 Picture overview

Figure 40. Upstream exit of the fishway with installed fishcounter


Figure 41. Upstream view over bridge and fishway entry


Figure 42. Upper bend of the fishway

Figure 43. Downstream view over main stretch of the fishway

Figure 44. End of main stretch where slope and turbulence increases


Figure 45. Downstream bend with turbulent flow


Figure 46. Downstream exit of the fishway

9.6.2 Cross Section 1

The first section was measured between the upstream exit and the bridge where the flow was relatively smooth, and the riverbed appeared to be relatively even. Rocks were counted as 5. The calculated n value was 0.017, translating to a M value of 6.

Figure 47. Cross section 1

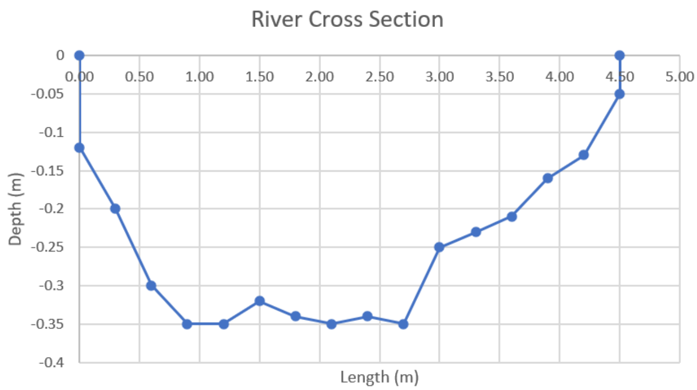

Figure 48. Cross section profile 1

Table 19. General info section 1

L (m)	5.0
dH (m)	0.07
S_0	0.014
A (m^2)	1.19
P (m)	4.74
R_h (m)	0.25
Q (m^3/s)	0.32
n	0.02
M	6

9.6.3 River Cross Section 2

The second cross section was through the bridge. The bottom profile was relatively rough with rocks of different sizes, rocks were counted as 8. The calculated n value was 0.084 and the M value was 12.

Figure 49. Cross section 2 at downstream side of the bridge

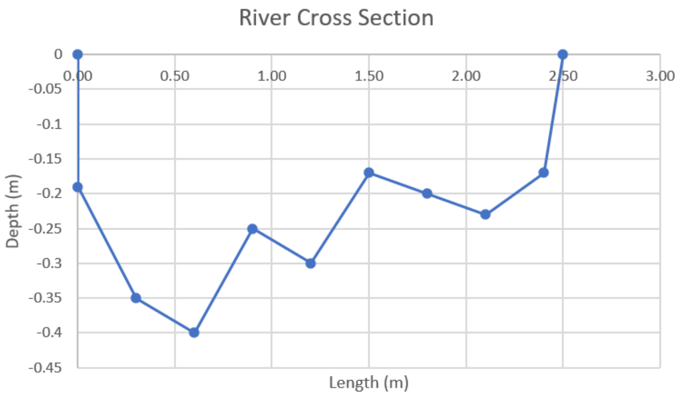

Figure 50. Cross section profile 2

Table 20.General info section 2

L (m)	5
dH (m)	0.07
S_0	0.014
A (m^2)	0.63

P (m)	2.91
R_h (m)	0.22
Q (m^3/s)	0.32
n	0.084
M	12

9.6.4 Cross section 3

The third cross section was measured after the first bend, approximately 8 meters downstream the bridge. This section was broader and calmer due to the lower slope. Rocks with diameters up to 50 cm were scattered but did not create any visible turbulence, rocks were counted as 7. The calculated n value was 0.062 and the M value was 16.

Figure 51. Cross Section 3

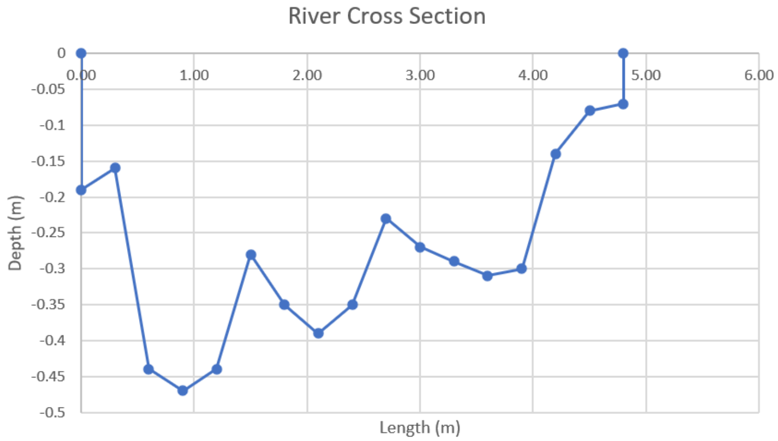

Figure 52. Cross section profile 3

Table 21. General info section 3

L (m)	6.5
dH (m)	0.11
S_0	0.016
A (m^2)	0.26
P (m)	3.17
R_h (m)	0.08
Q (m^3/s)	0.32
n	0.10
M	10.4

9.6.5 Cross section 4

The fourth cross section was measured at the end of the straight section where the slope began increasing again. The density of the rocks increased while their mean diameter decreased to approximately 35 cm, rocks were counted as 12. The calculated n value was 0.088 and the M value was 11.

Figure 53. Fourth cross section

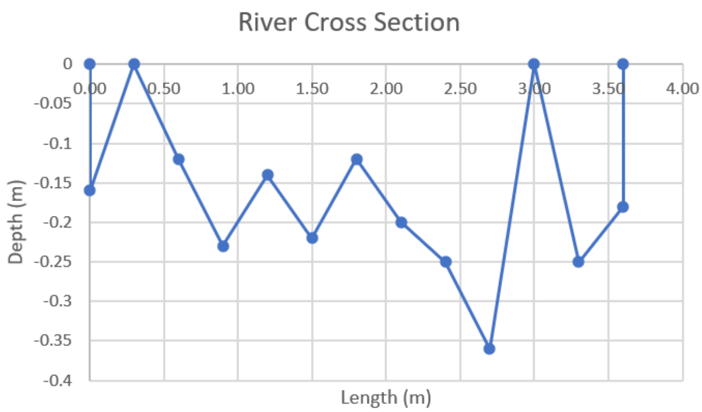

Figure 54. Cross section profile 4

Table 22. General info section 4

L (m)	6.5
dH (m)	0.11
S_0	0.016
A (m^2)	0.26
P (m)	3.17
R_h (m)	0.08
Q (m^3/s)	0.32
n	0.10
M	10

9.6.6 Cross Section 5

The final cross section at the steepest part was measured where the flow was compressed between two rocks. The calculated n value was 0.015 and the M value was 11.

Figure 55. Cross section 5

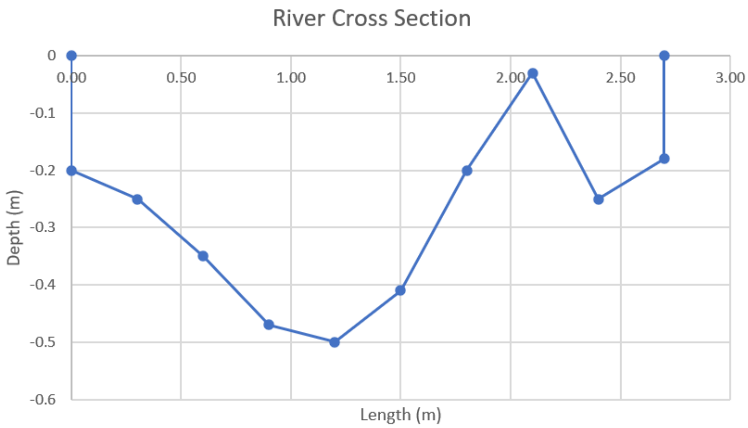

Figure 56. Cross section profile 5

Table 23.General info section 5

L (m)	6.5
dH (m)	0.11
S_0	0.016
A (m^2)	0.26
P (m)	3.17
R_h (m)	0.08
Q (m^3/s)	0.32
n	0.10
M	10

10 Results

In this study, 20 cross sections from 4 different fish passages and 1 natural stream were measured and analyzed. Since one measured cross section had no slope, it had to be disregarded from the rest of the results as no meaningful roughness value could be extracted. The average roughness value for the studied sections was n = 0.095 and M = 10.5. The results are summarized below:

Table 24. General info all sections

	Name	S_0	Rh	Mean Depth	Max Depth	Flow	Mean velocity	Rock density	M
1	Verkeån1	1.4	0.25	0.25	0.35	0.32	0.27	0.22	5.7
2	Verkeån2	1.4	0.22	0.25	0.4	0.32	0.51	0.64	11.9
3	Verkeån3	0.1	0.26	0.28	0.47	0.32	0.23	0.16	16
4	Verkeån4	2.7	0.15	0.17	0.36	0.32	0.52	0.45	11.3
5	Verkeån5	2.7	0.24	0.28	0.5	0.32	0.4	0.6	6.4
6	Skäralid1	0.3	0.09	0.09	0.14	0.07	0.2	0.33	19.3
7	Skäralid2	1.6	0.08	0.08	0.13	0.07	0.25	0.6	10.4
8	Skäralid3	4	0.12	0.13	0.18	0.07	0.2	1.04	3.7
9	Skäralid4	0.5	0.12	0.13	0.18	0.07	0.22	0.7	12.7
10	Skäralid5	3.4	0.13	0.15	0.22	0.07	0.19	0.49	3.8
11	Skäralid6	4.4	0.13	0.14	0.25	0.07	0.25	0.62	4
12	Ellinge1	0.3	0.27	0.31	0.44	0.36	0.33	0.12	13.6
13	Silverforsen1	0.9	0.26	0.28	0.42	0.73	0.82	0.25	20.7
14	Silverforsen2	1.2	0.31	0.41	0.55	0.73	0.66	0.4	13.1
15	Skarhult 1	4	0.14	0.17	0.27	0.22	0.82	0.63	15.5
16	Skarhult 2	4	0.19	0.18	0.32	0.22	0.43	0.37	6.6
17	Skarhult 3	1.7	0.23	0.25	0.42	0.22	0.43	0.25	8.6
18	Skarhult 4	0.5	0.28	0.3	0.4	0.22	0.33	0.25	11
19	Skarhult 6	5.8	0.23	0.27	0.4	0.22	0.47	0.47	5.3

11 Uncertainty Analysis

All measurements conducted results in a degree of uncertainty, and how this affects the calculated results is important to study in order to evaluate their applicability. In this section uncertainty in the velocity measurements, depth measurements and slope measurement swill first be evaluated individually, the combined uncertainty effect will be studied last.

11.1 Uncertainty in flow calculations

The uncertainty of the flow calculations includes both uncertainty in water velocity measurements and cross-section geometry measurements as these values are combined in the flow calculations. By studying the results from the control measurements, and assuming that the values presented by SMHI are correct, the two most deviating values from the performed measurements both deviate 5% from the SMHI values. Applying a 5% error in flow calculations directly result in a 5% uncertainty range of the roughness coefficient calculation.

11.2 Uncertainty in slope measurement

Evaluating the uncertainty of the slope measurements is rather complex since several factors interact in the actual value that is used in calculations. The largest source of error in measurement is most likely the height difference measurement, as it was sometimes very difficult to point down the position of the laser being in exact line of the water. A reasonable uncertainty level, based on experience from the field measurements, is that the laser might have deviated up to 3 mm from the actual water level. The worst-case scenario would then be a total height difference error of 6 mm, since two points must be measured to obtain a height difference. The effect of 6 mm error in height difference then depends on the length of the measured section: the longer the section, the lesser the effect, and the actual height difference. The length of sections varied, but 8 meters can be chosen as a standard value. If the heigh

difference measured was 0.15 meters, and a possible error was made of 0.006 meters, then the uncertainty of slope is 4 % which in turn translate to only 2% uncertainty of the actual roughness coefficient calculation.
For lesser slopes, however, a measurement error of that magnitude would have an increasingly adverse effect on roughness calculations. If the height difference is only 0.05 meters over a 8 meter length, with the potential error still at 0.006 meters, then the uncertainty of the slope is 12% and the uncertainty of the roughness calculation is 3.5 %. Lower slopes do, however, generally imply easier measuring conditions with more stable water levels and possibilities to enter the stream with the laser pointer for optimal positioning. Therefore, the worst-case scenario becomes less likely to happen as its effect increases.

11.3 Combined uncertainty effect

From above sections a 5 % uncertainty level from flow measurements and up to 4 % from slope measurements. With some errors from other geometry a reasonable approximation of error could be 10 %. This seems rather large, but the actual effect on roughness values is not adverse enough to exclude application of the findings. The effect of 10% uncertainty is shown below in Table 25.

Table 25. Effect of 10 % uncertainty on a range of roughness coefficient values.

M	+ 10%	- 10%
5	5.5	4.5
10	11	9
15	16.5	13.5
20	22	18

12 Linear Regression Analysis

Four different variables were tested for their correlation with M to search for appropriate ways to describe and estimate the factors with most significant effect on M/n. Plots of each respective variable and M is shown below as well as a table with Pearson correlation values. It is important to note that the correlation of variables that are also parameters in Manning's Equations has spurious tendencies as the correlation is made with values that has been calculated by the variables.

Table 26. Correlation coefficients for evaluated variables

Variable	**R value**
S_0	- 0.66
Maximum depth	0.15
Mean depth	0.16
Hydraulic radius	0.14
Flow	0.45
Mean Velocity	0.43
Rock density	-0.40

12.1 Slope

The first variable studied is the slope of the water level. The Pearson correlation related to M was -0.66, the most significant correlation of the studied variables. This result is to be expected as the reformulated equation for extracting Manning's roughness coefficient.

$$\frac{1}{M} = \frac{A}{Q} R^{2/3} S_0^{1/2} \qquad (22)$$

From the equation it is given that M and S_0 has an inverse relationship, which is further confirmed by the results. No one of the variables can be evaluated individually, all of them will be affected by the others. It is however reasonable to think that with increasing slopes the flow will become more turbulent, and the higher loss of energy will reflect a lower M-value.

A higher slope will also typically mean that the flow is less uniform and will deviate more from the uniform flow that Manning's Equation is formulated for.

Table 27. Slope values

	Slope
High	5.8 %
Low	0 %
Mean	2.2 %

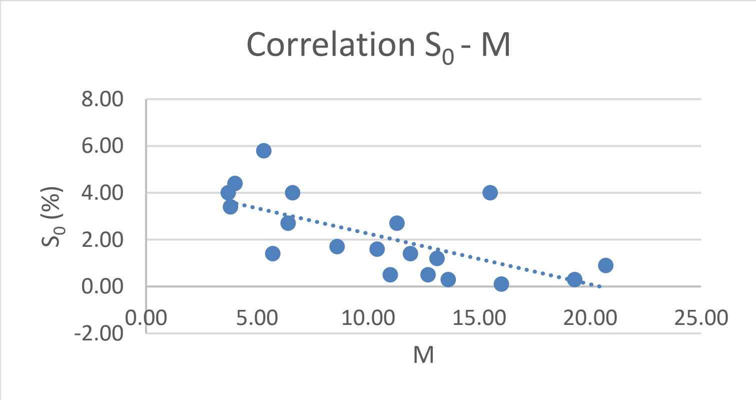

Figure 19. Fitted line for slope plotted against M

12.2 Maximum depth

The variable maximum depth was studied as it was hypothesized that greater maximum depths would lead to higher M values. This would be because deeper sections would be likely to have more uniform characteristics and a lower velocity close to the edges and bottom, that would in turn create less friction. From the dot diagram and correlation value, it does however not seem to exist any significant relation. The correlation factor was 0.13 which points to an almost random variation. This could be explained by the hypothesis being true for some cross section, while a high maximum depth was created by rocky sections at other locations. At the same time, some sections such as Section 1, Skäralid, had a very low max depth but also a rather even shape with low slope and few rocks, giving a high M value despite the depth. Interesting to note is that the mean maximum depth was only 0.34 m, while it is recommended by (DVWK, 2002) to have a minimum depth of 30 cm. Thus, evaluating the depth of small nature-like fishways could be interesting.

Table 28. Max depth values

	Max depth (m)
High	0.55
Low	0.13
Mean	0.34

Figure 20. Fitted line for max depth plotted against M

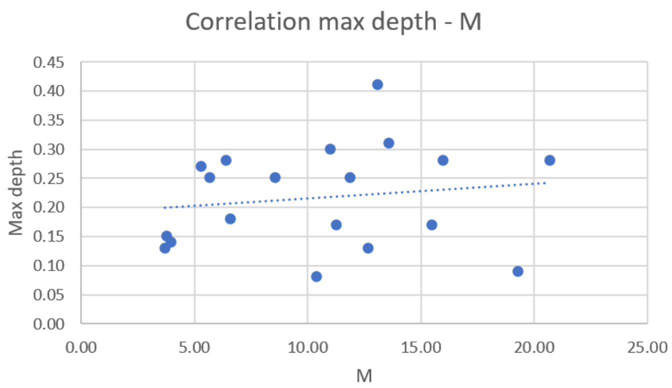

Figure 21. Fitted line for max depth plotted against M

12.3 Mean depth

The hypothesis for mean depth was similar to the one for max depth. Again, a low correlation factor, 0.15, marks an almost random relationship. Another factor that could explain this is the relative size of the rocks that are placed in the water. As depth and width expands, the rocks typically become bigger and thus have a similar effect as smaller rocks in more shallow water, thereby eradicating the effect of a greater mean depth. Similarly, to the max depth variable, other factors that are completely unrelated to depth such as slope can have greater effect on the roughness value.

Table 29. Mean deapth values

	Mean depth (m)
High	0.41
Low	0.08
Mean	0.22

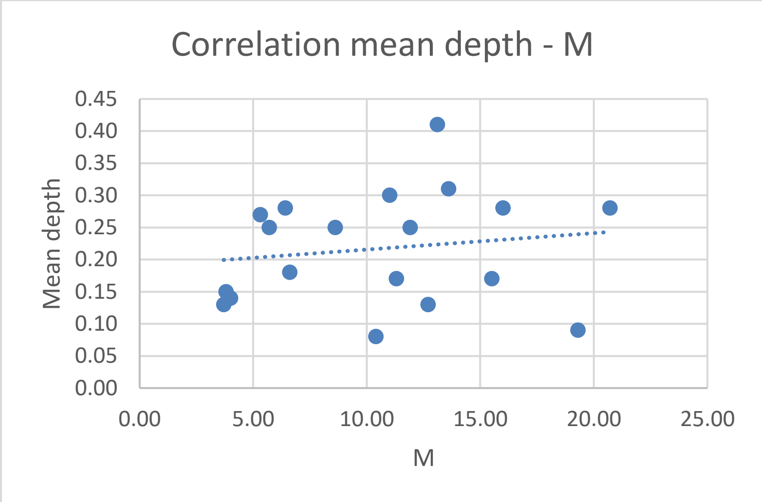

Figure 22. Fitted line for mean depth plotted against M

12.4 Hydraulic radius

It was hypothesised that a greater hydraulic radius – meaning that a greater share of the flow doesn't interact with the flow boundaries – would have an parallel relationship with M. From Eq. (19) it can however be seen that M would actually increase (lower friction) with an increase in R_h. Similar to mean depth, the potential friction-coefficient loss due to a greater hydraulic radius can, and often is, counteracted be simultaneous upscaling of flow barriers. Thus, the effect would be best measured in a single cross section with multiple flow levels. That way a potential relationship with R_H or mean depth as factors could be more individually studied. Such measurements was however not in the scope of this study.

$$\frac{1}{M} = \frac{A}{Q} R^{2/3} S_0^{1/2} \qquad (29)$$

Table 30. Hydraulic radius values

	Hydraulic radius
High	0.31
Low	0.08
Mean	0.19

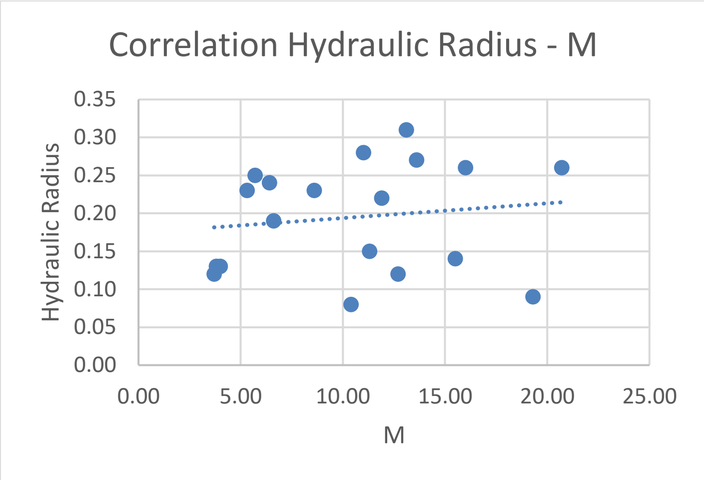

Figure 23. Fitted line for hydraulic radius plotted against M

12.5 Flow

The flow and the roughness seemed to have a positive relationship, with a correlation value of 0.45. This is however highly influenced by the two outliers from Silverforsen. If they are removed from the dataset the correlation factor decreases to 0.17. Again, a similar analysis can be done compared to R_h and max/mean depth where other factors such as rocks and slope affect the M-value.

Table 31. Flow values

	Flow (m^3/s)
High	0.73

Low	0.07
Mean	0.41

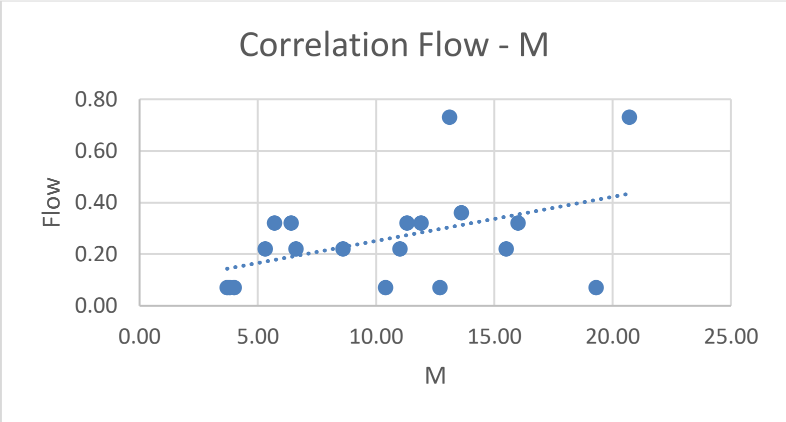

Figure 24. Fitted line for flow plotted against M

12.6 Mean velocity

It was hypothesized that a lower mean velocity should result in a higher M value due to lower turbulence and friction along the flow boundaries. From the initial dot plot it seems that the variable was positively related with a correlation value of 0.42. Again, the two values from Silverforsen have a heavy influence on the overall result, however, the first value from Skäralid acts in the opposite direction where it has same magnitude deviance from the fitted line.

Table 32. Mean velocity values

	Mean velocity (m/s)
High	0.82
Low	0.19
Mean	0.40

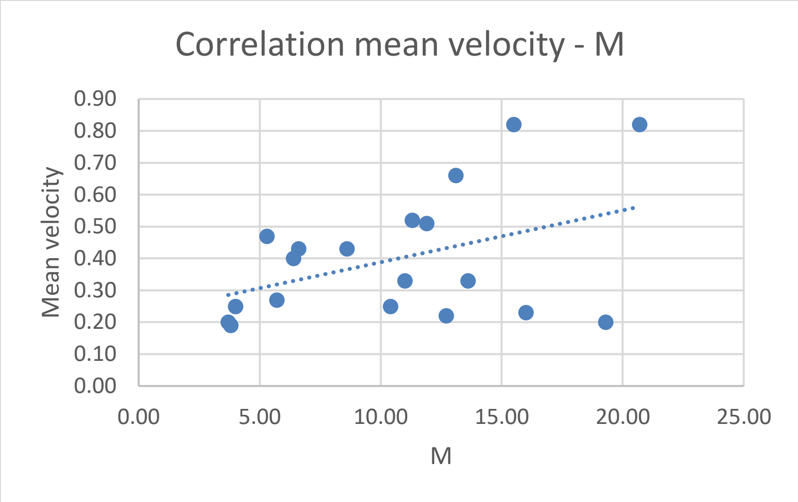

Figure 25. Fitted line for mean velocity plotted against M

12.7 Rock density

Rock density was one of the more subjective measurements and could be greatly improved with appropriate resources, but the hypothesis is that a higher rock density should create more friction and resistance to the flow, and thus a lower M value. The inverse should thus be inverse, which it seems to be with a correlation factor at -0.4, which still is not too significant. The measurement of the rock density is however not one obviously picked. The decision of what rocks that was counted was relatively subjective and it is natural that fewer larger rocks or more evenly spaced rocks will increase flow resistance for a stream with otherwise same qualities. Also shape and material of rocks will create differences on their effect on roughness. A more thorough measurement would require a substantial amount of time which was not possible in the scope of this study.

Table 33. Rock density values

	Flow (number/m^2)
High	1.04
Low	0.12
Mean	0.45

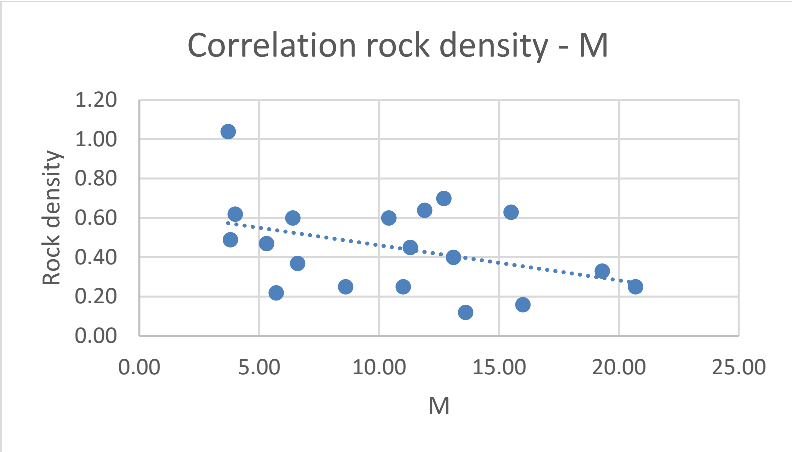

Figure 26. Fitted line for rock density plotted against M

13 Linear Multi Regression Analysis

To study the effect on Manning's roughness coefficient by several variables a multilinear regression with logarithmic transformation was performed. Four variables were included: flow (Q), slope (S_0), mean velocity (V_m) and rock density (R_d). The results for respective variable are presented in Table 34 below.

Table 34. results of multilinear regression

	Coefficient	*Std. error*	*t-value*	*p-value*	*Lower 95%*	*Upper 95%*
A	3.18	0.17	19.05	0.00	2.83	3.54
Q	-0.42	0.10	-4.22	0.00	-0.63	-0.21
S_0	-0.56	0.05	-12.20	0.00	-0.66	1.67

V_m	1.34	0.15	8.82	0.00	1.02	1.67
R_d	0.08	0.10	0.75	0.47	-0.15	0.30

The resulting formula to describe the roughness coefficient would then be

$$\ln M = 3.18 - 0.42 \ln Q - 0.42 \ln S_0 + 1.34 \ln V_m + 0.08 \ln R_d \quad (23)$$

Since the p-value for rock density was greater than 0.05 a second multilinear regression was made disregarding it. The R^2 value was still 0.94 and the standard error was 0.15. See Table 35.

$$\ln M = 3.08 - 0.46 \ln Q + 1.38 \ln V_m - 0.54 \ln S_0 \quad (24)$$

Table 35. Multilinear regression without rock density

	Coefficient	*Std. error*	*t-value*	*p-value*	*Lower 95%*	*Upper 95%*
A	3.08	0.09	34.67	0.00	2.89	3.27
Q	-0.46	0.08	-5.59	0.00	-0.64	-0.28
V_m	1.38	0.14	9.71	0.00	1.08	1.68
S_0	-0.54	0.04	-13.68	0.00	-0.63	-0.46

A step forward in Swedish research regarding nature-like fishway passages could be to expand data sets on variables and evaluate regression models to seek well-functioning equations to describe typical fishway conditions.

14 Roughness value comparisons

In current design of fishway passages it is common practice to assign a fixed roughness value that is used throughout the design process when evaluating flows and resulting water levels. As seen in the results from the data collected in this study, the actual values of the roughness coefficient can vary substantially both between different installations but also within the same passage. The design of fishways always deals with a range of unknown factors and a precise estimation of water levels down to centimetre level accuracy is very hard to achieve. As such, the impact of choosing potentially inaccurate roughness coefficients might be best dealt with by ensuring safety intervals.

To evaluate the effect of the roughness coefficient, each measured cross section was assigned four different roughness values: M = 5;10;15, and 20, values that represent the approximate range found when calculating actual roughness coefficients. The resulting flow given, assuming that the cross-sectional area and hydraulic radius remained constant, was calculated and compared to actual measured values. The results are shown in Table 36.

Table 36. Results of variable Manning's M flow calculation

M	5	10	15	20
Average factor value	2.16	1.08	0.72	0.57

This suggests that the commonly used value of 15 is not as accurate as a roughness coefficient value of 10, or somewhere in between, and that calculation of water levels based on M = 15, when in reality, M = 10 should be more accurate, would result in a mean water level error that was 38% too high.

14.1 Adjustment factor evaluation

Realizing the difficulty for easy data collection that can be used to calculate roughness coefficient it can be interesting to compare it to the more subjective approach used in USGS (1989):

$$n = (n_0 + n_1 + n_2 + n_3 + n_4) * m$$

Where

$n =$ total coefficient value

$n_0 =$ base value for straight uniform channel

$n_1 =$ cross section irregularity

$n_2 =$ variations in size and shape of the channel

$n_3 =$ effect of obstructions

$n_4 =$ effect of vegetation

$m =$ degree of meandering

With the relative similarities between the sites, it would probably not be possible to distinguish them with any meaning by this approach, but a general example can be made. From (Coon, 1998) base values are given according to the table below:

Table 37. Base n values depending on bottom material

		n	n	n
Bed material	**Median size (mm)**	**Benson and Dalrymple (1967)**	**Chow (1959)**	**Bray (1979)**
Coarse sand	1-2	0.026-0.035	-	-
Fine gravel	4-8	-	0.024	-
Gravel	2-64	0.028-0.035	-	-
Coarse gravel	16-32	-	0.028	-
Very coarse gravel	32-64	-	-	0.032
Small covvle	64-128	-	-	0.036
Cobble	64-256	0.030-0.050	-	-
Boulder	>256	0.040-0.070	-	-

Channel condition	***n* value adjustment**
Cross section irregularities, n_1	
Smooth	0.000
Minor	0.001-0.005
Moderate	0.006-0.010
Severe	0.011-0.020

Channel variation, n_2	
Gradual	0.000
Alternating occasionally	0.001-0.005
Alternating frequently	0.010-0.015
Effect of obstruction, n_3	
Negligble	0.000-0.004
Minor	0.005-0.015
Appreciable	0.020-0.030
Severe	0.040-0.060
Channel vegetation, n_4	
Negligble	0.000
Small	0.002-0.010
Medium	0.010-0.025
Large	0.025-0.050
Very large	0.050-0.100
Degree of meandering, m	
Minor	1.000
Appreciable	1.150
Severe	1.300

The bed material varied both between the different sites studied, but also within sites as different cross-sectional velocities will create different conditions for sedimentation. The finest bed material was fine gravel and the coarsest was cobble, resulting in a base value interval of 0.024 to 0.05.
Cross section irregularities accounts for erosion and irregularities mostly along the banks. Generally, the banks had scattered small rocks along them, resulting in a classification as moderately irregular with a n-value interval of 0.006 - 0.01.
All sites had some variations of the cross sections and a flow pattern that sometimes shifted side. The modification for channel variation could therefore be classified as Alternating occasionally with an n-value range of 0.010 - 0.015.

The effect of obstruction was mostly due to the rocks placed in the flow. As earlier described, the rock density varied but where in most sites appreciable, with an n-value range of 0.02-0.03.
Channel vegetation was in all cases negligible with $n_4 = 0$.
The degree of meandering also varied, with some sites such as Skäralid having an appreciable to severe degree, but most sites would be categorized as appreciable with m = 1.15.

Table 38. Chosen adjustment factors

	high	mean	low
n_0	0.05	0.037	0.024
n_1	0.01	0.008	0.006
n_2	0.015	0.0125	0.01
n_3	0.03	0.025	0.02
n_4	0	0	0
m	1.15	1.15	1.15
n	0.12	0.09	0.07
M	8.3	11.1	14.5

Table 38 shows three scenarios: the two extremes where either the lowest or the highest adjustment factors have been chosen, and one between where the mean of each adjustment was chosen. Even though the action of deciding adjustments factors is hard this displays a range for the studied fishways. The values are in line with the calculated values based on field measurments. The full range displayed by the measured sites is however not reflected, calculations varied almost between M = 3 and M = 20. This might be explained by the difference between the sites in this study and sites used to produce the adjustment factors and the inexperience of the author of this study.

14.2 DVWK Darcy roughness method evaluation

The method for Darcy roughness with added roughness from rocks presented in the section on 4 Darcy-Weisbachs equation and resistance from perturbation rocks was evaluated for four different cross sections. The results are presented in Table 39 below.

Table 39. Difference in measured flows compared to flows calculated with the method from (DVWK, 2002)

Site	**$Q_{measured}$**	**Q_{DVWK}**	**Factor difference**
Skarhult, section 6	0.22	0.60	0.37
Silverforsen, section 1	0.73	0.51	1.44
Skäralid, section 4	0.07	0.11	0.61
Verkeån, section 1	0.32	0.86	0.37

As seen, the difference between the measured flow value and the flow value calculated by the method in (DVWK, 2002) have at least a 35% difference up to a 60% difference. That magnitude of flow difference is too great to be practically useful. This does not mean that the DVWK method is not useful, but for the sites measured in this study it is likely that the irregular shapes of the channels, slopes diverging from the 5% optimum as stated in (DVWK, 2002). Furthermore, the rock placement and size are likely diverging from more controlled placement situations that better suits the (DVWK, 2002) approach. Further studies were more careful measurements of rocks and bottom material could be a way forward in evaluating the possibility of using this method in Swedish fishway design.

15 Discussion

15.1 Limitations

As with any study including field measurements and calculations, some simplifications must be done in order to keep the magnitude of the study manageable. This study deals with a few known simplifications and a series of more unknown sources of error. By trying to clearly state these the range of uncertainty for the given results can be estimated and hopefully the knowledge can be learned and applied in future studies.

The first well known and already discussed limitation is that of Manning's equation being formulated for uniform flow, a flow condition that will rarely apply at the natural conditions of fishway passages. This is clearly showcased for the one section of Skarhult where the slope of the water surface was zero, but there was a flow occurring. Since calculations made in the design process are based on the original Manning's equation, assuming uniform flow, the results are easiest to apply if they translate directly to the same conditions that are used in the design process. An argument could be made that also the design process should be calculated with greater care with a calculation method not based on the assumption of uniform flow. However, with the lengthy experience on fishway design and many other sources of error and limitations, such an advancement of theory might not pay off in actual applications.

Another limitation and source of error was the field measurements. In each step of measurements some uncertainty was introduced. The measurement of the cross-sections was performed with measuring rules at every 20-40 cm depending on the width of the channel. The calculation made for hydraulic radius etc. were based on these point measurements as can be seen from the cross-section plots in the Measurements section. This method does not capture the uneven shape of cobbles and small rocks on the bottom or the round shape of larger rocks. This will affect the length of the wetted perimeter and related factors. The water surface slope measurement was performed with laser that was pointed at objects at the water surface. This measurement was sometimes hard to perform where there was a lack of objects to point at and sunny conditions that made the laser hard to spot. A stronger laser or a two-person set up where one operates the laser, and another can stand closer to the object where the laser is pointed. Another source of error is the fluctuating water surface at sections with standing waves and similar flow conditions. For these sites, the laser was pointed in the middle between the lower and the higher line of the fluctuating water surface, a procedure that likely introduces a few millimetres of uncertainty into the measurement.

Lastly, the velocity measurement and conversion into a flow value also has a range of uncertainty. When performing the velocity measurement, it is very important to keep the velocity-meter straight into the direction of the flow, this operation does however become more difficult as turbulent flow wants to push the propeller head into different directions. Furthermore, the continuous method is based on the person carrying out the measurement to do an even movement that will create an accurate representation of the vertical velocity profile in each measured section.

15.2 Application of findings

One of the objectives of this study was to evaluate the need for adjusting roughness values in the design process of nature-like fishways and outlining guidelines for how to do that. From the calculated values, a range from M=3.7 to M=20.7 was found with an average value of M=10.5. This suggests that the previously used value of M = 15 is too high and should be adjusted to a slightly lower value. The range does however suggest that a single flat value does not accurately describe the different conditions that can be found in nature-like fishways. Table 40 below illustrates a theoretical scenario where flow and geometry are kept constant, but the M-value is gradually increased. The depth difference between M = 15 and the lower values are considerable. Underestimating the roughness coefficient results in a higher water level than designed for which might lead to complications at high flow situations. A too high coefficient does however result in a risk of constructing a fishway where the depth is insufficient for effective fish passage at normal or low water conditions.

Table 40. Comparison of water depths as a result of varying M-values for the same flow and geometry

M	Q	Depth (m)	Difference (m)
5	1.59	0.88	+0.38
7	1.57	0.74	+0.24
9	1.57	0.65	+0.15
11	1.60	0.59	+0.09
13	1.59	0.54	+0.04
15	1.60	0.50	0.00
17	1.55	0.46	-0.04
19	1.59	0.44	-0.06

Table 41. Comparison of water depths as a result of varying M-values for the same flow. Lower flow compared to Table 40.

M	Q	Depth (m)	Difference (m)
5	0.47	0.60	-0.25
7	0.47	0.51	-0.16
9	0.47	0.45	-0.10
11	0.48	0.41	-0.06
13	0.48	0.38	-0.03
15	0.48	0.35	0.00
17	0.48	0.33	0.02
19	0.48	0.31	0.04

From this limited data set it is hard to make an extensive and accurate list of guidelines for selection of Manning's roughness coefficient. As a rule of thumb, lower flow values result in lower M values and should be considered for smaller fishway passages or when evaluating low flow conditions in medium size passages.

16 Conclusions

In this study, Manning's roughness coefficients were calculated for 19 different cross-sections of four different nature-like fishway passages and one natural stream. Calculations were based on field measurements of the sites performed with laser, velocity-meter and folding rule. The calculated values were compared to the common design value M = 15, values obtained by the adjustment factor method from (Cowan, 1956) and the method based on the Darcy-Weisbach formula presented in (DVWK, 2002). From the measurements a range from M = 3 to M = 20 was found. The average calculated M value was 10.5. From estimation of roughness coefficients with adjustment factors a probable range between M = 8.2 and 14.5 was found, suggesting that the method could be used to estimate roughness coefficients for small fishway passages. Further studies should be performed to confirm this and propose accurate and concise guidelines for proper estimation. The flows calculated with the method from (DVWK, 2002) diverged at least 30 % from measured flow values at the sections where it was calculated, suggesting a poor ability to accurately describe the roughness of the cross-sections. This could be explained by a combination of rock measurements not being accurate enough and slopes diverging from the conditions the formulae are optimized for.

The general conclusion is that the current value of M = 15 is reasonable but for smaller fishways it could be adjusted to a lower value of about 10. Keeping in mind that in general, a 1 meter safety depth is added to all fishways that are now designed, this difference does not call for any drastic change in design. Instead of spending resources on more accurate measurements to better establish roughness coefficients other factors such as monitoring should be expanded. A functioning fishway is dependent on multiple factors, construction will seldom exactly follow design on paper and time will affect the fishway. This makes monitoring crucial to make sure that any constructed fishway stays operational.

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