Assessing the Flexibility of Small-Scale Hydropower under Environmental Measures

Development and Application of a Reproducible Modeling Framework Using Open Data

Master's thesis in Sustainable Energy Systems

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

Environmental measures introduced under the National Plan for Modern Environmental Conditions for Hydropower (NAP) are expected to affect the operational flexibility of Swedish hydropower systems. At the same time, flexibility is increasingly important in power systems with growing shares of intermittent renewable energy sources. Despite this, there is no standardized approach for assessing hydropower flexibility, and existing modeling studies often rely on aggregated system representations that fail to capture cumulative effects at the river-basin scale.

This thesis develops and demonstrates a reproducible and transparent modeling framework to assess the flexibility of small-scale hydropower under environmental constraints. The framework is based on open data and the Flow Optimization for River System Analysis (FORSA) modeling tool and is designed to support analyses within the Swedish regulatory context of the NAP. The framework addresses three key aspects: the identification and estimation of required input data using open sources, the translation of environmental measures into model scenarios, and the derivation of flexibility metrics from model results.

The framework is illustrated through a case study of the Emån river system. A baseline scenario representing current environmental conditions is compared with scenarios reflecting modern environmental conditions, based on proposed measures derived from the Water Information System Sweden (VattenInformationsSystem Sverige, VISS) database. Flexibility is assessed using a set of complementary metrics capturing both the magnitude and dynamics of hydropower operation, including the Flexibility Factor, High Value Production, High Value Share, Average Ramp in Production, and Amplitude Indicator.

The study develops and applies a systematic framework that enables environmental requirements to be consistently represented in FORSA and assessed through multiple flexibility metrics. The discussion highlights key modeling assumptions, data-related limitations, and trade-offs between model simplicity, data availability, and system-level representation that are relevant when applying the framework in regulatory analyses. To support reproducibility and practical application, the framework is synthesized into a structured manual describing data requirements, modeling steps, and interpretation of flexibility metrics. The proposed approach provides a transparent and transferable basis for assessing hydropower flexibility under environmental constraints and can support future analyses within the NAP.

Keywords: hydropower, hydropower flexibility, flexibility metrics, NAP, environmental constraints

Analys av småskalig vattenkrafts flexibilitet under miljöåtgärder
Utveckling och tillämpning av ett reproducerbart modelleringsramverk baserat på öppna data
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Sammanfattning

Miljöåtgärder som införs inom den Nationella planen för moderna miljövillkor (NAP) förväntas påverka flexibiliteten hos svensk vattenkraft, ofta förklarat som möjligheten att anpassa elproduktionen efter behov och variationer i elsystemet. Samtidigt blir denna flexibilitet allt viktigare, eftersom mer intermittenta förnybara energikällor introduceras i energisystemet. Trots detta finns det ingen etablerad metod för att bedöma vattenkraftens flexibilitet, och befintliga modelleringsstudier bygger ofta på aggregerade systemrepresentationer som inte fångar kumulativa effekter på en avrinningsområdesnivå.

Detta examensarbete utvecklar och demonstrerar ett reproducerbart och transparent modelleringsramverk för att bedöma flexibiliteten hos småskalig vattenkraft under miljömässiga begränsningar. Ramverket bygger på öppna data och modelleringsverktyget Flow Optimization for River System Analysis (FORSA), och är anpassat för analyser kopplade till NAP och omprövningen av den svenska vattenkraften. Det omfattar tre huvuddelar: att identifiera och uppskatta nödvändig indata med hjälp av öppna källor, att översätta miljöåtgärder till modellscenarier samt att härleda flexibilitetsmått från modellresultaten.

Ramverket illustreras genom en fallstudie av Emån med tillhörande biflöden. Ett referensscenario för dagens miljöförhållanden jämförs med scenarier för moderna miljövillkor, baserade på föreslagna åtgärder hämtade från Vatteninformationssystem Sverige (VISS). Flexibiliteten bedöms med flera olika mått som tillsammans visar både hur mycket el som produceras vid höga elpriser och hur snabbt produktionen kan förändras över tid, däribland Flexibility Factor, High Value Production, High Value Share, Average Ramp in Production och Amplitude Indicator.

Studien visar hur miljökrav kan beskrivas på ett enhetligt sätt i FORSA och hur resultaten kan användas för att bedöma vattenkraftens flexibilitet ur flera perspektiv. Diskussionen belyser viktiga begränsningar kopplade till tillgängliga data samt avvägningar mellan modellens enkelhet, datatillgång och hur detaljerat systemet bör beskrivas. För att stödja reproducerbarhet och praktisk tillämpning sammanfattas ramverket i en manual som beskriver datakrav, modelleringssteg och tolkning av flexibilitetsmått. Den föreslagna metoden ger en transparent och överförbar grund för att bedöma vattenkraftens flexibilitet under miljömässiga begränsningar och kan användas i framtida analyser inom NAP.

Nyckelord: vattenkraft, vattenkraftens flexibilitet, flexibilitetsmått, NAP, moderna miljövillkor

AI Declaration

In this master's thesis, AI tools have been used in a supportive manner. Sweco's internal AI tool, SwecoGPT, was used to improve language quality, such as wording, clarity, and grammar. SwecoGPT was also used as support during Excel-related tasks and for assistance with LaTeX formatting and technical handling.

The overall structure of the thesis, as well as all factual content, analyses, and arguments, are entirely our own.

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Furthermore, we are very grateful to the colleagues and experts at Sweco who generously shared their time, knowledge, and experience with us, and who helped us navigate some of the more challenging parts of the project. Special thanks also goes to everyone at the Sweco office in Gothenburg for making us feel so welcome and for contributing to a memorable time filled with laughter.

Finally, we would like to thank our examiner, Lina Reichenberg, for taking on the role and for her valuable input during the thesis work.

Nikesh Harari and Julia Johansson, Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

EQS	Environmental Quality Standards
EU	European Union
FORSA	Flow Optimization for River System Analysis
GCS	Good Chemical Status
GEP	Good Ecological Potential
GES	Good Ecological Status
HARO	Main River Basin (Huvudavrinningsområde)
HMWB	Heavily Modified Water Body
NAP	National Plan for Modern Environmental Conditions
RoR	Run-of-river
SMHI	Swedish Institute for Meteorology and Hydrology
VISS	Water Information System Sweden (Vatteninformationssystem Sverige)
WFD	Water Framework Directive

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables used throughout this thesis.

Indices

sc	Index for sub-catchment
t	Index for time step

Sets

$t \in \mathcal{T} = \{1, 2, \ldots, T\}$	Set of time steps
$\{\, t \in \mathcal{T} \mid \pi_{\mathrm{t}} > \tilde{\pi} \,\}$	Subset of time steps with electricity prices above the median price

Parameters

$A_{\mathrm{sc,total}}$	Total area of a sub-catchment
$A_{\mathrm{sc,upstream}}$	Area of a sub-catchment upstream of a station
A_{surface}	Surface area of a reservoir
d_{r}	Depth of river
f_{station}	Fraction of sub-catchment area upstream of a station relative to the total sub-catchment area
g	Gravitational acceleration
H	Hydraulic head
H_{max}	Maximum hydraulic head
h_{reg}	Regulation amplitude
k	Maximum turbine discharge scaling factor
L_{r}	Length of river
$L_{\mathrm{r,sc}}$	Length of river for a specified sub-catchment

LRL	Lower Regulation Limit
MQ	Mean water flow
MQ_{sc}	Mean water flow of a specified sub-catchment
Q_{inflow}	Non-regulated inflow
$Q_{\mathrm{t},\eta=0}$	Turbine discharge at 0 efficiency
$Q_{\mathrm{t},\eta=\mathrm{max}}$	Turbine discharge at maximum efficiency
$Q_{\mathrm{t,max}}$	Maximum turbine discharge
S_{r}	Cross-section area of river (perpendicular to the flow)
$S_{\mathrm{r,sc}}$	Cross-section area of river (perpendicular to the flow) for a specified sub-catchment
T	Number of time steps
t_{flow}	Water flow time
URL	Upper Regulation Limit
V_{reg}	Regulation volume
w_{r}	Width of river
$W_{\mathrm{downstream}}$	Downstream water surface elevation
W_{upstream}	Upstream water surface elevation
η_{max}	Maximum turbine efficiency
η_{tot}	Total efficiency
ρ	Density
$\bar{\pi}$	Average electricity price
$\tilde{\pi}$	Median electricity price

Variables

E_{el}	Electrical energy
P	Net power output
P_{max}	Maximum electricity production output
$\bar{P}$	Average hourly electricity production
Q	Water flow rate
$\hat{I}$	Revenue from electricity production
$\hat{P}$	Electricity production
π_{t}	Electricity market price at time step t
π^{*}	Average achieved electricity price

Translations of Swedish Authorities and Key Terms

This report addresses Swedish regulatory and institutional conditions. Throughout the thesis, Swedish authorities, legal frameworks, and key terms are referred to using their English translations. For clarity and consistency, the original Swedish terms corresponding to these English translations are listed below in alphabetical order, divided into Swedish authorities and Key terms.

Swedish authorities and organizations

English name	**Swedish name**
County Administrative Board	Länsstyrelsen
Hydroelectric Environmental Fund	Vattenkraftens Miljöfond
Land and Environment Court	Mark- och miljödomstolen
Swedish Agency for Marine and Water Management	Havs- och vattenmyndigheten
Swedish Energy Agency	Energimyndigheten
Swedish Environmental Protection Agency	Naturvårdsverket
Swedish Meteorological and Hydrological Institute	Sveriges meteorologiska och hydrologiska institut
Swedish Mapping, Cadastral and Land Registration Authority	Lantmäteriet
Swedish Society for Nature Conservation	Naturskyddsföreningen
Swedish Transmission System Operator	Svenska kraftnät
Swedish Water Authorities	Vattenmyndigheterna

Key terms

English term	Swedish term
Availability Factor	Tillgänglighetsfaktor
Baseline description	Nulägesbeskrivning
Collaboration process	Samverkansprocess
High Value Production	Högvärdesproduktion
High Value Ratio	Högvärdeskvot
National Plan for Modern Environmental Conditions for Hydropower	Nationella planen för moderna miljövillkor
Reassessment group	Prövningsgrupp
Relative regulation contribution	Relativt reglerbidrag
Swedish Environmental Code	Miljöbalken
Swedish Water Information System	Vatteninformationssystem Sverige
Water Management Ordinance	Vattenförvaltningsförordning

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1
Introduction

Hydropower has been a cornerstone of Sweden's renewable energy system and has contributed significantly to fossil-free electricity production for the last century [2, 3]. Today, hydropower accounts for approximately 40% of electricity production in Sweden, making it the single largest source of power generation in the country [4]. In addition to this, hydropower plays a vital role due to its flexibility and is expected to continue to do so as the share of intermittent renewable electricity sources, such as wind and solar power, increases [4, 5, 6]. However, hydropower development has also caused significant alterations to river flow regimes, disrupted fish migration, and negatively affected ecosystems and biodiversity in and around rivers [2].

To enable coordinated water management across the European Union (EU) and to safeguard both surface water and groundwater, the EU established the Water Framework Directive (WFD) in 2000 [7]. In Sweden, the interpretation and implementation of the WFD with respect to hydropower are reflected in the National Plan for Modern Environmental Conditions for Hydropower (NAP), under which all Swedish hydropower facilities are to be reassessed and granted modern environmental permits [2]. In the adopted framework for the NAP process, a strong emphasis is placed on the trade-off between the availability of hydropower-generated electricity and environmental benefits [2]. As a result, the implementation of the NAP requires that proposed environmental measures are assessed with particular attention to their impacts on electricity production and regulation capacity [2].

Environmental constraints on hydropower systems may lead to a loss in operational flexibility [8, 9, 10]. Despite the importance of flexibility in modern energy systems, there is no widely accepted definition or standardized method for quantifying hydropower flexibility [11, 12]. Furthermore, many existing hydropower modeling approaches rely on aggregated representations in which entire hydropower systems are modeled as a single plant, thereby limiting the ability to capture cumulative and system-wide effects at the river-basin scale [13]. As hydropower systems are expected to be subject to environmental measures under the NAP, there is a need for transparent and consistent system-level analytical approaches for evaluating hydropower flexibility.

1.1 Aim

The purpose of this study is to develop and demonstrate a reproducible and transparent modeling framework, based on open data and the modeling tool Flow Optimization for River System Analysis (FORSA), to assess the flexibility of small-scale hydropower. The framework aims to support analyses of how environmental measures may affect hydropower flexibility, thereby contributing additional insight for reassessment and decision-making processes under the National Plan for Modern Environmental Conditions for Hydropower (NAP).

1.2 Research questions

To fulfill the aim of this study, the following three research questions are addressed:

RQ1: What input data are required to model river systems in FORSA, and how can these data be retrieved or estimated using only open data sources?

RQ2: How can environmental measures under the NAP be translated into model parameters and scenarios?

RQ3: What metrics can be derived from the model results, and how can these be used to assess the flexibility of small-scale hydropower?

The first two questions, RQ1 and RQ2, are related to the modeling and the corresponding input data, whereas RQ3 is related to the model output and the analysis that can be carried out using these results.

To address these research questions, the report is structured around a modeling framework, illustrated in Figure 1.1.

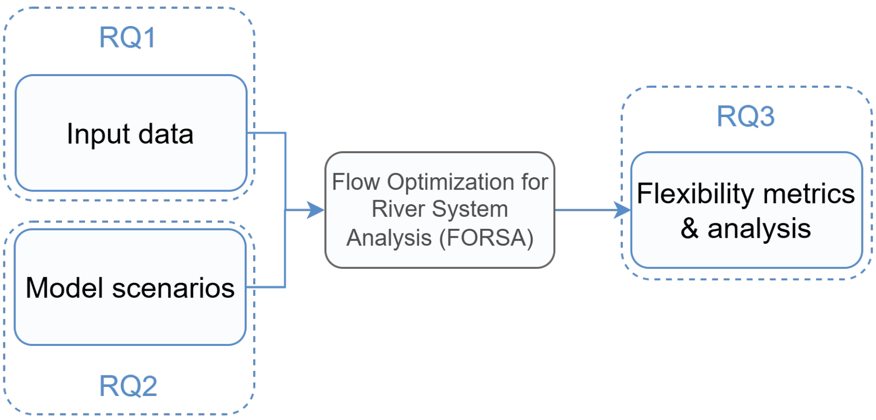


Figure 1.1: Modeling framework used to address the research questions of this study, illustrating how input data (RQ1) and model scenarios (RQ2) define the system in FORSA and enable the derivation and analysis of flexibility metrics (RQ3).

The framework builds on the existing modeling tool FORSA, which provides the basis for required input data, scenario definitions, and the derivation of flexibility metrics. In Figure 1.1, FORSA is shown in grey to emphasize that model development is not part of the framework. Instead, FORSA serves as the tool that defines the structure of the inputs and outputs. The framework supports the assessment of RQ1–RQ3.

1.3 Scope, delimitations and limitations

This thesis applies a modeling framework to assess how environmental measures implemented under the NAP affect operational flexibility in small-scale hydropower production. Consequently, the study is situated within a Swedish context.

The modeling framework developed in this study is illustrated through a case study of the Emån river system. The resulting input data, modeling outcomes, and flexibility metrics are therefore not intended as definitive assessments of the Emån system, but rather to demonstrate the functionality and applicability of the proposed framework.

The input data are based on historical observations, while the model scenarios represent plausible future conditions. Accordingly, the results should be interpreted as illustrative rather than predictive.

1.4 Report outline

This study is structured according to the following outline.

Chapters 2, 3, and 4 provide the background relevant to the study. Chapter 2 presents the principles of hydropower energy conversion and technology, establishing the fundamental understanding required for the thesis. Chapter 3 outlines the environmental regulation of hydropower, including the European legal framework and its implementation in Sweden through the NAP. Chapter 4 introduces the theoretical background of hydropower system modeling, with particular emphasis on the FORSA modeling tool used in this study, as well as the flexibility metrics selected for the modeling framework.

The core of the thesis is presented in Chapter 5, which describes the developed modeling framework in detail. In accordance with the framework in Figure 1.1, the chapter is structured around three main components: input data, model scenarios, and flexibility metrics and analysis. The chapter provides a detailed description of all steps in the modeling framework, with the Emån case study serving as a consistent illustrative example.

Chapter 6 synthesizes the modeling framework and provides a structured overview of the results. This chapter also includes a sensitivity analysis of the input data and a discussion of the framework and its implications.

Finally, Chapter 7 presents the conclusions of the study and provides answers to the research questions RQ1–RQ3.

2
Hydropower

Hydropower is a renewable energy source in which electricity is generated by water flowing from higher to lower elevations. It is the third largest source of electricity generation worldwide, supplying 14% of global electricity in 2024 [14], and the largest renewable source with a share of 45% [15]. In Sweden, hydropower accounts for approximately 40% of total electricity generation, making it the country's largest source of electricity [16]. For centuries, access to clean and reliable hydropower has shaped Swedish society and contributed significantly to economic growth and development [2].

This chapter presents the fundamental theoretical background of hydropower electricity generation, starting with the hydrological prerequisites and energy conversion principles and hydropower technology, followed by a discussion of hydropower's benefits to the electricity system and its environmental consequences. In the final section, and where relevant, Swedish perspectives are introduced to provide context aligned with the objectives of this study.

2.1 Hydrological cycle and seasonal flow patterns

Hydropower is among the most efficient renewable energy generation technologies, with a water-to-wire efficiency of approximately 90% [17]. It is driven by solar energy through the hydrological cycle, where solar radiation causes evaporation from the Earth's surface, increasing atmospheric water vapor that is transported by global, regional, and local wind systems before eventually returning to the surface as precipitation [18, p. 271]. According to the Intergovernmental Panel on Climate Change (IPCC), approximately 78% of global precipitation occurs over the oceans and 22% over land, resulting in a net transport of water from oceanic to terrestrial systems [19]. As the hydrological cycle is a closed system, the total volume of water on Earth remains constant, thereby allowing hydropower to serve as a renewable energy source capable of continuous electricity generation [19].

In Sweden, annual precipitation and river flow patterns are monitored and documented by the Swedish Meteorological and Hydrological Institute (SMHI). SMHI [20] reports that in northern Sweden, river flow is characterized by low winter flow, when precipitation is stored as snow, and high spring flows resulting from snowmelt, leading to pronounced spring floods. In contrast, southern Sweden is described as typically experiencing peak flow during late autumn and winter due to rainfall, whereas lower river flow conditions often occur during summer as a result of increased evapotranspiration (the combined water losses from evaporation and plant transpiration).

In addition to seasonal variations within a year, there are notable differences between years, often described as dry, normal, and wet years [21]. Yearly hydropower production is therefore governed by annual variations in inflow, together with reservoir storage capacity and electricity demand [3, 22]. Bladh and Funkquist [23] emphasize the importance of analyzing hydropower systems across different years, as the results vary depending on the hydrological conditions during the considered period. However, they also conclude that to draw generalizable conclusions about system outcomes and the distinction between dry, normal, and wet years, additional statistical analysis using data over a large number of years is required.

2.2 Hydropower energy conversion

As mentioned, hydropower utilizes water flowing over a height difference to produce electricity. More specifically, it converts the energy associated with this flow, from the potential energy stored in water at a higher elevation, through the kinetic energy of the moving water, into mechanical energy as the turbine rotates [17]. This mechanical energy is subsequently converted into electrical energy by a generator, typically connected directly to the turbine shaft [17]. The generated electricity is then transformed to the appropriate voltage of the transmission grid and finally distributed to its users [19]. Figure 2.1 illustrates how water is converted into electrical energy in a hydropower plant.

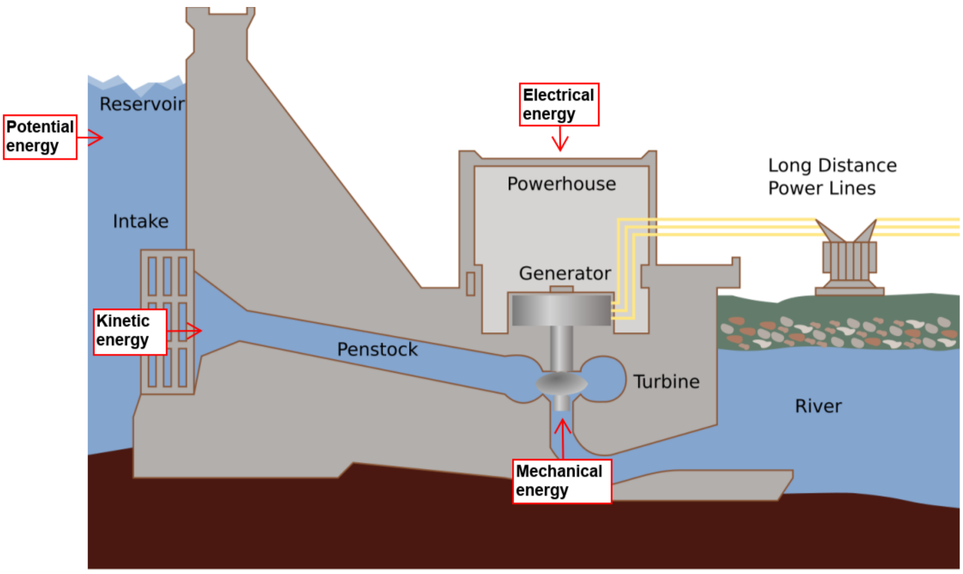


Figure 2.1: Conceptual layout of a hydropower plant and its main components [24]. Red boxes illustrating the energy conversion process have been added manually [25].

The energy conversion process illustrated in Figure 2.1 can be quantified by the following expression for the net power output of a hydropower plant:

$$P = \rho \cdot g \cdot Q \cdot H \cdot \eta_{\text{tot}} \tag{2.1}$$

where P is the net power output (W), ρ the density of water (kg/m^3), g the gravitational acceleration (m/s^2), Q the water flow rate (m^3/s), H the net hydraulic head (m) and η_{tot} the total efficiency. η_{tot} accounts for the efficiencies of all mechanical and electrical components in the plant, including the turbine and generator, as well as additional energy losses, for example those caused by friction in the penstock [26].

In Equation 2.1, g and ρ are commonly treated as constants, with values of 9.81 m/s^2 and 1000 kg/m^3, respectively, [27], which leaves Q, H, and η_{tot} as variables, directly proportional to the power output. Evidently, the amount of electricity that can be generated is highly dependent on the site-specific environmental conditions [18, 27]. Both Q and H determine the available hydraulic energy at a given site, and thereby the potential for electricity generation [17, 18]. In addition, H is not fixed at a given plant but depends on the upstream and downstream water levels, which are governed by the incoming water flow, power generation at the plant, and downstream operations [28].

While local conditions determine the amount of hydraulic energy available, turbine efficiency governs how much of this energy is ultimately converted into mechanical power, accounting for hydraulic and mechanical losses within the turbine [17]. Turbine efficiency is defined as the ratio of the mechanical power delivered at the turbine shaft to the hydraulic power available to the turbine [29]. Different turbine types achieve maximum efficiency at different combinations of discharge and H, with efficiency decreasing at both lower and higher discharge levels relative to the optimum [13].

The amount of electrical energy produced depends on the duration of the flow through the turbines. Given the power output P and the time interval Δt, the electrical energy E_{el} is calculated as:

$$E_{el} = P \cdot \Delta t \tag{2.2}$$

measured in Wh, usually with a suitable prefix.

2.2.1 Turbine design

Due to the strong dependence of power output on Q and H, different turbine designs have been developed to optimally utilize the site-specific head and flow conditions [17].

The most common turbines used in hydropower plants are Francis, Kaplan, and Pelton turbines [17, 27, 29]. Each turbine type is designed for specific combinations of Q and H.

In addition to turbine type, the turbine size is highly relevant in the plant configuration. They are traditionally dimensioned according to the rotational speed, head and discharge under which they operate most efficiently, which depends on the site-specific conditions [17]. Optimal performance is thus achieved at a specific operating point, corresponding to a certain discharge [17]. There is also a maximum discharge, Q_{max}, at which turbines can operate, which is the upper flow limit a turbine is dimensioned for. A commonly used rule of thumb for small-scale hydropower is to design the turbine for a Q_{max} of about 1.5 times the mean water flow, MQ, which yields approximately 60–80% of the optimal operation under conditions of no or moderate regulation [30, p. 19].

Operating away from the optimal point typically results in considerable reduction in efficiency and a lower power output [31]. If the inflow exceeds the $Q_{\max}$ and storage is not available, excess water must be spilled, leading to production losses [17]. Conversely, when the water flow is much lower than the $Q_{\max}$, the turbines might need to run at a reduced output and lower efficiency, or even stop operation and bypass water to prevent damage to the turbines. It is therefore preferable to select a turbine that operates close to its optimal point for most of the time. In systems with highly variable inflows, installing multiple turbines, with different operating ranges, can be advantageous, as it allows the plant operation to be better adapted to changing flow conditions [17].

2.3 Classifications of hydropower

Hydropower plants can be classified according to several criteria that reflect their technical design and operational role in the power system. This section presents classifications based on plant type, installed capacity, and regulation contribution.

2.3.1 Plant type

Hydropower plants are commonly classified into three main categories based on their storage capacity and mode of operation: reservoir hydropower, run-of-river (RoR) hydropower, and pumped storage hydropower, all of varying size [19]. The first two categories represent the most conventional forms of hydropower, whereas pumped storage hydropower has seen increasing deployment in recent years. An additional, less developed technology is in-stream hydropower, which is not addressed in this report.

Reservoir hydropower plants store water inflow from snowmelt, precipitation, and runoff [17]. Some reservoirs can store water over seasons or even years, while others provide weekly or daily storage. Reservoir size directly corresponds to the amount of potential energy that can be stored in the water and, consequently, affects the plant's ability to respond to load variations.

RoR plants are hydropower plants with little or no water storage capacity [17, 19]. Where storage exists, it is typically limited to short-term regulation on an hourly to daily basis. Consequently, electricity production mainly follows the natural river flow or the flow released from upstream stations.

Pumped storage hydropower is not considered an energy source but rather an energy storage technology [19]. It consists of a lower reservoir from which water is pumped to an upper reservoir during periods of low electricity demand and subsequently released to generate electricity during periods of high demand [17, 19]. In Sweden, only three pumped storage hydropower plants are currently in operation, indicating that this form of hydropower is not common or established in the Swedish energy system [32].

2.3.2 Installed capacity

Hydropower plants in Sweden are classified as small-scale, medium-scale, or large-scale based on their installed power capacity [33]. An overview of this classification is provided in Table 2.1.

Table 2.1: Classification of Swedish hydropower plants by installed capacity according to the Swedish Transmission System Operator [33], showing the number of plants in each class as well as the total and average installed capacity per class.

Classification	Capacity range (MW)	Number of plants	Total capacity (MW)	Average capacity (MW)
Small-scale	< 1.5	1 129	333	0.3
Medium-scale	$1.5 - 10$	180	987	5.5
Large-scale	> 10	211	15 071	71.4

Note that the data in Table 2.1 represent all hydropower plants registered for the National Plan for Modern Environmental Conditions for Hydropower (NAP), for which installed capacity is known, and approximately 400 additional plants are not accounted for in the data [33]. These plants are estimated to be small-scale, with a negligible installed capacity compared to the total installed capacity in Sweden [33]. Furthermore, the classification thresholds provided in Table 2.1 are specific to Sweden and vary internationally. For instance, in Norway, small-scale hydropower is considered to include all plants with an installed capacity below 10 MW, while in China and Canada, small-scale hydropower includes all plants with an installed capacity below 50 MW [17, 19].

From Table 2.1, it can be seen that although the majority of hydropower plants in Sweden are small-scale, the vast majority of the total installed capacity is accounted for by large-scale plants.

2.3.3 Relative regulation contribution

The Swedish Energy Agency has, since 2016, classified Swedish hydropower according to its relative regulatory contribution, which measures how closely electricity production follows the residual load [5]. In this context, the residual load is defined as the difference between electricity demand and electricity production from wind and solar power.

The purpose of the classification is to support the County Administrative Boards in identifying hydropower plants of greater importance for the security of electricity supply in the Swedish power system [34]. In 2026, the Swedish Energy Agency updated the classification system, which previously consisted of three classes, to a simplified structure comprising only *Class-1 hydropower plants* and *Other hydropower plants* [34]. According to the updated classification system, 326 hydropower plants are classified as Class-1, and are therefore considered to be of particular importance for the regulation and reliability of the Swedish power system.

2.4 System services and values of hydropower

In addition to being a renewable and stable electricity generation technology, hydropower provides a range of benefits to the power system, which are outlined in this section.

2.4.1 Energy storage and dispatch flexibility

For proper operation, the power system must remain in balance, meaning that electricity supply and demand must be equal at all times within the grid. Integrating a large share of renewable energy sources, particularly wind and solar power, increases the need for dispatchable generation to balance the variability of these sources [35, 36]. The presence of reservoirs allows hydropower production to be shifted over time, enabling generation to be concentrated in periods with higher electricity prices, for example during times of low wind and solar output. At present, there is no equally effective alternative in Sweden that can provide the same degree of dispatch flexibility as hydropower [2]. In the Nordic power system, water reservoirs constitute a large energy storage capacity, amounting to approximately 127 TWh, of which about 34 TWh (approximately 27%) is located in Sweden [23].

2.4.2 Hydropower system services and operation

In addition to electricity generation, hydropower provides several grid services essential for a safe and efficient operation of the power system, including system inertia, frequency control, voltage regulation, and black-start capability [17]. System inertia is supplied by the rotating electromechanical components of hydropower plants and helps stabilize system frequency during disturbances [18, 26]. This service becomes increasingly important with rising shares of converter-connected wind and solar power, which do not inherently provide system inertia.

To manage frequency deviations caused by system disturbances or imbalances, transmission system operators must ensure the availability of generation resources that can rapidly ramp up or down in response to demand [5]. In Sweden, such frequency reserves are currently provided almost entirely by hydropower. Hydropower generators can also supply or absorb reactive power, thereby contributing to voltage stability, which is particularly important in weak grids or remote areas with limited transmission capacity [37, 38]. Finally, some hydropower plants can provide black start services, referring to the ability to restart generation without an external power supply. This capability is critical for system restoration following widespread outages [17, 19].

Increasing shares of intermittent generation are changing how hydropower is operated in the power system. Studies on new operational patterns of hydropower, such as those by Öberg et al. [28] on how production cycle and system regulation time scales may shift, and by Ek Fälth et al. [39] on how long hydropower can sustain high output over extended periods of low-supply conditions, are essential for understanding how hydropower will be operated and valued in future power systems.

2.5 Environmental impacts of hydropower

As mentioned in the introduction of this chapter, hydropower has played a vital role in Sweden's economic growth and development [2]. However, much of Sweden's hydropower development took place during a period when limited consideration was given to local ecosystems and the environmental impacts of hydropower projects [40]. Consequently, many Swedish rivers are today regulated or exploited in ways that do not adequately account for environmental considerations.

According to a report by the Swedish Society for Nature Conservation and the World Wildlife Fund [41], hydropower plants, dams, and other barriers are among the primary reasons why approximately 40% of European water bodies fail to meet the ecological quality objectives of the Water Framework Directive (WFD). Under the WFD, surface water status is assessed using several quality elements, including biological, hydromorphological, and chemical components [7]. Hydropower development primarily affects riverine ecosystems through hydromorphological alterations [19, 42], defined as changes to the hydrological regime, river continuity, and river morphology [43]. Among these, hydropower particularly alters the hydrological regime and river continuity [19, 42], which are described in more detail in the following sections.

Note that hydropower development may also entail other types of impacts, such as social consequences including involuntary population displacement [19]. However, such impacts are outside the scope of this study and are therefore not further discussed.

2.5.1 Hydrological regime

Hydrological regime refers to the quantity and dynamics of water flows [43]. In natural rivers, variations in water discharge during the year are of great importance for the riverine ecosystems and species [41]. Changes in those variations, driven by operational constraints and water regulation, may lead to the degradation of aquatic habitats and negatively affect the structure and abundance of species [43]. Specifically, reservoir hydropower plants significantly modify downstream flow regimes, potentially leading to changes in the annual flow patterns, as well as frequent fluctuations in the water level downstream [19].

Altered annual flow patterns can affect riverine habitats and disrupt the natural life cycles of downstream floodplains, where periodic flooding of riparian zones is essential for sediment and nutrient transport that supports biodiversity and vegetation [41]. Daily fluctuations and sudden water releases can also create problems for mammals and birds [19]. Other impacts include changes in water temperature and salt intrusion, which depends on the freshwater-discharge [19].

2.5.2 River continuity

River continuity, or connectivity, traditionally refers to the transportation and movement of organisms, material and nutrients along a river system [40]. With growing understanding of natural watercourse processes, the concept has expanded to also encompass exchanges between aquatic and terrestrial environments, as well as between surface water and groundwater [40].

Although the extent of impacts may vary, all types of hydropower and dam structures create barriers for fish migration and navigation, as well as to sediment transport [19]. Migratory fish species, such as eel, salmon and trout, all migrate during their life cycle to reach spawning grounds and rearing zones, as well as for food and protection [19, 41]. Barriers created by hydropower may reduce access to these vital parts of a river, leading to a decrease in migratory fish populations [19].

In Sweden, hydropower constitutes the most extensive pressure on lake and river water bodies, with water regulation and disrupted connectivity affecting nearly 4,000 river water bodies and around 1,000 lakes [44]. According to the Swedish Society for Nature Conservation and the World Wildlife Fund [41], only 16 of the previous 37 rivers populated by salmon remain today, mainly due to the development of hydropower during the 20th century.

3

Environmental Regulation of Hydropower

Based on the system benefits and environmental impacts of hydropower outlined in the previous chapter, this chapter introduces the regulatory frameworks governing environmental impacts in Sweden, including the European Water Framework Directive (WFD) and the National Plan for Modern Environmental Conditions for Hydropower (NAP).

3.1 Water Framework Directive

In 2000, the European Union (EU) introduced the WFD to establish an integrated EU policy on water and to support Member States in the protection and management of water resources [45]. It declares that water is not merely a commercial product but, rather, a heritage that must be treated accordingly through protection and preservation [7].

By organizing water management into river basin districts, the framework promotes coordinated management of water bodies, including those that cross national borders [7]. It requires all Member States to interpret and implement the directive through national legislation [7]. The objective of the WFD is to protect water bodies by preventing deterioration and by promoting measures to achieve good status in accordance with defined Environmental Quality Standards (EQS) [7].

3.1.1 Status classifications and Environmental Quality Standards

The Swedish Water Authorities are responsible for assigning status classifications and EQS to all water bodies in the country [46]. Status classifications reflect the current condition of a water body and are determined through a combined assessment of the individual quality elements defined under the WFD (general, biological, physico-chemical, and hydromorphological). EQS define the environmental requirements that apply to the water body and provide the framework for proposing measures in the process of establishing new environmental permits for hydropower.

Together with the Swedish Agency for Marine and Water Management and the County Administrative Boards, the Water Authorities have developed the Swedish Water Information System (VISS), a database that contains status classifications, EQS, and proposed measures for all water bodies in the country [47]. Information entered into the database is used for reporting to the EU on the condition of Sweden's water bodies [47].

3.1.2 Hydropower within the WFD

As mentioned, all water bodies within the EU Member States are required to meet the objectives of the WFD, which include achieving good status, defined as both good ecological status (GES) and good chemical status (GCS) [7]. While the WFD requires both GES and GCS, chemical status is primarily influenced by emissions of priority substances originating from sources such as industrial discharges, agriculture, and urban runoff [48]. Consequently, its relevance for hydropower is generally limited, as hydropower operations rarely involve direct emissions of priority substances. Instead, the main interaction between hydropower and the WFD concerns ecological status, particularly through hydromorphological pressures affecting hydrological regimes, river continuity and habitat conditions [49], which was presented in Section 2.5.

Ecological status is classified into five status classes under the WFD: high, good, moderate, poor, and bad [7]. For rivers, GES refers to conditions in which the biological quality elements are only slightly affected by human activities and remain close to their natural, undisturbed reference conditions, thus representing a condition in which anthropogenic pressures result in only minor deviations from natural reference conditions.

3.2 National Plan for Modern Environmental Conditions for Hydropower

The WFD was implemented in Swedish law in 2004 through the Water Management Ordinance [50] and the Swedish Environmental Code [51]. In the years following the Directive's implementation, Sweden developed a national water management system, which included the establishment of five water districts and the characterization and mapping of water bodies, resulting in EQS and action plans, as well as the identification of HMWB [3]. During this process, it became evident that hydropower was a major driver of physical pressures and morphological alterations in many water bodies, thereby contributing to difficulties in achieving GES [3]. In response, the Swedish Government developed a national plan for the renewal of environmental permits for hydropower plants in Sweden, referred to as modern environmental conditions, aiming to introduce measures that improve the aquatic environment while ensuring an efficient national supply of hydropower-generated electricity [3].

The result of this process was the NAP, proposed in 2019 by the Swedish Agency for Marine and Water Management, the Swedish Energy Agency, and the Swedish Transmission System Operator [2] and adopted by the Swedish Government in 2020 [52].

3.2.1 National reference value and HARO value

The Swedish Agency for Marine and Water Management and the Swedish Energy Agency have developed a national strategy to support decision-making and prioritization in the trade-off between environmental objectives and hydropower generation [6]. As part of this strategy, a guideline value is stated at the national level for what can be considered to have a significant negative impact on power generation, and thus the maximum allowable loss of hydropower production due to environmental measures implemented through the NAP process. This guideline value is set at 2.3% of Sweden's total annual hydropower production, corresponding to a national reference value of 1.5 TWh (based on 2014 production levels). In addition, the strategy states that environmental measures implemented through the NAP must not have a significant adverse effect on the balancing and regulation capabilities of the Swedish hydropower system.

This guideline value is subsequently adopted in the NAP framework and is referred to as the HARO value, reflecting the allocation principle where the reference value is distributed across Sweden's main river basins [6]. The objective of the HARO value is to guide the Swedish Water Authorities when assessing what constitutes a significant loss of production within the NAP process, thereby providing a basis for identifying water bodies as heavily modified and for considering exemptions with regards to EQS [6].

3.2.2 Overview of the NAP process

In the framework developed for the NAP in 2019, the reassessment process was planned to run over 20 years, with the first application deadline in 2022 and the last in 2037, so that all hydropower facilities would have modern environmental conditions by the early 2040s [2].

Figure 3.1 presents a schematic overview of the main steps of the NAP process, starting from the registration of individual facilities to the allocation of modern environmental conditions and the subsequent implementation.

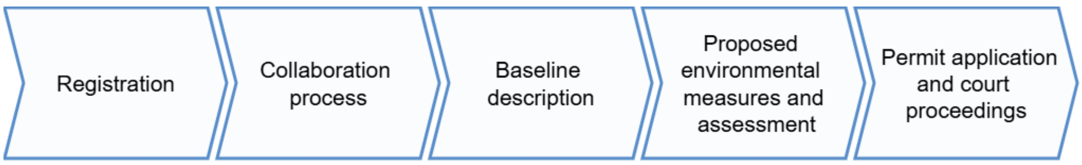


Figure 3.1: Schematic overview of the NAP process, from registration to the determination of modern environmental conditions.

The Swedish Agency for Marine and Water Management has an overarching responsibility for following up and coordinating the implementation of the NAP [2]. The subsequent sections provide a more detailed description of the individual steps outlined in Figure 3.1.

Registration

Any hydropower facility that is currently used for electricity generation, or that, although not generating electricity today, was originally established for that purpose, is subject to the NAP [2]. This includes both hydropower plants and other facilities used in hydropower operations, such as reservoirs [2].

To ensure an efficient reassessment process under the NAP framework, all Swedish hydropower facilities registered in the NAP have been divided into reassessment groups, primarily based on their main river basin [2]. All facilities within the same reassessment group have the same deadline for submitting their application to the Land and Environmental court.

Collaboration process

The Swedish Government has highlighted that, given the ambitious timeline of the NAP, collaboration is needed to ensure an efficient reassessment process [53].

Each County Administrative Board in Sweden is responsible for carrying out the collaboration process for the reassessment groups within its jurisdiction. If a reassessment group covers more than one County Administrative Board jurisdiction, it is recommended that the County Administrative Board with the largest share of facilities in the group take primary responsibility [53]. In addition to the operators themselves and the County Administrative Boards, other stakeholders deemed by the County Administrative Board to be able to provide relevant input are also part of the collaboration process. These stakeholders include the Water Authorities, municipalities, public authorities (e.g. the Swedish Environmental Protection Agency and the Swedish Agency for Marine and Water Management), and interest organizations (e.g. fishing, hydropower, and cultural organizations) [53].

The collaboration process is intended to ensure that a comprehensive national perspective is reflected in the assessment materials and to provide a consolidated basis for the court proceedings [53]. Furthermore, the collaboration process aims to facilitate the assessment of the effects of environmental measures across entire catchment areas and to evaluate how these effects interact. This intends to ensure that measures are implemented where they are most effective in meeting the NAP objective while ensuring an efficient national supply of hydropower-generated electricity [53].

Baseline description

The material from the collaboration process is summarized in the baseline description, and is intended to describe the different interests relevant to the geographical area in relation to the aquatic environment that might be affected by the NAP [53]. It is often divided into three main areas: aquatic environment benefits, efficient access to hydropower-generated electricity, and other public interests. The first area should cover environmental and conservation aspects, including national interests, protected areas, status classification, species of concern, and non-native species. The second should address hydropower assets and their energy-system relevance, including affected facilities, current permits, and importance for regulation capacity and electricity preparedness. The third should, where relevant, encompass other societal interests potentially affected by the NAP, such as cultural heritage, flood risk, and reindeer husbandry.

Note that the baseline description is not intended to propose environmental measures, but rather to serve as a basis for the subsequent analysis where environmental measures are to be proposed for the facilities within the reassessment group [53].

Proposed environmental measures and assessment

As mentioned, the baseline description serves as a basis for the analysis of potential environmental measures. Proposed measures often originate from the VISS database, introduced in section 3.1.1. It is however up to individual operators to assess the feasibility of the proposed measures, as well as the potential effects on electricity production and regulation capacity [53].

The results of this process are to be summarized and published on the County Administrative Board's website so that the public and the court can access the information [53]. This summary should also include information on how the collaboration process was conducted, which stakeholders that were involved, a summary of the baseline description, proposed environmental measures and their estimated consequences, whether there was disagreement regarding these measures, as well as any significant information that is missing [53].

Permit application and court proceedings

It is up to each individual operator to submit their permit application to the Land and Environmental Court once the collaboration process has been completed [54]. It is up to them to decide what measures to suggest in their application and have enough material to support that the measures will be sufficient to reach GES or GEP. An operator is deemed to have modern environmental conditions if, after the Environmental Code entered into force in 1999, its entire operation has been subject to a permit renewal and a permit has been granted with legal force covering all parts of the hydropower operation [54].

4

Hydropower System Modeling and Assessment

The implementation of the National Plan for Modern Environmental Conditions for Hydropower (NAP) highlights the need for systematic analysis of hydropower systems and the impacts of environmental measures. In a study by Ek Fälth et al. [13], the authors develop hydropower models with varying levels of detail and assess the trade-offs between them with respect to the representation of technical and physical constraints in hydropower systems. One of the developed models, denoted as *B:L* in the mentioned report, forms the basis for the hydropower model used in this study, namely *Flow Optimization of River System Analysis* (FORSA). This model will be presented in Section 4.1, followed by a description of flexibility metrics that can be derived from the model results.

The choice of modeling approach is closely linked to how hydropower systems are represented in different available models, as such systems can be modeled with varying degrees of complexity and physical detail. However, as noted by Ek Fälth et al. [13], hydropower is often represented using simplified models in which an entire system is aggregated into a single power plant rather than a network of plants and reservoirs. Such simplifications neglect interactions between stations and reservoirs, as well as variations in hydraulic head and turbine efficiency resulting from changing water levels and flows. According to Ek Fälth et al. [13], neglecting these factors leads to an overestimation of the flexibility that a hydropower system can provide.

One such model, in which the system can be represented in an aggregated manner, is Python for Power System Analysis (PyPSA) [55]. In PyPSA, hydropower can be represented as a storage unit, where reservoir inflow is included as an external inflow and unused water can be represented as spillage. In this way, the model can capture the general ability of hydropower to shift production over time. However, this representation is primarily designed for power-system optimization. Such a representation may be useful for broader power-system analyses, but it simplifies hydropower operation and is less suitable for assessing local measures at individual plants. Since the NAP measures considered in this study are assigned to specific hydropower plants, an aggregated representation was not considered appropriate.

An example of a long-term scheduling model that retains such a non-aggregated representation is the Stochastic Fan Problem (SFP) presented by Helseth et al. [56]. The authors conclude that the model shows good potential for valuating the flexibility of hydropower in systems with a high share of intermittent renewable generation. However, the stochastic formulation of the model makes the problem computationally demanding. In the application to the full Nordic power system, this is handled partly by using a relatively coarse temporal resolution with weekly time steps. As a result, the model is not suited for analyzing intra-week flexibility, such as hourly variations. This makes it difficult to meaningfully assess the short-term flexibility of the system.

Another tool, used for hydraulic and hydrologic modeling, is MIKE Hydro basin, developed by DHI [57]. MIKE Hydro Basin is a general-purpose river basin and water-resources model designed to simulate allocation and operation of reservoirs, water users and hydropower plants within a basin context [58, 59]. Hydropower production is represented by explicitly defining hydropower plants connected to reservoirs, where power generation depends on effective head, turbine efficiency, flow constraints and operational rules such as guide curves and water allocation priorities [59]. Since the primary purpose of MIKE Hydro Basin is integrated basin and water-allocation modeling, environmental constraints are mainly implemented as operational or allocation constraints rather than being the core object of analysis. In contrast, in FORSA such requirements are typically treated as explicit environmental scenario constraints, enabling a more direct assessment of their effects on hydropower flexibility.

Developed by the Hydrologic Engineering Center, the U.S. Army Corps of Engineers River Analysis System (HEC-RAS) is a modeling tool that can be used for flow calculations, sediment transport computation, and water temperature/quality modeling [60]. As a public domain software and free to download, it is openly available. However, its outputs primarily consist of hydrological and hydraulic results, such as hydrographs, water-surface profiles, and rating curves (i.e., the relationship between discharge and water-surface elevation) [60]. HEC-RAS is therefore well suited for analyzing river hydraulics rather than for hydropower system optimization.

In a Swedish context, the Hydroelectric Environmental Fund has developed the calculation model Beppe to quantify long-term hydropower production losses resulting from environmental measures introduced under the NAP [61]. Production loss is defined as the difference in normal-year electricity production before and after the implementation of environmental measures at individual hydropower plants. Since hydropower facilities registered under the NAP are assessed jointly with other stations within their reassessment group, a model that allows entire river systems to be represented is therefore preferred.

4.1 Flow Optimization for River System Analysis (FORSA)

As mentioned, the model used in this study is FORSA, developed by Älvbyrån [62].

FORSA represents a non-aggregated, station-based hydropower model in which individual power plants and reservoirs are modeled explicitly, together with their hydraulic connections. As discussed by Ek Fälth et al. [13], this type of representation captures important technical and physical characteristics of hydropower systems, including reservoir balances, head-dependent production, and operational interdependencies between upstream and downstream stations. Compared to aggregated hydropower models, FORSA allows for a more realistic description of river-system dynamics and coordinated operation across the system. At the same time, the level of detail is chosen such that the model remains computationally tractable, making it suitable for system-level optimization studies where both physical realism and computational efficiency are important.

Moreover, FORSA is well suited for analyzing the impacts of environmental constraints on hydropower operation, which further supports its applicability to the present study.

4.1.1 Model objective

FORSA is a revenue-optimizing model with the objective of maximizing revenues from electricity production based on electricity prices. The electricity price data, as well as the water inflow data, are exogenous, meaning that price and inflow data are treated as fixed inputs and are not affected by the model's production decisions. The electricity price data used in FORSA consist of historical hourly prices retrieved from NordPool, and are specified for Sweden's four electricity price areas. In addition to historical data, the model can also be supplied with alternative price datasets, including fabricated or scenario-based data, for example to model future electricity market conditions.

Furthermore, FORSA assumes perfect foresight, implying that all data over the entire simulation period are known in advance, allowing production to be optimized over the full time horizon.

4.1.2 System representation and interdependencies

In FORSA, a hydropower system is represented by a set of power plants and reservoirs, including their hydraulic connections and the travel time of water between upstream and downstream stations. The model accounts for reservoir water levels, which vary over time in response to water inflow and power production. Water levels are interdependent across the system, as the hydraulic head at a plant is determined by both upstream and downstream water levels. These water levels are, in turn, influenced by reservoir levels and operations at upstream and downstream stations, creating coupled dependencies throughout the river system. Furthermore, the water levels are affected by the reservoir storage content, which is represented in the model through reservoir tables (storage–level relationships).

While the model allows for a station-based representation of an entire hydropower system, revenue optimization is performed for the river system as a whole rather than for individual power plants. Consequently, revenues are not necessarily maximized at each plant. Instead, operational decisions are made to maximize the total revenue of the entire system, taking into account interdependencies between upstream and downstream plants.

4.1.3 Input data

To model hydropower production, FORSA requires information on hydraulic head, water flow, and turbine efficiency for each power plant, as described by Equation 2.1. Since the model is designed to represent entire river systems, data describing the system configuration are also required, including the connectivity between stations and the travel time of water between them. The available water flow within the system is further constrained by reservoir storage levels and their regulation capacities.

The level of detail with which a hydropower system is represented depends on data availability. In addition to the essential system-defining inputs, supplementary data may be provided to improve model accuracy. These include turbine efficiency data for individual units, spill capacity at specific stations, tailrace level functions based on historical relationships between discharge and downstream water levels, reservoir tables, and reservoir water levels at the beginning and end of the simulation period. If such data are not provided, they are determined by standard assumptions.

The required essential data will be further described in Section 5.1.

4.2 Flexibility metrics

Hydropower flexibility, and the growing need for it in future energy systems, has become an increasingly prominent topic among hydropower stakeholders [5, 13, 23, 63]. However, despite its prominence, "flexibility" is not defined or quantified in a single, consistent way across the sector [11, 12]. Flexibility is often described as the ability to respond to demand fluctuations, which is frequently represented by electricity price variations and the ability to generate during high price periods [8, 9, 11, 36, 63, 64]. This section reviews some of the metrics currently proposed to quantify hydropower flexibility and discusses their strengths, limitations, and applicability.

Note that the metrics presented in this chapter are selected for their potential to provide useful insights into hydropower flexibility in the context of the NAP and for their relevance to hydropower system modeling. The selection is therefore not intended to be comprehensive, but instead reflects the set of metrics chosen for this study based on the outputs available from FORSA.

4.2.1 Flexibility Factor

The Flexibility Factor is a measure of operational flexibility that appears in the literature under different names, including the Flexibility Factor [63], the Value Factor [65], and the Capture Rate [34]. In this study, the term Flexibility Factor is used consistently.

The Flexibility Factor reflects how well a power plant or a power system can adapt its production over time in response to variations in electricity prices [34, 63, 65]. It is defined as the ratio between the average achieved electricity price of the system and the average market price over the considered time period [63]. The average achieved price represents the mean price received per unit of electricity produced and increases if production is shifted towards periods with higher prices, and decreases if production is shifted towards periods with lower prices. Mathisen et al. [63] defines the Flexibility Factor as:

$$\text{Flexibility Factor} = \frac{\pi^*}{\bar{\pi}} = \frac{\hat{I}/\hat{P}}{\bar{\pi}} \tag{4.1}$$

where π^* denotes the average achieved price and $\bar{\pi}$ the average market price. The average achieved price can be obtained from the total revenue $\hat{I}$ and the total production $\hat{P}$. A Flexibility Factor equal to 1 indicates that electricity production has, on average, occurred at the market average price. A Flexibility Factor below 1 imply that production has predominantly taken place during periods with prices below the market average, whereas a Flexibility Factor above 1 indicates that production has been shifted towards periods with prices above the average. Consequently, higher values of the Flexibility Factor reflect a more favorable alignment of production with high-price periods.

Note that in models with endogenous (internally determined rather than externally imposed) prices, the Flexibility Factor is not an ideal metric [10, 65]. In such models, electricity prices are influenced by changes in hydropower operation, for example through the introduction of new environmental constraints, making it difficult to isolate the effect of hydropower flexibility on the Flexibility Factor [65].

4.2.2 Average Ramp in Production and Amplitude Indicator

In a study using a model with endogenous electricity prices, Aubin et al. [65] present the Average Ramp in Production and the Amplitude Indicator as alternative metrics to the Flexibility Factor.

The Average Ramp in Production reflects short-term operational flexibility, and is defined by Aubin et al. [65] as the average of the absolute difference in production between consecutive time steps over a certain time period:

$$\text{Average Ramp in Production} = \frac{1}{T-1} \sum_{t=2}^{T} |P_{\mathrm{t}} - P_{\mathrm{t-1}}| \tag{4.2}$$

where t denotes the time step index, P_{t} is the production at time step t, and T is the total number of time steps in the considered time period.

The Amplitude Indicator captures the overall variability in production over time, by measuring how much production deviates from its average level [65]. It reflects the extent to which a plant utilizes its production range rather than remaining close to a constant output level. Aubin et al. [65] define it as the average absolute deviation from the mean production, normalized by the maximum production:

$$\text{Amplitude Indicator} = \frac{1}{T} \sum_{t=1}^{T} \frac{\left|P_t - \bar{P}\right|}{P_{\max}} \tag{4.3}$$

where t denotes the time step index, P_{t} is the production at time step t, $\bar{P}$ is the average production over the considered period, $P_{\max}$ is the maximum production output, and T is the total number of time steps.

The relationship between flexibility and these two indicators should be interpreted with care. Aubin et al. [65] emphasize that higher variability in production does not necessarily imply greater flexibility. This is further illustrated by wind and solar power, which exhibit high production variability depending on weather conditions. However, Aubin et al. [65] conclude that, for dispatchable sources such as hydropower, production variability is relevant in the context of flexibility.

4.2.3 High Value Production and High Value Share

In a study by Bladh and Funkquist [23], two new metrics wer developed to measure flexibility of production units. The study's context is specifically from a Swedish hydropower perspective and the examples made are directly related to the NAP process. However, the measures may be applied in other contexts as well. The first metric, High Value Production, reflects the sum of electricity produced during hours when the electricity price is above its median value for the considered time period. The second metric, High Value Share, builds on this and reflects the share of production classified as high value production relative to total production. Based on the definitions of the metrics in [23], the following equations are derived to represent the two metrics in this study.

$$\text{High Value Production} = \sum_{t \in T:\, \pi_{\mathrm{t}} > \tilde{\pi}} P_{\mathrm{t}} \tag{4.4}$$

$$\text{High Value Share} = \frac{\sum\limits_{t \in T:\, \pi_{\mathrm{t}} > \tilde{\pi}} P_{\mathrm{t}}}{\sum\limits_{t \in T} P_{\mathrm{t}}} \tag{4.5}$$

where t denotes the time step index, P_{t} is the production at time step t, π_{t} is the electricity price at time step t, $\tilde{\pi}$ is the median electricity price over the considered period, and T is the total number of time steps. A High Value Share above 50% is described as indicating a greater regulation contribution, whereas a High Value Share equal to 50% corresponds to constant production over the entire time period [23].

5
Illustrative Application of the Modeling Framework

This chapter presents the modeling framework introduced in Section 1.2, presented once more in Figure 5.1.

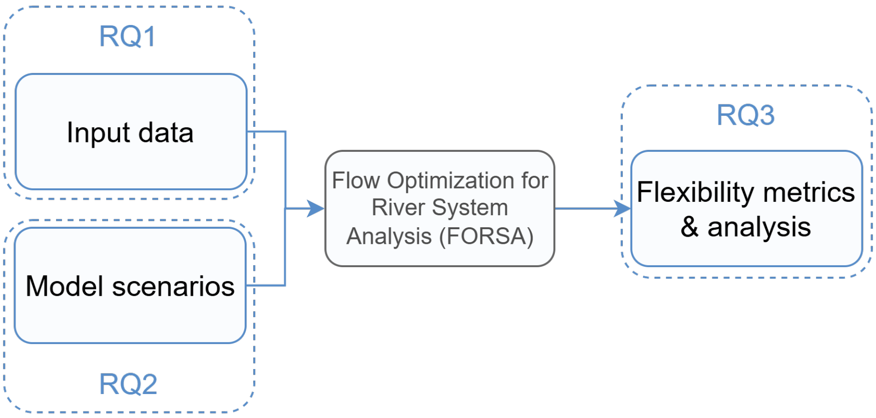


Figure 5.1: Modeling framework used to address the three research questions of this study, illustrating how input data (RQ1) and model scenarios (RQ2) define the system in FORSA and enable the derivation and analysis of flexibility metrics (RQ3).

The framework consists of three main components, each corresponding to one of the research questions. Input data and model scenarios, addressing RQ1 and RQ2 respectively, define the hydropower system and its operating conditions and serve as inputs to FORSA. The output from the model is then used to derive flexibility metrics and perform the analysis, addressing RQ3. Each component is described in more detail in the following sections.

To illustrate the application of the framework, a case study of an existing river system was conducted. The case study provides an applied context in which the framework steps could be defined, tested, and refined. The Emån river system, located in south-eastern Sweden, was selected for this purpose.

The case study serves as a practical example to support the implementation of the steps shown in Figure 5.1. Its purpose is not to derive generally applicable conclusions from the results, but to demonstrate and facilitate the development of a transparent and reproducible framework.

5.1 Input data

This section describes the first step of the modeling framework, which addresses the first research question of this study:

RQ1: What input data are required to model river systems in FORSA, and how can these data be retrieved or estimated using only open data sources?

Since the aim of this study is to develop a framework based on open-source data, the river system was modeled using the minimum amount of data required for it to run. Thus, the first step focuses on data available from open sources and on how missing information can be retrieved or estimated in a consistent and transparent manner.

To enable this approach, a distinction was made between essential and non-essential input data. The essential data were grouped into three main categories: system network data, station data, and turbine data. Figure 5.2 provides a schematic expansion of the first step of the modeling framework shown in Figure 5.1, indicating the breakdown of the input-data step addressed in this section.

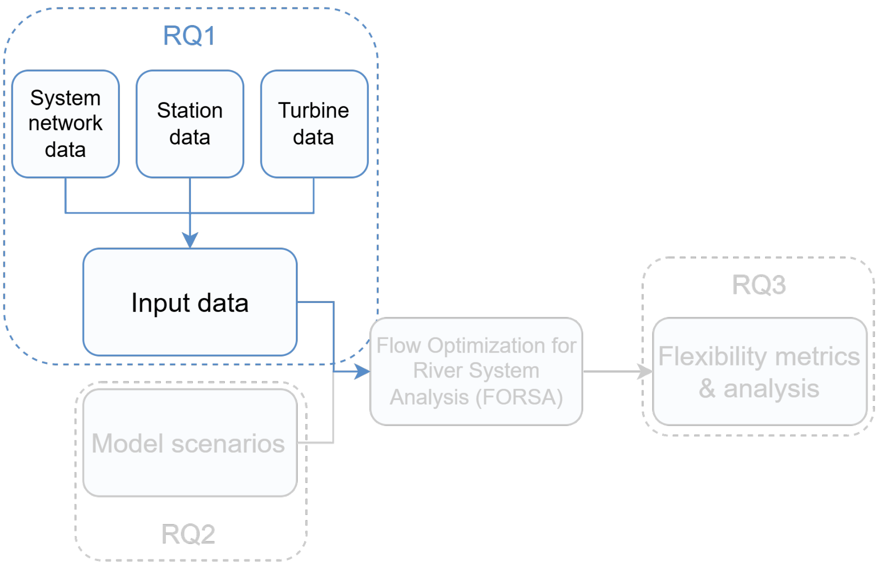


Figure 5.2: Schematic expansion of the first step within the overall modeling framework, showing the data categories considered in this section.

All essential input data, grouped by category and accompanied by brief descriptions, are summarized in Table 5.1. The table provides an overview of the data types required at this stage, while the subsequent sections of this chapter describe each data type in more detail, together with the data-retrieval process.

Table 5.1: Essential data by category

Category	Input data	Notation	Unit	Explanation
System network data	Station configuration	-	-	The set of stations (power plants and reservoirs) included in the system and the hydrological connection between them.
	Inflow	-	m^3/s	Hourly inflow data at each station.
	Flow time	t_{flow}	hour	The time for water to flow between two stations.
	Flow paths	-	-	The type of passages for water at each station.
	Electricity price region	-	-	The applicable electricity price area where the system is located.
Station data	Upper regulation limit	URL	m a.s.l	The maximum permitted water level in the reservoir.
	Lower regulation limit	LRL	m a.s.l	The minimum permitted water level in the reservoir.
	Regulation reservoir volume	V_{reg}	Mm^3	Usable reservoir volume within the permitted regulation limits.
	Hydraulic head	H	m	The difference between the upstream and downstream water levels.
Turbine data	Maximum turbine discharge	$Q_{\text{t,max}}$	m^3/s	The maximum discharge the turbine is designed for.
	Optimal turbine discharge	$Q_{\text{t},\eta=\text{max}}$	m^3/s	Turbine discharge at which the efficiency is maximized.
	Zero-efficiency turbine discharge	$Q_{\text{t},\eta=0}$	m^3/s	The turbine discharge at which the efficiency equals zero.
	Maximum turbine efficiency	η_{max}	%	The maximum efficiency of the turbine.

5.1.1 System network data

The first data category, presented in Table 5.1, includes station configuration, inflow, flow time (t_{flow}), flow paths and electricity price region. The methods for retrieving or estimating these data are described in the following five sections.

5.1.1.1 Station configuration

The first step in modeling the river system was to identify the hydropower plants and reservoirs to be included in the system representation, and to define their hydrological connections. Since the purpose is to represent how water is regulated and utilized for electricity generation, the primary criterion was that power plants must actively use water, and that reservoirs must have a defined regulation volume.

When selecting power plants, baseline descriptions and court decisions from the Swedish Land and Environment Court were reviewed to identify facilities that produce electricity. All reservoirs for which data on regulation volume or regulation amplitude were available were included. This information was obtained by screening the Water Regulation Database [66] and the Lake and Reservoir Register [67], both provided by the Swedish Institute of Meteorology and Hydrology (SMHI).

In addition to the plants and reservoirs included in the system representation, one additional station was included in the station configuration. This station represents a paper production facility located downstream in the Emån system, for which a minimum water discharge is required for production purposes. In the model, the facility is represented as a reservoir acting as a proxy, which enables the specification of a required minimum flow past the station. This is described in further detail in Section 5.2.2.1. Figure 5.3 provides an overview of all stations included in the Emån case study.

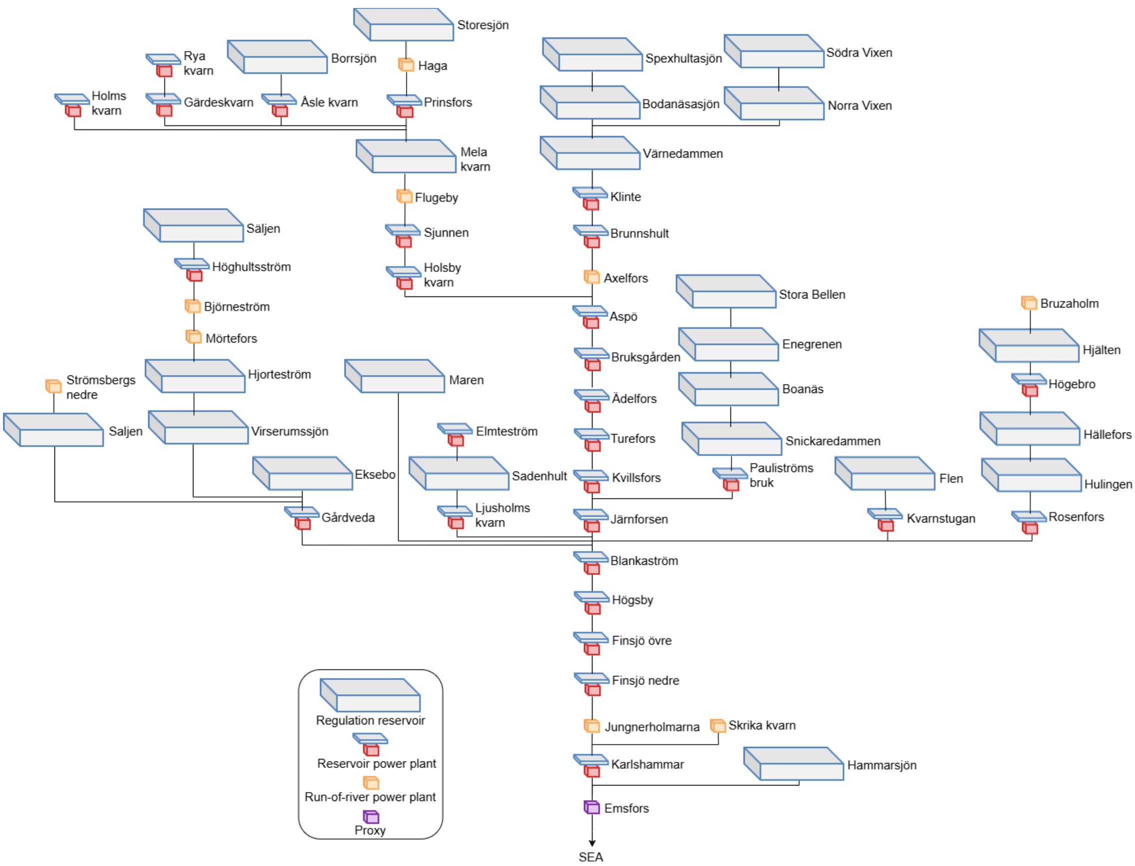


Figure 5.3: Schematic of the Emån river system network.

5.1.1.2 Inflow

The inflow data represent the incremental catchment inflow to each station, and corresponds to all water contributions not already accounted for in upstream inflows in the model. For this, data were retrieved from the SMHI Catchment Hydrology Database, [68], which contains both total and local inflow for all sub-catchments in all of Sweden's river basin districts. The total inflow includes contributions from all upstream sub-catchments of the selected sub-catchment, whereas the local inflow includes contributions only from the selected sub-catchment. Each sub-catchment has a so called subID and an associated measurement point where the data can be extracted. This measurement point represents the geographical location along the river network where the river discharge corresponds to the accumulated contribution from the selected sub-catchment and all upstream sub-catchments.

To construct the inflow data file, the first step was to map the geographical location of each station and identify the measurement points appropriate for estimating inflow to each station. Figure 5.4 shows a map view from the SMHI Catchment Hydrology Database of the main river basin of Emån, as well as all stations included in this case study.

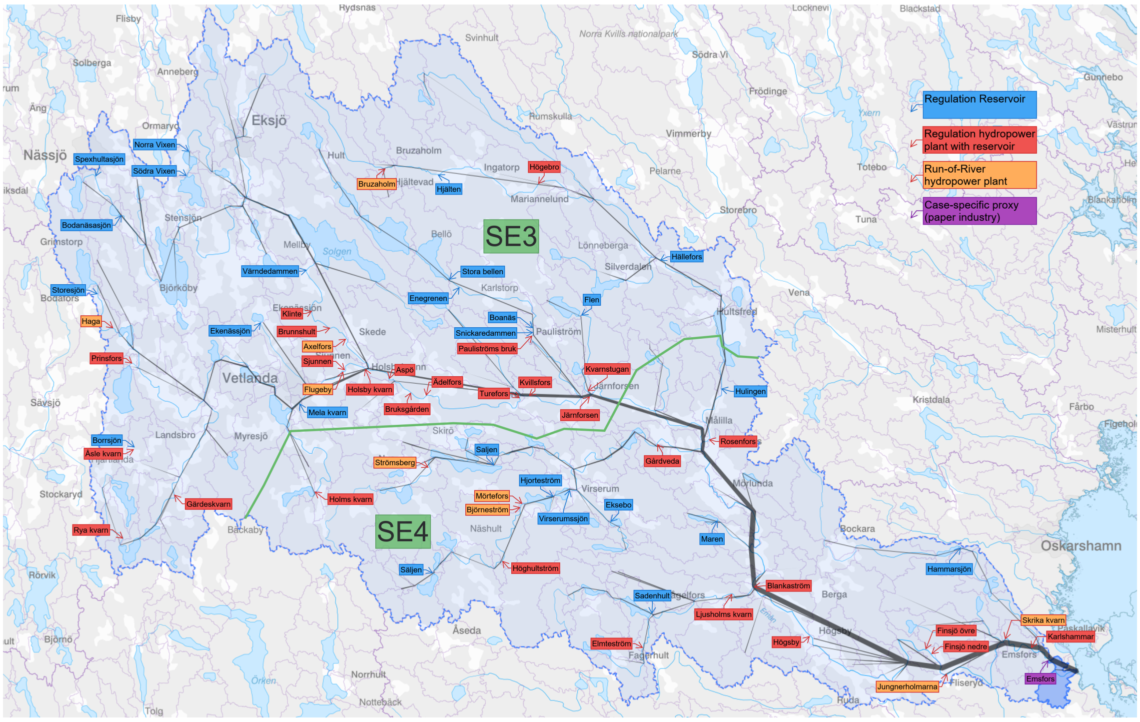


Figure 5.4: The Emån main river basin from the SMHI Catchment Hydrology Database [68], shown schematically in Figure 5.3. The green line, boxes, and arrows have been added and indicate the division into electricity price regions SE3 and SE4, the stations included in the case study, and their geographical locations, respectively.

The total inflow of a sub-catchment includes all upstream contributions, which must be taken into account for all stations located downstream other stations in one or more upstream tributaries. This was done by subtracting the total, and where relevant also local, contributions of the nearest upstream station in each upstream tributary of a given station. In some cases, multiple upstream measurement points were required to encompass additional catchment areas from tributaries that enter the river between the measurement point and the station.

Accordingly, the inflow data file was constructed by mapping the river network from the most upstream stations downstream. For stations located immediately upstream or downstream of a measurement point, total inflow data from that point were used directly. Otherwise, inflow was estimated by combining total inflow from the nearest upstream point with local inflow from the nearest downstream point. For each station, the relevant sub-catchment subIDs were identified, specifying total and local contributions as well as required subtractions.

In cases when stations were not located directly adjacent to a measurement point and local inflow was used, the contribution was assumed to correspond to the fraction of the sub-catchment area upstream of the station relative to the total sub-catchment area. This was defined as described in the equation below:

$$f_{\text{station}} = \frac{A_{\text{sc,upstream}}\ (\text{km}^2)}{A_{\text{sc,total}}\ (\text{km}^2)} \tag{5.1}$$

where f_{station} denotes the fraction of the local inflow of the sub-catchment allocated to the station, $A_{\text{sc,upstream}}$ is the area of the sub-catchment upstream of the station, and $A_{\text{sc,total}}$ is the total area of the sub-catchment. The total area of each sub-catchment is provided in the SMHI Catchment Hydrology Database. This work flow is exemplified later in Figure 5.6 and Equation 5.2.

Focusing on the stations located in the uppermost part of Emån (to the left in Figure 5.4), Figure 5.5 presents a workflow example in which these stations are used to illustrate how inflow data were constructed.

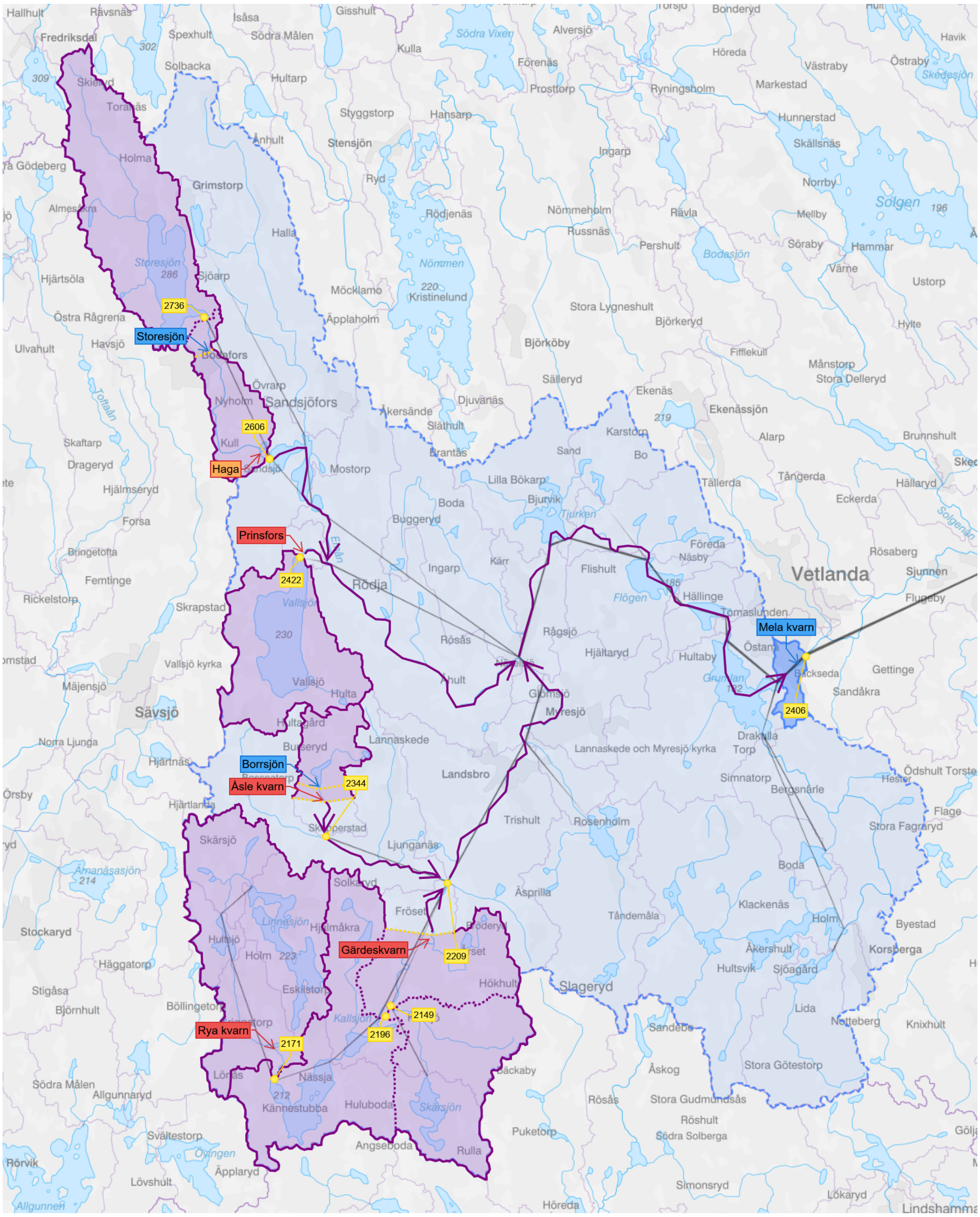


Figure 5.5: Map view from the SMHI Catchment Hydrology Database showing the sub-catchments, stations, and measurement points included in the worked inflow example. The blue delineation indicates the total contributing area upstream of Mela kvarn (sub-catchment 2406). The purple shaded areas, yellow boxes, dotted lines, and arrows have been added. Purple shaded areas indicate the sub-catchments included in the example, yellow boxes mark measurement points used for inflow extraction (labeled with subIDs), yellow dotted lines indicate divisions of local inflow data, purple dotted lines show boundaries between extraction areas allocated to the same station, and purple arrows indicate flow paths and directions toward Mela kvarn.

While Figure 5.5 provides a spatial overview of the stations, sub-catchments, and measurement points included in the worked inflow example, Table 5.2 provides a concise summary of the information shown in the figure. Together, the figure and table illustrate how inflow data were constructed for each station by combining total inflow, local inflow, and subtractions of upstream contributions. A full summary of the entire Emån river network and the corresponding inflow configuration is provided in Table A.2 in Appendix A.

Table 5.2: Summary of inflow allocation for hydropower stations shown in Figure 5.5, including SubIDs for total and local contributions, local inflow fractions where applicable, and upstream inflows subtracted to avoid double counting.

Station	**subID (Total)**	**subID (Local)**	**Local fraction**	**Upstream stations to be subtracted**
Rya kvarn	2171	–	–	–
Gärdeskvarn	2196 2149	2209	0.76	Rya kvarn (1 total)
Borrsjön	–	2344	0.60	–
Åsle kvarn	–	2344	0.11	–
Holms kvarn	2231	–	–	–
Prinsfors	2422	–	–	–
Storesjön	2736	2606	0.13	–
Haga	2606	–	–	Storesjön (1 total + 1 local)
Mela kvarn	2406	–	–	Gärdeskvarn (2 total + 1 local) Borrsjön (1 local) Åsle kvarn (1 local) Holms kvarn (1 total) Prinsfors (1 local) Haga (1 total)

From Table 5.2, Rya kvarn can be identified as the farthest upstream station in one of the tributaries of Emån, since no upstream stations need to be subtracted. Rya kvarn is located sufficiently close to a measurement point for the total inflow of sub-catchment 2171 to be used directly, without including any local inflow contribution.

Downstream in the same tributary, Gärdeskvarn is located. The inflow to Gärdeskvarn is calculated as the sum of the total inflow from sub-catchments 2196 and 2149, combined with 76% of the local inflow from sub-catchment 2209. Since Rya kvarn is upstream of Gärdeskvarn in this tributary, the total inflow already accounted for at Rya kvarn must be subtracted from the inflow dataset of Gärdeskvarn.

In another tributary, Borrsjön and Åsle kvarn are the farthest upstream stations. Neither of these stations have any upstream stations from which inflow must be subtracted. Both stations are assigned a fraction of the local inflow from sub-catchment 2344, which has no upstream sub-catchments. Consequently, the total and local inflow for this sub-catchment are identical. Although Borrsjön is located upstream of Åsle kvarn, no subtraction is required for Åsle kvarn, since only local inflow contributions are included for both stations.

Holms kvarn, Prinsfors and Storesjön are the farthest upstream stations in three additional tributaries of Emån. Both Holms kvarn and Prinsfors only includes the total inflow of sub-catchments 2231 and 2422, respectively. Storesjön includes both the total inflow from sub-catchment 2736 and 13% of the local inflow from sub-catchment 2606. The station Haga, located downstream of Storesjön, therefore requires subtraction of both these contributions, as they have already been accounted for at Storesjön.

Finally, Mela kvarn is located downstream of all tributaries in the example. As a result, the inflow contributions of the closest upstream station in each tributary must be subtracted from the inflow dataset of Mela kvarn. These stations are Gärdeskvarn, Borrsjön, Åsle kvarn, Holms kvarn, Prinsfors and Haga. Note that Rya kvarn and Storesjön are not subtracted directly, since their inflow contributions are already included in the datasets of their respective downstream stations, Gärdeskvarn and Haga. Furthermore, since Gärdeskvarn receives total inflow from two separate sub-catchments belonging to different tributaries, two corresponding total inflow contributions from Gärdeskvarn must be subtracted from the inflow dataset of Mela kvarn.

Figure 5.6 and Equation 5.2 provide an example of how the area upstream the station Gärdeskvarn was estimated and then used to calculate the fraction of local inflow from sub-catchment 2209 to be allocated to the station.

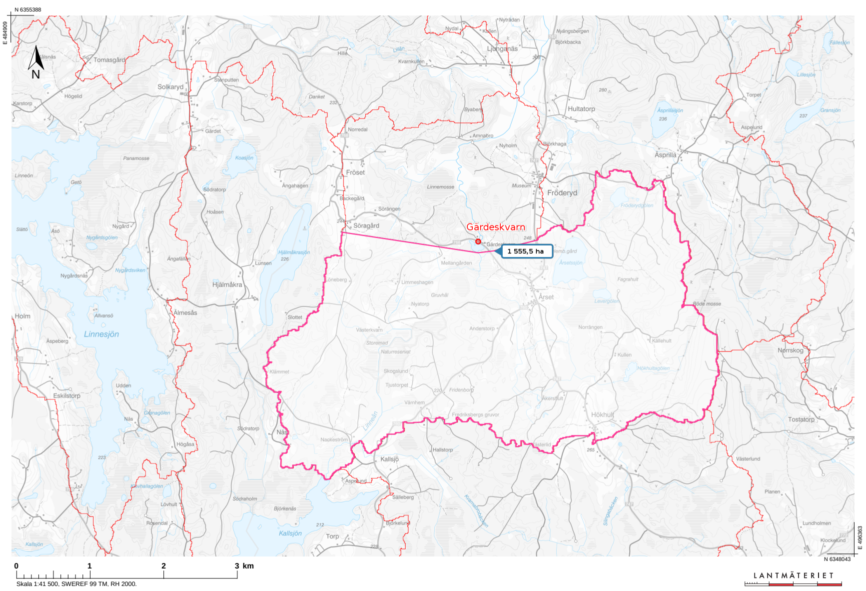


Figure 5.6: Map view from the Swedish Mapping, Cadastral and Land Registration Authority map tool showing sub-catchment boundaries in red. The red dot was manually added to indicate the location of Gärdeskvarn, and the pink delineation shows the area measured within the map tool. The shaded area represents A_{upstream} in Equation 5.2.

Figure 5.6 shows that the area upstream of Gärdeskvarn is $A_{\text{upstream}} = 1555.5$ ha $=$ 15.555 km^2, while the total catchment area is $A_{\text{tot}} = 20.34$ km^2. This results in approximately 76% of the inflow from sub-catchment 2209 being allocated to the Gärdeskvarn station.

$$f_{\text{Gärdeskvarn}} = \frac{15.555\ (\text{km}^2)}{20.34 (\text{km}^2)} \approx 0.76 \tag{5.2}$$

In Table A.1 in Appendix A.1, all stations for which local inflow fractions were calculated are provided together with the underlying area data.

5.1.1.3 Flow time

The time it takes for the water to travel from one station to the nearest downstream station in each flow path is represented by t_{flow}. For this project, t_{flow} was estimated using a simplified method, where the only factors considered were the mean water flow, MQ, the distance and the average cross-section area between two stations. This relation is defined in Equation 5.3 below:

$$t_{\text{flow}}\ (\text{h}) = \frac{L\ (\text{m}) \cdot S_{\text{r}}\ (\text{m}^2)}{3600\ (\text{s/h}) \cdot MQ\ (\text{m}^3/\text{s})} \tag{5.3}$$

where t_{flow} is the flow time in hours, L is the distance that the water travels between two stations, S_{r} is the average cross-section area of the river and MQ is the mean water flow. In this study, the cross-section area, S_{r}, was represented by a triangle with the base equal to the average width of the river, w_{r}, between two stations, and the height equal to the depth of the river, d_{r}.

$$S_{\text{r}}\ (\text{m}^2) = \frac{w_{\text{r}}\ (\text{m}) \cdot d_{\text{r}}\ (\text{m})}{2} \tag{5.4}$$

The MQ for all relevant sub-catchments was obtained from the SMHI Catchment Hydrology Database [68] and represents the mean flow for the period 1990–2020. The distance between stations and the corresponding average river width were estimated using the Swedish Mapping, Cadastral and Land Registration Authority map tool [69]. Distances were measured manually by following the river path between stations using the tool's measurement function, while river width was estimated by measuring the width at several evenly distributed locations along each reach and calculating the average. Due to the lack of data on the depth of the river, this variable was set to 1 m for the entire system.

In cases where the water path between two stations passes multiple sub-catchments, multiple MQ values affect the travel time. Therefore, the total t_{flow} between two stations was calculated as the sum of t_{flow} within each sub-catchment between two stations:

$$t_{\text{flow}}\ (\text{h}) = \frac{1}{3600\ (\text{s/h})} \sum_{\text{sc}} \frac{L_{\text{r,sc}}\ (\text{m}) \cdot S_{\text{r,sc}}\ (\text{m}^2)}{MQ_{\text{sc}}\ (\text{m}^3/\text{s})} \tag{5.5}$$

where $L_{\text{r,sc}}$ is the distance the water travels, $S_{\text{r,sc}}$ is the average cross section area of the river and MQ_{sc} is the mean water flow, all within the same sub-catchment.

Figure 5.7 shows an example of how the length and width were estimated for the calculation of t_{flow} between Rya kvarn and Gärdeskvarn.

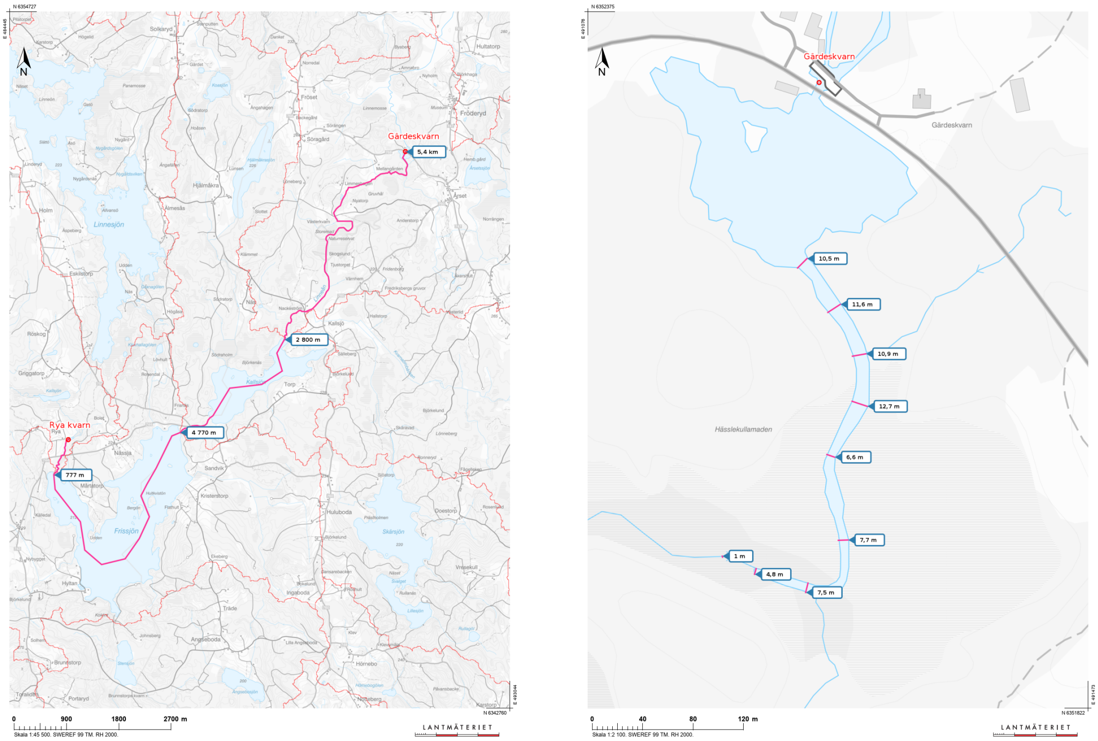


Figure 5.7: Map view from the Swedish Mapping, Cadastral and Land Registration Authority map tool, showing sub-catchment boundaries in red lines. The red dots were manually added within the map tool to indicate the location of Rya kvarn and Gärdeskvarn. In the left figure, pink lines show the use of the measurement tool, which was used to measure distances between stations, separated by sub-catchments. In the right figure, pink lines show the use of the measurement tool, where the river width was measured at different locations.

For sub-catchments without lakes, the length was measured directly by following the river. For sub-catchments containing lakes, the length across the lake was estimated by following the centerline of the lake. Furthermore, for sub-catchments consisting solely of a lake, the river width was estimated as the average of the inlet and outlet river widths.

A detailed summary of all t_{flow}-values, as well as the underlying measurement data, for all stations in the Emån river system can be found in Tables A.3 and A.4 in Appendix A.2.

5.1.1.4 Flow paths

Spillways are always present, while stations with power generation also include turbine flow paths. This allows the system representation to account for situations where water levels exceed the discharge capacity of the turbines.

For each type of flow path, t_{flow} is set independently, but for this project the same time was used for all flow paths present at each station.

5.1.1.5 Electricity price region

Historical electricity price data are included in the model for all four Swedish electricity price regions. In most cases, a river basin district is entirely located within a single price region, making that region the natural choice for price data. For the Emån river system, however, the northern part of the basin lies in price region SE3, while the southern part lies in SE4. In total, 21 hydropower stations are located in SE3 and 16 in SE4 (see Figure 5.4).

The FORSA interface used in this study allows only one electricity price region to be assigned to the entire system, although the model itself can handle different price regions for individual stations. Consequently, a single price region had to be selected, with the selection based on the region accounting for the largest share of hydropower production.

An initial model run was therefore performed to estimate the distribution of production between the two regions. The results indicated that approximately 53% of the total production occurs in SE3 and 47% in SE4. Based on this, electricity price data from SE3 were used in the model.

For comparative purposes, the specific choice of electricity price region is of limited importance, as the same price assumptions are consistently applied across all scenarios. Electricity prices primarily influence the production optimization, while the analysis focuses on relative differences between scenarios rather than absolute production levels.

5.1.2 Station data

The second data category, presented in Table 5.1, includes the upper regulation limit (URL), lower regulation limit (LRL), and regulation reservoir volume (V_{reg}) (all three parameters treated as reservoir data), as well as average hydraulic head (H). The methods for retrieving or estimating these data are described in the sections below.

5.1.2.1 Reservoir data

For all stations, the URL, LRL, and V_{reg}, was required. The URL and LRL define the maximum and minimum water levels allowed in a reservoir, expressed in meters above sea level (m a.s.l.), and V_{reg} is defined as the usable volume between the permitted regulation limits, expressed in Mm^3. Data for these parameters was obtained from various sources according to the hierarchy in the list below:

1. Baseline description [70]
2. SMHI Water Regulation Database [66]
3. SMHI Lake and Reservoir Register [67]
4. vattenkraft.info [71]

5. Estimation based on the relationship between reservoir volume, surface area, and regulation amplitude, using surface area data obtained from the sources listed above or from the Swedish Mapping, Cadastral and Land Registration Authority map tool [69]

6. Estimation based on the mean value derived from stations with available data

In many cases, the regulation limits were provided as a regulation amplitude (h_{reg}) rather than as explicit upper and lower regulation limits. In these cases, the reservoir water surface elevation was derived using the Swedish Mapping, Cadastral and Land Registration Authority map tool, and used as URL. The LRL was then estimated using h_{reg}:

$$LRL \text{ (ma.s.l.)} = URL \text{ (ma.s.l.)} - h_{\text{reg}} \text{ (m)} \tag{5.6}$$

In cases where either the regulation limits or the reservoir volume could not be obtained from the available sources, the reservoir surface area was used to derive the missing parameter. With the simplified assumption that the reservoir sidewalls are vertical relative to the water surface, V_{reg} could be estimated from h_{reg}, or vice versa:

$$V_{\text{reg}} \text{ (m}^3\text{)} = h_{\text{reg}} \text{ (m)} \cdot A_{\text{surface}} \text{ (m}^2\text{)} \tag{5.7}$$

In cases where neither h_{reg} nor the reservoir volume could be directly obtained from the listed sources, h_{reg} was assumed to be equal to the mean value derived from stations with available data. Two separate means were calculated, one for reservoirs and one for reservoir power plants, as it was found that these exhibit different regulation characteristics, see Figure A.1-A.3 in Appendix A.3. The average amplitude was estimated as 0.34 m for power plants and 1.40 m for reservoirs. The reservoir surface area was then used together with the assumed h_{reg}-value, according to Equation 5.7, to estimate the reservoir volume.

Lastly, all stations representing run-of-river (RoR) power plants also require input data for reservoir limits and volumes, even though both are technically zero, reflecting the lack of regulation capacity. Consequently, no empirical data are available for the reservoir parameters of RoR power plants. However, the model still requires numerical input values in order to run successfully. Therefore, all RoR power plants were assigned a regulation amplitude of $h_{\text{reg}} = 0.05$ m and a regulation volume of $V_{\text{reg}} = 1$ m^3.

5.1.2.2 Hydraulic head

All stations representing a hydropower plant data on H, expressed in metres, and defined as the difference between the upstream and downstream water levels. Data on the maximum available hydraulic head (H_{max}) was obtained through various sources according to the hierarchy in the list below:

1. Baseline description [70]

2. vattenkaft.info [71]

3. Estimation based on water surface elevations upstream and downstream of the powerhouse, obtained from the Swedish Mapping, Cadastral and Land Registration Authority map tool [69]

For a few stations, H_{max} could not be obtained directly from either the baseline description or vattenkraft.info, in which case an estimation was made, using the Swedish Mapping, Cadastral and Land Registration Authority map tool. The water surface elevations upstream and downstream of the powerhouse were retrieved, and the difference between them was set as H_{max} of the plant. Figure 5.8 illustrates the procedure used to determine H_{max} for the Mörtefors station.

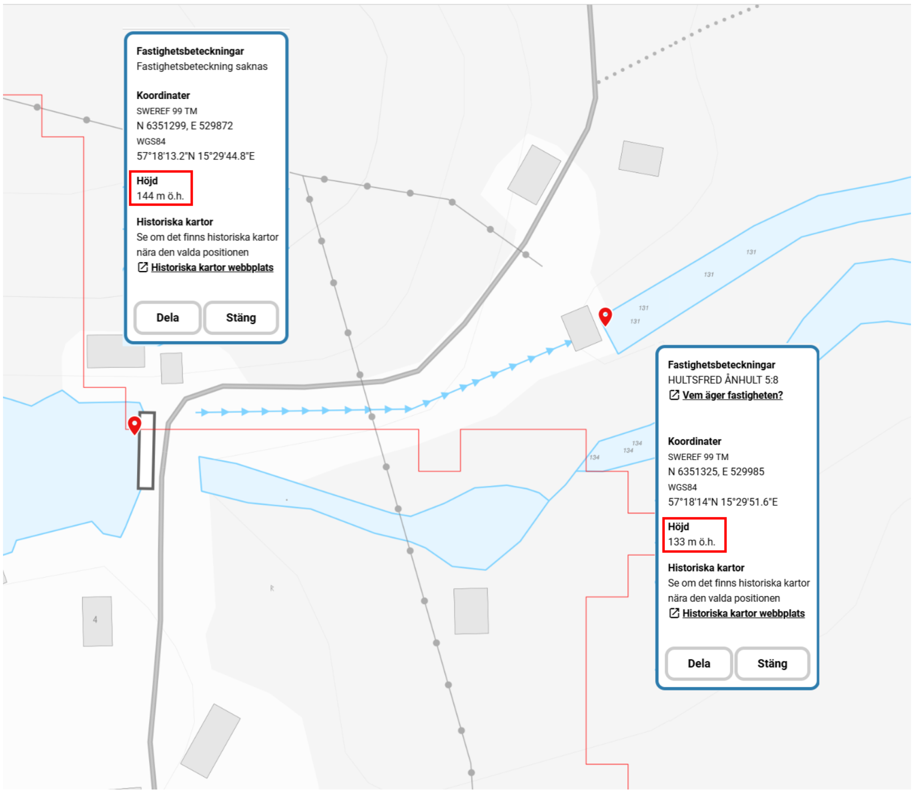


Figure 5.8: Example of H_{max} determination at the Mörtefors station using the Swedish Mapping, Cadastral and Land Registration Authority map tool. The upstream and downstream water surface (Höjd) elevations are indicated by the red boxes. The water is lead through a penstock, indicated by the arrowed line, to the powerhouse, showed as the gray box.

As shown in Figure 5.8, the upstream and downstream water surface elevations at Mörtefors were identified as $W_{\text{upstream}} = 144$ m a.s.l. and $W_{\text{downstream}} = 133$ m a.s.l., respectively, resulting in a H_{max} of $H_{\text{Mörtefors}} = (144 - 133)$ m $= 11$ m.

H_{max} reported in the sources refers to the maximum available difference between the upstream and downstream water levels, i.e. when the water level in the upstream reservoir is at its URL. However, this value had to be adjusted to represent the most frequently occurring H during operation. Therefore, H_{max} was adjusted to correspond to the situation in which the upstream reservoir water level is exactly between URL and LRL:

$$H\ (\mathrm{m}) = H_{\max}\ (\mathrm{m}) - \frac{h_{\mathrm{reg}}\ (\mathrm{m})}{2} = H_{\max}\ (\mathrm{m}) - \frac{URL - LRL\ (\mathrm{m})}{2} \tag{5.8}$$

This adjustment ensures that H better reflects the hydraulic conditions most commonly occurring during normal operation and reservoir regulation.

5.1.3 Turbine data

The third and final data category, presented in Table 5.1, includes four turbine parameters used by FORSA to construct efficiency curves. For each turbine in the modeled system, these parameters are the maximum turbine discharge ($Q_{\mathrm{t,max}}$), optimal turbine discharge ($Q_{\mathrm{t},\eta=\eta_{\max}}$), zero-efficiency turbine discharge ($Q_{\eta=0}$), and the maximum efficiency ($Q_{\mathrm{t,max}}$). It is also necessary to determine the number of units at each individual power station.

Due to insufficient data access of all four parameters in open sources, a method was developed to estimate the missing data, based on generalized turbine efficiency curves and factors for different turbine types. The method is described in the following section.

5.1.3.1 Generalized turbine factors

Of the four turbine parameters, only $Q_{\mathrm{t,max}}$ could be obtained from open sources. Therefore, a method was developed to derive the remaining three parameters solely based on $Q_{\mathrm{t,max}}$. This was achieved by using generalized turbine efficiency curves expressed as functions of relative discharge for different turbine types, see Figure 5.9.

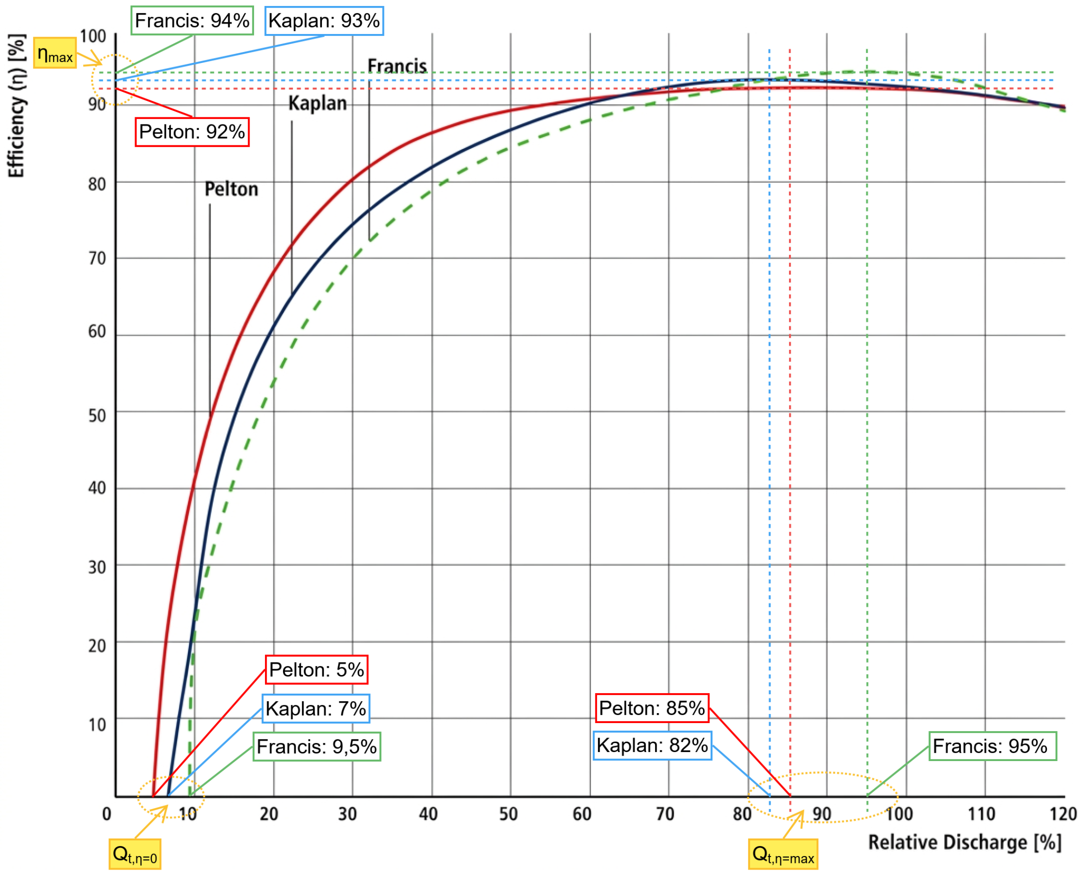


Figure 5.9: Normalized efficiency curves for Pelton, Francis, and Kaplan turbines as a function of relative discharge [29]. All dotted lines and text boxes have been added to the original graph. The horizontal dotted lines represent η_{max}, and the vertical dotted lines denote the corresponding relative discharge at which $Q_{\text{t,max}}$ occurs for each turbine type, representing $Q_{\text{t},\eta=\eta_{\text{max}}}$. In addition, the point corresponding to $Q_{\eta=0}$, where the curves intersect the x-axis, is indicated.

The input data is required for each individual turbine. When a plant consists of multiple turbines, the discharge limit must therefore be specified on a per-turbine basis. For plants where this limit is reported for the installation as a whole, it was assumed to be evenly distributed among the turbines, allowing an estimate of the corresponding per-turbine $Q_{\text{t,max}}$.

Using the standardized efficiency curves, η_{max} of the turbines was set to 93% for all Francis turbines and 94% for all Kaplan turbines. The remaining turbine parameters could then be obtained by multiplying the percentages presented in Figure 5.9 with $Q_{\text{t,max}}$, for each turbine.

In practice, turbines are not operated from $Q_{\eta=0}$, but only above a minimum operating discharge. In FORSA, this threshold is derived from the turbine efficiency curve and is defined as the discharge at which the efficiency reaches $\eta = 30\%$. Figures A.4 and A.5 in Appendix A.4 present two examples of efficiency curves and their corresponding operation curves in FORSA, representing a Francis turbine and a Kaplan turbine, respectively.

Note that the standardized efficiency curves in Figure 5.9 represent the efficiencies of the turbines alone, whereas the power output depends on η_{tot}, as shown in Equation 2.1. To properly model the power output of a plant, the turbine efficiency parameters must therefore be adjusted to account for additional sources of loss, such as generator losses. This is done by multiplying the parameters by the efficiencies of the remaining components contributing to the total efficiency.

5.1.3.2 Turbine configuration

Since the above mention method to derive the turbine parameters require the number of turbines, as well as their type, this data was required for all power plant stations. This was obtained through various sources according to the hierarchy list below:

1. Baseline description [70]
2. vattenkaft.info [71]
3. Estimation based on typical turbine application ranges as a function of H and mean river discharge [29, p. 16].

In cases where data on the number of turbines at a given power plant were not available, the number of turbines was assumed to be one. Furthermore, when the turbine type could not be obtained from the available sources, the turbine type was assigned based on typical turbine application ranges as a function of H and MQ, illustrated in Figure 5.10.

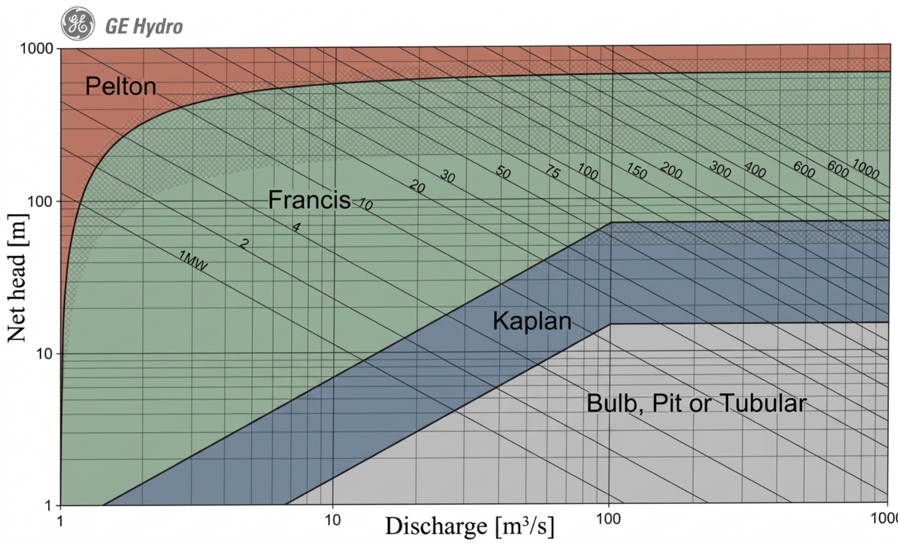


Figure 5.10: Turbine application ranges as a function of H (vertical axis) and MQ (horizontal axis) [29, p. 16]. The zones indicate typical operating ranges for different turbine types, allowing the most likely turbine type to be identified based on the combination of H and MQ.

For the Emån river system, turbine type information was unavailable for 12 power plants. In these cases, the classification shown in Figure 5.10 was used to determine the most likely turbine type. Of these plants, 11 were classified as Francis turbines, while one was classified as a Kaplan turbine based on its relatively low H and high MQ. The power plants concerned and corresponding data are listed in Table A.5 in Appendix A.5.

5.1.3.3 Maximum turbine discharge

The maximum flow for which the turbine is designed is represented by $Q_{\mathrm{t,max}}$. Any discharge exceeding this value is diverted away from the turbine and released through spillways or other bypass structures. Data on $Q_{\mathrm{t,max}}$ was found through various sources according to the hierarchy list below:

1. Baseline description [70]
2. vattenkraft.info [71]
3. Estimation based on the relationship between MQ and $Q_{\mathrm{t,max}}$

For stations where data were not available from the sources listed above, $Q_{\mathrm{t,max}}$ was estimated based on a proportional relationship with the MQ at the turbine location:

$$Q_{\mathrm{t,max}}\ (\mathrm{m^3/s}) = k \cdot MQ\ (\mathrm{m^3/s}) \tag{5.9}$$

where MQ denotes the mean water flow at the site, and k represents the installed discharge ratio. As mentioned in Section 2.2.1, $Q_{\mathrm{t,max}}$ is commonly assumed to be 1.5 times the MQ. However, in order to adapt this relationship to the specific hydrological conditions of the Emån river system, site-specific values of k were derived. The parameter k was calculated for all stations within the Emån catchment for which data on $Q_{\mathrm{t,max}}$ were available:

$$k = \frac{Q_{\mathrm{t,max}}\ (\mathrm{m^3/s})}{MQ\ (\mathrm{m^3/s})} \tag{5.10}$$

An ordered bar chart of the calculated k-values revealed a skewed distribution with several outliers, see Table A.6 and Figure A.6 in Appendix A.6. To reduce the influence of extreme values, the median k-value was therefore used instead of the mean. The resulting median was $k \approx 1.2$, compared to a mean value of approximately $k \approx 1.3$. Subsequently, Equation 5.9 was applied using the median k-value for power plants for which data on $Q_{\mathrm{t,max}}$ were unavailable.

5.2 Model scenarios

This section describes the second step of the modeling framework, which addresses the second research question of this study:

RQ2: How can environmental measures under the NAP be translated into model parameters and scenarios?

The model scenarios developed in this study, demonstrated through a case study of the Emån river system, reflect the specific environmental characteristics of the system. However, the approach used to define these scenarios is generic and can be reproduced for other river systems. This is particularly evident for the baseline scenario, which represents the current environmental conditions.

As discussed in Section 2.5, hydropower can affect river systems in different ways, requiring different types of environmental measures. Accordingly, three environmental conditions scenarios were defined to represent alternative approaches. These scenarios enable a comparison of model results and support the assessment of changes in system flexibility under different environmental conditions.

Figure 5.11 provides a schematic expansion of the second step of the modeling framework shown in Figure 5.1, illustrating the different model scenarios considered in this framework.

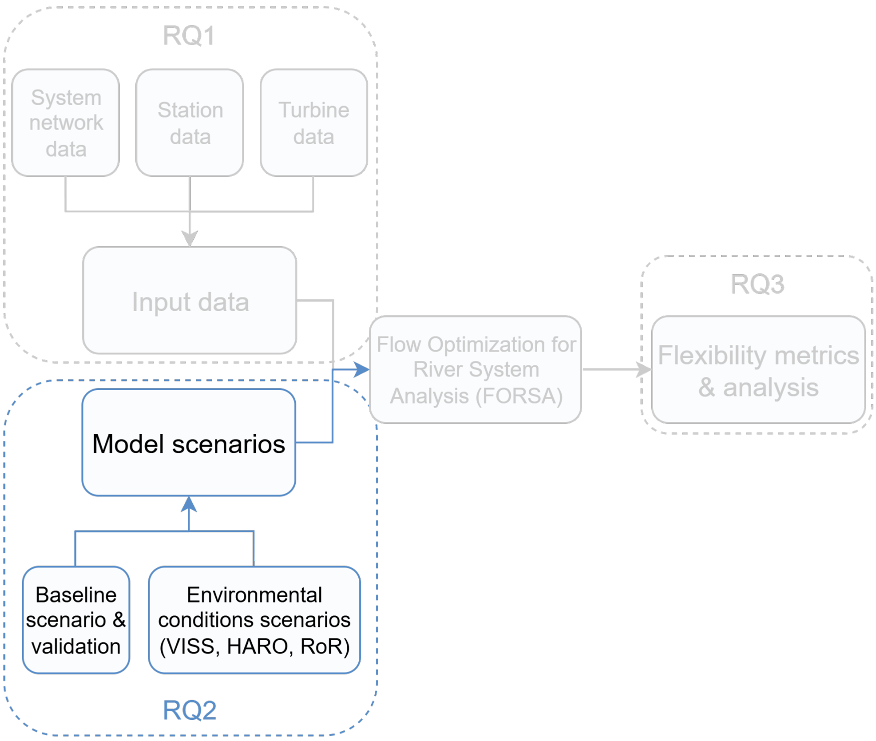


Figure 5.11: Schematic expansion of the second step within the overall modeling framework, showing the model scenarios considered in this section.

To facilitate understanding of the scenario construction and the translation of measures into constraints in FORSA, this section begins with a brief overview of the types of constraints that can be implemented in FORSA. This is followed by a description of how the different scenarios were constructed and which constraints were applied in each case, starting with the baseline scenario, followed by the environmental conditions scenarios.

5.2.1 Environmental constraints in FORSA

Constraints can be applied either to water flows or water levels in FORSA.

Flow constraints may be imposed on any of the following three flow paths at a station: the fish passage, the spillways, or the total discharge, where the total discharge includes the combined flow through the fish passage, spillways, and turbine at the same station. These constraints can specify minimum and/or maximum discharge requirements for a given flow path. The discharge limits may be defined either as fixed values or as model-derived values, such as fractions of MQ or of the total inflow, Q_{inflow} for each hour. Similarly, constraints may be defined for the average discharge over a specified time period, by imposing minimum and/or maximum limits on period-averaged flows. Flow variability can also be constrained by limiting the allowable rate of change in discharge. Such ramping constraints may be applied either between predefined periods (i.e. limiting changes between periods) or within periods, by restricting hour-to-hour variations in discharge.

Water-level constraints may be imposed on either the upstream or downstream water level. These constraints can specify minimum and/or maximum allowable water levels. Furthermore, limits may be placed on water-level variations by constraining the allowable rate of change. Similar to the flow constraints, water-level variation constraints may be applied either between predefined periods or within periods, by restricting hour-to-hour changes in water level.

5.2.1.1 Conditional constraints

The implementation of environmental constraints depends on the prevailing conditions at a station, such as available inflow or water levels. Consequently, these constraints cannot always be fully satisfied. For example, minimum discharge requirements can only be met when sufficient inflow from the upstream system is available.

To represent these physical limitations realistically and to ensure model feasibility, all environmental measures were implemented as conditional constraints in FORSA. The approach is illustrated below using minimum discharge requirements as an example.

$$Q_{\text{min,path}} = \begin{cases} Q_{\text{min,path}}, & \text{if } Q_{\text{inflow}} \geq Q_{\text{min,path}} \\ Q_{\text{inflow}}, & \text{if } Q_{\text{inflow}} < Q_{\text{min,path}} \end{cases} \tag{5.11}$$

where $Q_{\text{min,path}}$ is the enforced minimum discharge through a given flow path and Q_{inflow} is the total non-regulated inflow to the station from the upstream system.

This formulation ensures that the minimum discharge is respected whenever hydrologically possible, while avoiding infeasible model states during low-flow conditions.

In some cases, minimum discharge requirements apply to multiple flow paths at the same station. In such situations, a hierarchical allocation approach was adopted to define the priority between constraints.

The following formulation illustrates the case where minimum discharge requirements apply to the fish passage and the total discharge. An equivalent formulation would apply if the constraint were imposed on the spillways instead of the fish passage, as both flow paths are treated with equal priority relative to the total discharge requirement.

$$
\begin{aligned}
Q_{\text{min,passage}} &= \begin{cases} Q_{\text{min,passage}}, & \text{if } Q_{\text{inflow}} \geq Q_{\text{min,passage}} \\ Q_{\text{inflow}}, & \text{if } Q_{\text{inflow}} < Q_{\text{min,passage}} \end{cases} \\
Q_{\text{min,total}} &= \begin{cases} Q_{\text{min,total}}, & \text{if } Q_{\text{inflow}} \geq Q_{\text{min,passage}} + Q_{\text{min,total}} \\ Q_{\text{inflow}}, & \text{if } Q_{\text{inflow}} < Q_{\text{min,passage}} + Q_{\text{min,total}} \end{cases}
\end{aligned} \tag{5.12}
$$

Here, the minimum discharge requirement for the fish passage is prioritized. Any remaining inflow is allocated to satisfy the total discharge requirement.

The following formulation applies when minimum discharge requirements are imposed on the fish passage, the spillways, and the total discharge. In this case, the fish passage and the spillways are assigned equal priority and are both prioritized over the total discharge requirement.

$$
\begin{aligned}
Q_{\text{min,passage}} &= \begin{cases} Q_{\text{min,passage}}, & \text{if } Q_{\text{inflow}} \geq Q_{\text{min,passage}} + Q_{\text{min,spill}} \\ 0.5\, Q_{\text{inflow}}, & \text{if } Q_{\text{inflow}} < Q_{\text{min,passage}} + Q_{\text{min,spill}} \end{cases} \\
Q_{\text{min,spill}} &= \begin{cases} Q_{\text{min,spill}}, & \text{if } Q_{\text{inflow}} \geq Q_{\text{min,passage}} + Q_{\text{min,spill}} \\ 0.5\, Q_{\text{inflow}}, & \text{if } Q_{\text{inflow}} < Q_{\text{min,passage}} + Q_{\text{min,spill}} \end{cases} \\
Q_{\text{min,total}} &= \begin{cases} Q_{\text{min,total}}, & \text{if } Q_{\text{inflow}} \geq Q_{\text{min,total}} + Q_{\text{min,passage}} + Q_{\text{min,spill}} \\ Q_{\text{inflow}}, & \text{if } Q_{\text{inflow}} < Q_{\text{min,total}} + Q_{\text{min,passage}} + Q_{\text{min,spill}} \end{cases}
\end{aligned} \tag{5.13}
$$

In this formulation, the minimum discharge requirements for the fish passage and the spillways are prioritized over the total discharge requirement. When the available inflow is insufficient to fully satisfy both path-specific requirements, the inflow is evenly distributed between the fish passage and the spillways. If both path-specific requirements are fully satisfied, any remaining inflow is allocated to meet the total discharge requirement.

Note that this constraint hierarchy was adopted in this study for simplicity and may not always reflect real-world operational practices.

5.2.2 Baseline scenario of current environmental constraints

To enable a meaningful comparison of results and an analysis of the metrics used in this study, a baseline scenario was constructed to represent the Emån river system as realistically as possible. The baseline scenario includes all environmental measures currently in effect within the system. These primarily consist of minimum discharge requirements for spillways and/or fish passages at the stations.

Information on existing minimum discharge requirements was obtained from the baseline description of the system as well as from rulings issued by the Land and Environment Court. A complete overview of all constraints included in the baseline scenario for the Emån river system is provided in Table A.7 in Appendix A.7.

5.2.2.1 Case-specific proxy

In addition to the current environmental constraints included in the baseline scenario, one additional constraint was applied. Downstream of all stations in the modeled Emån system, a paper-production facility is located downstream of Karlshammar at Emsfors, where it extracts water. This industry requires a minimum water flow of 4.5 m^3/s in order to operate, and this requirement imposes an operational constraint on the upstream reservoirs.

In order to represent this constraint in FORSA, a proxy was configured in which a regulation reservoir was included. This reservoir was assigned the same h_{reg} and V_{reg} as a RoR plant, with $h_{\text{reg}} = 0.05$ m and $V_{\text{reg}} = 1$ m^3. By introducing this proxy, a minimum flow constraint of 4.5 m^3/s was enforced at the downstream station Emsfors. In contrast to the conditional constraints described in Section 5.2.1.1, this constraint was modeled as a non-conditional constraint, thereby forcing all upstream stations to operate in a manner that satisfies this flow requirement downstream.

5.2.3 Baseline scenario validation

After modeling the baseline system, a validation and error analysis was carried out to ensure model reliability before continuing with the environmental scenarios and comparative analysis. Two main indicators were used to verify that the modeled system is a fair representation of the real river system: water discharge and hydropower production.

5.2.3.1 Validation of water discharge

Inflow data was evaluated by comparing the modeled water discharge at the most downstream station with observations from SMHI of the MQ in the corresponding sub-catchment area. This provides a system level validation of the hydrological representation. If discrepancies in total discharge are identified, station specific modeled discharge can be compared with corresponding observations of MQ for the same year to identify potential errors in the inflow data. By initiating the comparison at the most downstream station and subsequently moving upstream, the location where discrepancies first arise can be identified, thereby enabling more efficient error identification. However, a full comparison of water discharge per station may be appropriate to ensure consistency and reliability across the entire river system.

When conducting the analysis of the water discharge of Emån, discrepencies of water discharge were identified in the stations furthest downstream of the river system. Table 5.3 provide the analysis of the inflow in the first simulation of the baseline scenario.

Table 5.3: Comparison of MQ and modeled water discharge for the most downstream stations in the Emån river system, including absolute and relative differences identified.

Station	**subID**	***MQ* (SMHI)**	***MQ* (FORSA)**	**Absolute difference (m^3/s)**	**Relative difference (%)**
Högsby	1964+ 2033+ 2034	24.69	23.35	-1.35	-5
Finsjö övre	1919+ 2007	25.28	23.41	-1.86	-7
Finsjö nedre	1919+ 2007	25.28	23.42	-1.86	-7
Skrika kvarn	1929	0.24	0.24	0.00	0
Jungnerholmarna	1916	25.31	48.60	23.30	92
Karlshammar	1901	25.65	48.94	23.29	91
Hammarsjön	2108	0.35	0.35	0.00	0
Emsfors	1886	25.86	49.40	23.54	91

Discrepancies of low magnitude, such as those observed for Högsby, Finsjö nedre, and Finsjö övre, are likely to occur in systems where local contributions are accounted for at individual stations and may therefore be considered negligible. These differences arise because the MQ values provided by SMHI represent averages over entire sub-catchment areas in which the stations are located, whereas the discharge values in FORSA account for the specific location of each station within the sub-catchment. However, larger discrepancies, such as those observed at Jungnerholmarna and the stations downstream, indicate potential errors in the inflow data and were therefore investigated further.

The investigation of inflow data for Jungnerholmarna revealed a clerical error in which upstream subtractions were not accounted for, causing discharge to be double counted and leading to similar discrepancies at all downstream stations. All of these discrepancies were resolved after correcting this error.

5.2.3.2 Validation of hydropower production

Once the inflow data of the system were considered sufficiently reliable, hydropower production was analyzed both for the river system as a whole and on a per station basis. Such an analysis requires reliable information on the annual electricity production of the river system and its individual hydropower stations.

For the Emån river system, total annual production figures were retrived both from the baseline description [72] and from a report by Norconsult and the county administrative board of Jönköping [73]. However, these values differ and are associated with uncertainties regarding which hydropower plants are included. In addition, annual production data per plant were obtained from vattenkraft.info [71] and aggregated to represent the entire river system. The reported production values, the corresponding results in FORSA, and the relative differences between them, are presented in Table 5.4.

Table 5.4: Annual production values from different sources and from FORSA. For normal production, the FORSA value represents the average annual output for 2015–2024 and for year-specific data, it represents the modeled output for the corresponding year.

Source	**Production basis**	**Reported production (GWh)**	**FORSA production (GWh)**	**Production difference (%)**
Norconsult	Normal production	88.0	100.8	14.6
vattenkraft.info	Normal production	110.4	100.8	0.4
Baseline description	2019 production	73.8	89.2	20.8
Norconsult	2020 production	92.0	104.5	13.6

As shown in Table 5.4, the reported production values vary considerably between sources, which complicates validation of the systen modeled in FORSA against these data. Consequently, the available production figures are not suitable for direct and consistent validation of the modeled Emån river system.

Nevertheless, such data may still be useful for identifying large relative deviations at individual hydropower stations, which could indicate potential modeling errors. In these cases, further investigation and validation are warranted, both within FORSA (to identify possible input data or model formulation issues) and with respect to the underlying data sources.

Since FORSA is a perfect-foresight model, some degree of overestimation in production is to be expected. In a system with accurate and complete input data, this overestimation is typically limited. However, when the model is configured using only open source data, as in this study, larger deviations can reasonably be expected due to uncertainties and simplifications in the underlying data.

In this case, several factors may contribute to an overestimation of production. First, the turbine parameters represent the efficiency of the turbine alone rather than the total efficiency of the plant, which leads to higher estimated power output. Furthermore, uncertainties in the estimation of $Q_{\mathrm{t,max}}$ and the k-value may result in overestimation if these parameters are set too high. In addition, the model does not account for periods when stations are temporarily unavailable due to maintenance, inspections, or revisions, which in reality reduce annual production.

5.2.4 Environmental conditions scenarios

Three different environmental conditions scenarios were constructed, which enables an analysis of the metrics chosen in this study to assess hydropower flexibility under different regulatory and environmental assumptions.

The first two scenarios, the VISS and HARO scenario, serve as representations of potential outcomes of the NAP-process. These scenarios are based on the site-specific conditions of each station, together with the measures proposed by the County Administrative Boards to address the ecological status of individual river sections, in accordance with the Water Framework Directive (WFD).

The third scenario, the RoR scenario, represents a case in which the river system follows its natural flow regime, reflecting conditions corresponding to conditions without hydropower regulation.

5.2.4.1 VISS scenario

The first environmental conditions scenario was developed using data from the Swedish Water Information System (VISS). Each water body is identified by a unique ID enabling proposed measures to be linked to individual hydropower stations. Hydropower-relevant measures were translated into model-compatible FORSA constraints. Table 5.5 summarizes the relevant VISS measures for stations in the Emån river system and their corresponding FORSA constraints. The interpretation of these measures and the associated modeling assumptions are described in this section.

Table 5.5: Summary of proposed measures for stations in the Emån river system and their corresponding constraint in FORSA.

Proposed VISS measure	**FORSA constraint**
Enable upstream and downstream passage	Minimum flow requirement for the discharge in the fish passage
Technical fish passage at a hydropower plant	
Minimum flow/flow in fish passage at a hydropower plant	
Fish passage/removal	
Preserve or improve the hydrological regime	Minimum flow requirement for the total discharge
Environmentally adapted flows	Minimum flow requirement for the total discharge equal to the total inflow

Note the measures presented in Table 5.5 do not constitute a comprehensive overview of all proposed measures in VISS. However, any additional measures identified in VISS are subcategories or more detailed variants of those identified for Emån.

Consequently, they do not introduce any new types of constraints in FORSA, but are already accounted for through the constraints presented in Table 5.5.

As mentioned in Section 5.2.1, the minimum flow requirements can be modeled for three flow paths: the fish passage, the spillways, or as a total minimum flow including the fish passage, spillways, and turbine.

All measures related to fish migration were implemented as minimum flow requirements in the fish passage. The proposed measure *Fish passage/removal* could alternatively be represented by complete removal of a hydropower plant. However, as the choice between removal and construction of a fish passage is primarily an economic decision, depending on the costs of the fish passage and associated minimum discharge, plant removal was not considered in this study.

The measure *Preserve or improve the hydrological regime* was implemented as a minimum flow requirement on the total discharge. According to VISS documentation, this measure aims to support fish migration and improve ecological conditions in flowing waters and may require minimum flows through both turbines and spillways.

To simplify the modeling of small-scale hydropower, given that the relevance of minimum flow requirements depends on plant layout, it was assumed that turbine and spillway discharges enter the river at the same downstream location for all stations. Under this assumption, minimum flow requirements for both paths can be represented by a single constraint on the total discharge, allowing the model to allocate flow between turbines and spillways depending on operating conditions. Although minimum spillway flows were not explicitly added as part of the scenario measures, some stations already had such requirements in the baseline scenario and were therefore accounted for in addition to the scenario constraints.

A minimum discharge equal to 10% of the MQ was applied to all minimum flow constraints. Values of MQ were obtained from the SMHI Catchment Hydrology Database. This threshold was selected as it is used in economic evaluations of measures involving minimum discharge requirements within VISS. With this definition, Equation 5.14 becomes:

$$Q_{\text{min,path}} = \begin{cases} 0.1MQ, & \text{if } Q_{\text{inflow}} \geq 0.1MQ \\ Q_{\text{inflow}}, & \text{if } Q_{\text{inflow}} < 0.1MQ \end{cases} \tag{5.14}$$

If a minimum discharge constraint was already included in the baseline scenario for a given station and its value exceeded 10% of MQ, the higher reference value was retained.

In addition to fixed minimum discharge requirements, VISS also proposes measures aimed at restoring more natural flow dynamics. One such measure is *Environmentally adapted flows*, which is described as a measure that enables ecologically sustainable flow regimes that support natural aquatic life and hydrological dynamics [74].

In this study, this measure was interpreted as removing flow regulation in order to approximate a natural flow regime. In FORSA, it was represented by a constraint that sets the minimum total discharge past a station equal to the total inflow, effectively eliminating regulation. This constraint is given by:

$$Q_{\text{min,total}} = Q_{\text{inflow}} \tag{5.15}$$

In FORSA, Q_{inflow} represents the sum of natural inflow at each timestep, rather than regulated releases from upstream reservoirs. Consequently, this constraint is only applicable to stations without upstream regulation. For stations with regulated upstream inflows, the constraint leads to a conflict between natural flow requirements and regulated releases, resulting in an infeasible model solution. For Emån, this measure applied for two stations, out of which one was located downstream several other stations, and therefore had to be omitted.

5.2.4.2 HARO scenario

After running the VISS scenario for the selected time period 2015–2024, the average production loss was calculated to be approximately 13.3% compared to the baseline scenario.

According to the distribution of the HARO value, Emån is considered to be associated with an indicative production loss of 22.1% due to environmental measures implemented through the NAP [2]. Based on this indication, a second scenario was created in which the fraction of MQ used to define all minimum flow constraints was increased until the resulting average production loss was approximately equal to the loss suggested by the HARO value.

This required several iterations using different fractions of MQ. The first two scenarios were constructed by increasing the minimum-flow constraint to 15% and 20%, resulting in average production losses of 19.5% and 25.7%, respectively. A third scenario was then constructed with the fraction set to 17%, resulting in an average production loss of 22.0%, which is the closest to the HARO-indicated value of 22.1%. This fraction was therefore selected for the final HARO scenario.

The annual and average production losses for the iterated HARO scenarios, as well as for the original VISS scenario, are presented in Table A.8 in Appendix A.8.

5.2.4.3 RoR scenario

Finally, an additional scenario was created in which the entire Emån river system was modeled as a run-of-river (RoR) system, meaning that all hydropower plants were assumed to have no regulation capacity.

By applying constraint 5.15, presented in the VISS scenario, all inflowing water is discharged immediately, and no regulation of flows or reservoir storage is possible. The scenario is built on top of the original VISS scenario in order to preserve the same minimum flow requirements in fish passages and spillways.

In FORSA, specifying a minimum water flow as a fraction of the total inflow refers to the natural flow, which is here defined as the sum of all upstream inflows at each time step. To ensure that FORSA can consistently model inflows when this constraint is applied to all stations, not only those located farthest upstream, the requirement is implemented by setting the minimum total discharge to 95% of the total inflow.

$$Q_{\text{min,total}} = 0.95\, Q_{\text{inflow}} \tag{5.16}$$

For this scenario, the paper-industry proxy was removed. This proxy represents an industry regulating all upstream water releases. Since the RoR scenario is intended to represent a non-regulated system, its removal was necessary.

5.3 Flexibility metrics and analysis

This section describes the last step of the modeling framework, which addresses the third research question of this study:

RQ3: What metrics can be derived from the model results, and how can these be used to assess the flexibility of small-scale hydropower?

The metrics described in Section 4.2 are applied to the results obtained from the previous steps of the framework and are used to analyze system flexibility under different environmental conditions scenarios. Figure 5.12 provides a schematic expansion of the last step of the modeling framework shown in Figure 5.1, comprising the selected flexibility metrics and the subsequent analysis of the model results.

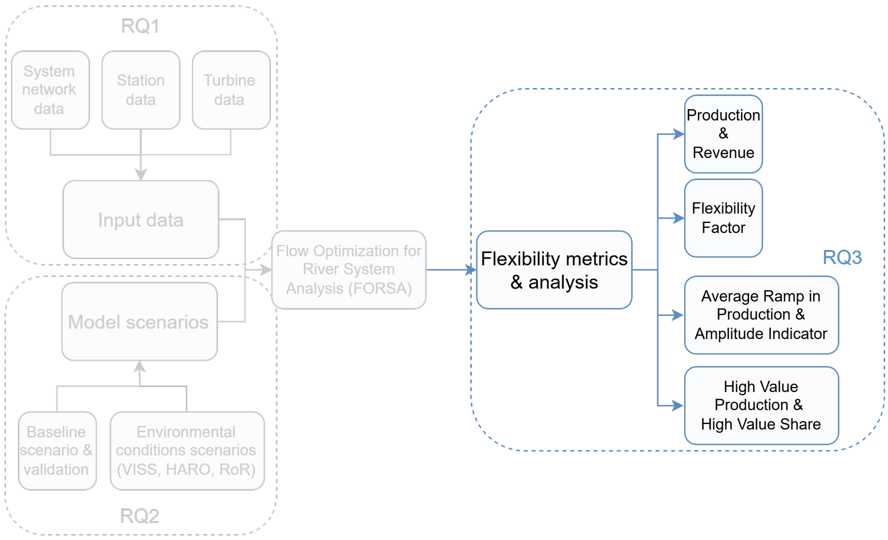


Figure 5.12: Schematic expansion of the last step within the overall modeling framework, showing the flexibility metrics considered in this section.

In FORSA, three categories of output data can be extracted: production and revenue data, flow data, and water level data.

Production and revenue data consist of timestamps and corresponding production values, as well as the total revenue over the modeled period. For stations with multiple turbines, production is provided both per turbine and as a station total. Flow data consist of timestamps and corresponding discharge through each flow path (turbines, fish passages, and spillways), as well as the total discharge. Water level data consist of timestamps and corresponding reservoir volume, along with the upstream and downstream water levels of the station. Only production and revenue data, together with the input electricity price data, were considered in the flexibility analysis and used to calculate the metrics.

All scenarios for the Emån river system were simulated on an annual basis for the time period 2015–2024, and the average values over all years were used for the parameters and metrics applied in the comparison against the baseline scenario. All calculations were performed in Microsoft Excel. The following sections present the calculation and analysis of each metric. This is followed by a comprehensive analysis of all metrics, with a summary for each metric and scenario shown in Figure 5.14. The tabulated values from Figure 5.14, an extended summary of the annual results, and the underlying output data are presented in Appendix A.9.

5.3.1 Production and revenue

Since flexibility is often described as the ability to align production with price signals, see Section 4.2, total production and revenue can provide insights into how environmental measures affect the flexibility of the system.

A larger relative decrease in revenue compared to the relative decrease in production indicates that production is shifted away from high-price hours. Conversely, a smaller relative decrease in revenue than in production suggests that production is maintained during periods of higher electricity prices. Table 5.6 presents the changes in production and revenue for the three scenarios relative to the baseline scenario.

Table 5.6: Changes relative to the baseline scenario for key parameters and flexibility metrics. All values represent averages for the period 2015–2024.

Metric	VISS	HARO	RoR
Production (%)	-13	-22	-17
Revenue (%)	-12	-21	-28

In both the VISS and HARO scenarios, the relative decrease in production is larger than in revenue. The similar results for the two scenarios are not unexpected as the HARO scenario is identical to the VISS scenario except for an increased discharge requirement for all minimum flow constraints.

The observed relationship between production and revenue indicates that production losses are primarily driven by a reduction in the total volume of water available for power generation, rather than by a loss of operational flexibility. The nearly identical reductions in production and revenue further suggest that these losses are distributed relatively evenly across hours.

While the relative reduction in total production in the RoR scenario is comparable to that in the VISS and HARO scenarios, the relative revenue loss is considerably larger. This indicates that, although a comparable amount of water remains available for power generation, the ability to adapt production to electricity price variations is largely lost. The result is consistent with the limited storage and regulation capability inherent to RoR operation.

5.3.2 Flexibility Factor

The Flexibility Factor was calculated using Equation 4.1, and represents the ratio of average achieved price to average electricity price. The former was obtained from the model output as the ratio of total revenue to total electricity production, while the latter was derived from the input electricity price data.

A decrease in the Flexibility Factor indicates that production has been shifted towards hours with lower electricity prices, resulting in a lower average achieved price relative to the average market price, while an increase indicates the opposite. Table 5.7 presents the changes in Flexibility Factor for the three scenarios relative to the baseline scenario.

Table 5.7: Changes in Flexibility Factor relative to the baseline scenario. All values represent averages for the period 2015–2024.

Metric	VISS	HARO	RoR
Flexibility Factor (%)	1	2	-13

The small positive changes in the Flexibility Factor for the VISS and HARO scenarios reflect that the production has decreased slightly more than revenue. In contrast, the substantial decrease in the Flexibility Factor for the RoR scenario reflects the pronounced loss of price-responsive operation, consistent with the significantly larger relative revenue loss compared to the production loss observed for this scenario.

The results for the Flexibility Factor largely mirror the findings based on changes in production and revenue. This is expected, as the factor represents a normalized expression of the relationship between production and revenue, reflecting whether the remaining production can be shifted towards higher-price periods, rather than how much electricity is produced in total.

5.3.3 Average Ramp in Production and Amplitude Indicator

The Average Ramp in Production was calculated using Equation 4.2. First, the absolute difference in production between all consecutive time steps was calculated and stored in a new column. The Average Ramp in Production was then obtained as the mean of this column.

The Amplitude indicator was calculated using Equation 4.3. Firstly, the average production was calculated as a single value. Secondly, the absolute difference between the production and the average production was calculated for each time step and stored in a new column. The Amplitude Indicator was then obtained as the mean of this column.

A decrease in the Average Ramp in Production indicates smaller hour-to-hour changes in production, while an increase indicates larger production changes between consecutive hours. A decrease in the Amplitude Indicator implies smaller deviations in production from average production levels, whereas an increase indicates larger deviations. Table 5.8 presents the changes in the two metrics for the three scenarios relative to the baseline scenario.

Table 5.8: Changes in Average Ramp in Production and Amplitude Indicator relative to the baseline scenario. All values represent averages for the period 2015–2024.

Metric	VISS	HARO	RoR
Average Ramp in Production (%)	-8	-17	-78
Amplitude Indicator (%)	-1	-5	-11

For the VISS and HARO scenarios, the decreases in Average Ramp in Production suggest a smoother production profile. The difference between the scenarios is likely a result of constraints on available water at each time step. As minimum flow requirements in the fish passage increase, the amount of water that can be allocated to power production is reduced, which inherently limits the extent for short-term production changes between consecutive hours. Consequently, a higher minimum flow requirement, as in the HARO scenario (17% of MQ compared to 10% in VISS), leads to less available water for electricity generation at each time step and thus a more pronounced reduction in production variability, as captured by the Average Ramp in Production.

The substantial decrease in the Average Ramp in Production for the RoR scenario reflects the limited ability of RoR plants to actively adjust production, as generation largely follows the natural inflow. This results from the fact that large differences in natural water flow between consecutive hours are unlikely, leading to smaller hour-to-hour changes in production, which is illustrated in Figure 5.13 below.

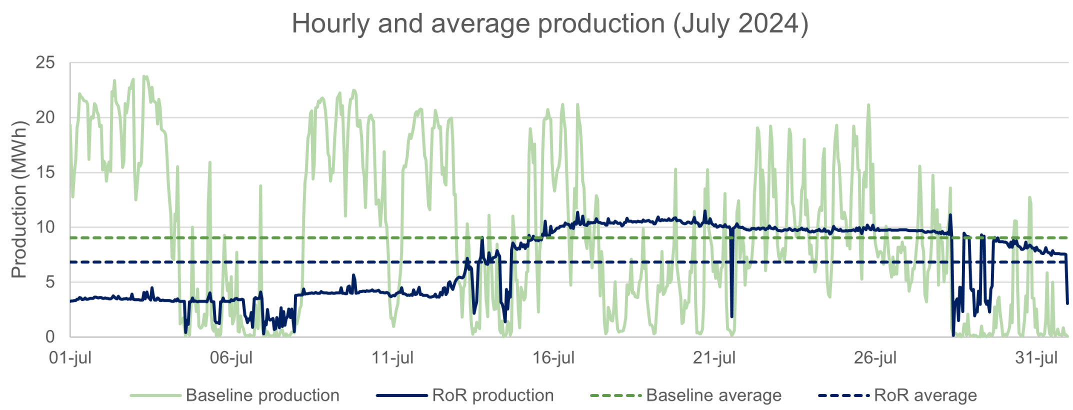


Figure 5.13: Production output for July 2024, showing the baseline profile (blue) and the RoR profile (red), along with their respective average production levels (dotted lines).

Figure 5.13 illustrates how reduced storage flexibility in the RoR scenario leads to a smoother and less variable production profile, due to the limited ability to actively regulate generation.

The change in the Amplitude Indicator is also likely a result of reduced water availability at each time step, which forces production to vary within a narrower range across all three scenarios. The additional decrease observed for the RoR scenario compared to the VISS scenario, which share the same minimum discharge constraints, is once again likely due to the restricted ability to actively adjust production. Since the total annual water volume available for production is the same, a similar average production can be expected, implying comparable conditions for deviations from the mean. However, as the RoR system lacks storage capacity, there are fewer opportunities for the system to actually realize such deviations.

Note that the same available water volume does not imply identical average production levels. Production is constrained by the minimum discharge required for the turbines to generate electricity, and any inflows below this threshold must be spilled in the absence of storage capacity. This explains the difference in average production between the VISS and RoR scenarios, despite the same total available water volume.

5.3.4 High Value Production and High Value Share

The High Value Production was calculated using Equation 4.4. The median electricity price was derived from the input electricity price data. The sum of all production occurring during hours when the electricity price was above the median price was then calculated using Excel's built-in SUMIF function.

The High Value Share was calculated using Equation 4.5. It was obtained as the ratio of High Value Production to total production.

A decrease in High Value Production indicates reduced production during hours when the electricity price is above the median price, while an increase indicates higher production during such hours. A decrease in High Value Share indicates that a smaller share of total production occurs during hours with prices above the median, while an increase indicates the opposite. Table 5.9 presents the changes in High Value Production and High Value Share for the three scenarios compared to the baseline scenario.

Table 5.9: Change in High Value Production and High Value Share relative to the baseline scenario. All values represent averages for the period 2015–2024.

Metric	VISS	HARO	RoR
High Value Production (%)	-13	-24	-36
High Value Share (pp)	0	-1	-15

For the VISS scenario, High Value Production decreases in absolute terms, which is consistent with the overall reduction in total production. However, the the High Value Share is not affected, indicating that the production decrease is distributed evenly across hours when the price is above and below the median price.

For the HARO scenario, both High Value Production and High Value Share decrease; however, the reduction in the latter is small. This indicates that a slightly larger share of the production loss occurs during hours with prices above the median. Consequently, the ability to prioritize generation during higher price periods is reduced, albeit only marginally, compared to both the baseline and the VISS scenario.

For the RoR scenario, both High Value Production and High Value Share decrease substantially, reflecting the inherently limited flexibility of RoR operation, where generation closely follows inflow and opportunities to shift production towards higher-price hours are minimal.

5.3.5 Summary and comparison of flexibility impacts

Based on the calculated metrics, Figure 5.14 summarizes the relative changes in all key parameters and flexibility metrics presented in Tables 5.6–5.9.

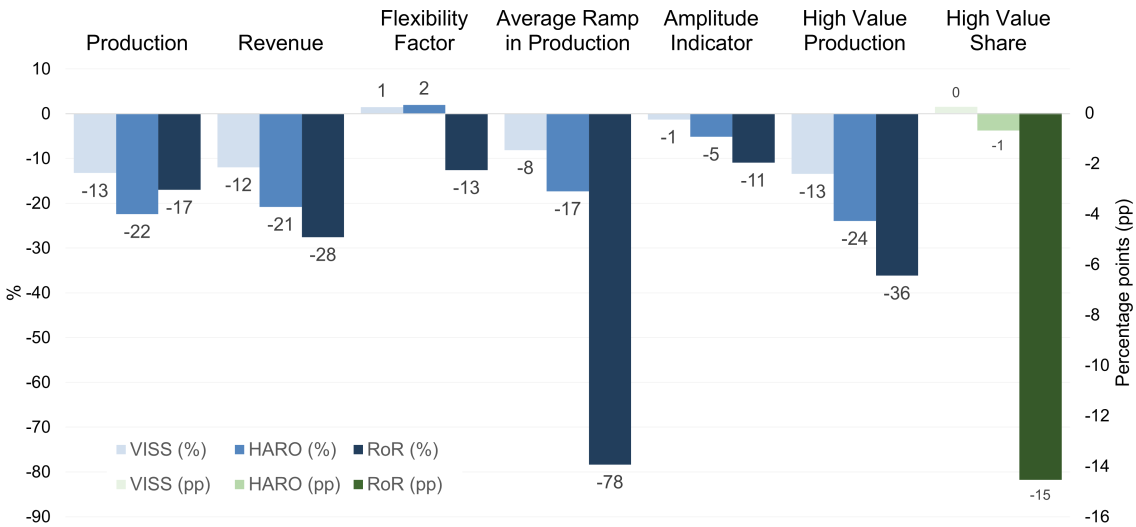


Figure 5.14: Changes relative to the baseline scenario for key parameters and flexibility metrics. All values represent averages for the period 2015–2024 and are expressed in %, except from the High Value Share, expressed in percentage points (pp).

While all scenarios lead to similar reductions in total production, the magnitude of the impacts on the remaining metrics differs between scenarios. The VISS and HARO scenarios exhibit changes of comparable magnitude, whereas the RoR scenario shows consistently larger decreases across most metrics.

This outcome is expected, as the model optimizes production based on electricity price signals, thereby rewarding systems with a greater ability to adjust production in response to these signals. Under RoR operation, where water storage and active regulation are not possible, generation closely follows inflow conditions. This results in inherently limited operational flexibility and a reduced capacity to shift production toward periods of higher electricity prices.

In contrast, the remaining storage and regulation capacity in the VISS and HARO scenarios allows these systems to retain flexibility, as indicated by the Flexibility Factor and the High Value Share, for which the relative changes in both metrics are small. This indicates that even under environmental measures involving minimum flow constraints, operational flexibility is largely preserved as long as storage and regulation capacity remain available.

However, a stable or increased High Value Share should be interpreted with caution. Even if the proportion of production occurring during high-price periods remains similar, the loss of high-value electricity in absolute terms may still be significant to the electricity system, as reflected by the decrease in High Value Production.

6

Summary of Modeling Framework

This chapter synthesizes the modeling framework and provides a structured overview of the results. It also includes a sensitivity analysis of input data and a discussion of the framework and its implications.

6.1 Resulting modeling framework

The initial modeling framework presented in Figure 1.1 at the beginning of this report serves as the foundation for the workflow of the developed modeling framework and, consequently, underpins the results. An extended and final version of this framework, incorporating additional steps introduced throughout the study, is presented in Figure 6.1.

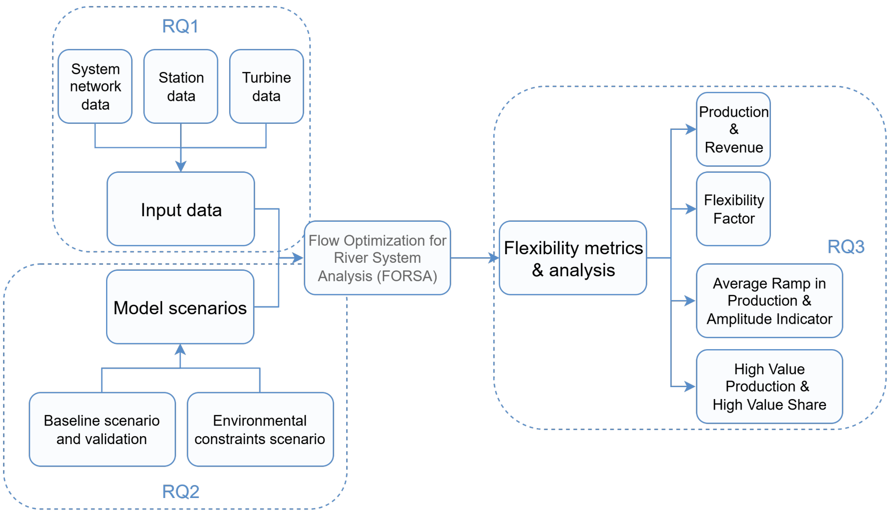


Figure 6.1: The resulting modeling framework, developed from the initial framework shown in Figure 1.1 in the aim of this study.

The framework is summarized according to the steps illustrated in Figure 6.1 and is presented in the following sections.

6.1.1 Input data

Input data - System network data

Station configuration: Define the system by establishing which power plants and reservoirs to include

- Include all power plants producing electricity and distinguish between reservoir power plants and run-of-river power plants.
- Include all reservoirs with a defined regulation volume.
- Map the hydrological connections between all plants.

Inflow data: Establish the inflow data

- Identify the geographical location of each station along the river network.
- Establish incremental inflow contributions from upstream sub-catchments and distinguish between total and local contributions, as well as identify upstream stations to be excluded.
- Estimate the fraction of sub-catchment area upstream of stations, for which local contributions are considered, using map tools.

$$f_{\text{station}} = \frac{A_{\text{sc,upstream}}}{A_{\text{sc,total}}}$$

where
f_{station}: fraction of upstream sub-catchment area
$A_{\text{sc,upstream}}$: area of a sub-catchment upstream a station
$A_{\text{sc,total}}$: total area of a sub-catchment

- Finalize the inflow dataset to consist of a timestamp column followed by one column per station containing the corresponding inflow data.

Flow time: Estimate the flow time between all stations.

- Use map tools to estimate the river distance and average width for all sections between all consecutive stations, where the sections are defined by different sub-catchments.
- Assume a constant river depth of 1 m for all river sections and calculate the average river cross-sectional area for all sections, assuming a triangular-shaped area.

$$S_{\text{r}} = \frac{w_{\text{r}} \cdot d_{\text{r}}}{2}$$

where
S_{r}: cross-sectional area of river
w_{r}: width of river
d_{r}: depth of river

- Use the relationship between mean flow and cross-sectional area to calculate the flow time for all sections, and sum the flow times for all sections between consecutive stations.

$$t_{\text{flow}} = \frac{1}{3600} \sum_{\text{sc}} \frac{L_{\text{r,sc}} \cdot S_{\text{r,sc}}}{MQ_{\text{sc}}} \quad \text{where}$$

t_{flow} flow time
$L_{\text{r,sc}}$: length of river
$S_{\text{r,sc}}$: cross-section area of river
MQ_{sc}: mean water flow
sc: sub-catchment index

Flow paths: Define which flow paths to include at each station

- Model all power plants with flow paths through turbines and spillways, and all reservoirs with flow paths through spillways.

Electricity price region: Define the electricity price region of the system.

- Identify the electricity price region in which the system is located.
- If the system spans multiple price regions, select the region in which the majority of electricity production occurs.

Input data - Station data

Reservoir data: Retrieve or estimate the regulation limits and volume for all stations.

- Retrieve data on the upper and lower regulation limits for all stations, obtained either directly or derived from the regulation amplitude, from open data sources.

$$LRL = URL - h_{\text{reg}} \quad \text{where}$$

LRL: lower regulation limit
URL: upper regulation limit
h_{reg}: regulation amplitude

- Retrieve data on the reservoir regulation volume for all stations from open data sources
- If either the regulation amplitude or the reservoir volume is missing, assume the reservoir to be cuboid. Estimate the surface area using map tools and use the relationship between regulation amplitude, surface area, and regulation volume to derive the missing parameter.

$$V_{\text{reg}} = h_{\text{reg}} \cdot A_{\text{surface}} \quad \text{where}$$

V_{reg}: regulation volume
h_{reg}: regulation amplitude
A_{surface}: reservoir surface area

- If both the regulation amplitude and the regulation volume is missing, calculate an average regulation amplitude based on all available data, calculated separately for power plants and reservoirs, and assign the corresponding average to the station with missing data.

- For all stations representing run-of-river power plants, the regulation amplitude is set to 0.05 m and the reservoir volume to 1 m^3.

Average hydraulic head: Retrieve or estimate the hydraulic head for all power plants

- Retrieve data on maximum available hydraulic head for all power plants from open data sources.
- If data is missing, estimate the head, as the difference between the upstream and downstream reservoir levels using map tools.

$$H_{\max} = W_{\text{upstream}} - W_{\text{downstream}} \quad \text{where}$$

$H_{\max}$: maximum hydraulic head
W_{upstream}: upstream reservoir level
$W_{\text{downstream}}$: downstream reservoir level

- Adjust the head by subtracting half of the regulation amplitude to better represent the hydraulic head.

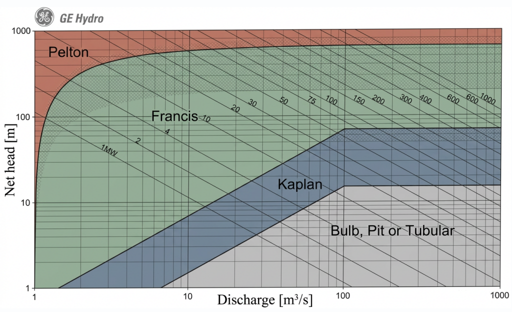
$$H = H_{\max} - \frac{h_{\text{reg}}}{2} \quad \text{where}$$

H: hydraulic head
$H_{\max}$: maximum available hydraulic head
h_{reg}: regulation amplitude

Input data - Turbine data

Turbine configuration: Retrieve or estimate the number and type of turbines for all power plants

- Retrieve data on the turbine type(s) at each plant.
- If the number of turbines is missing, assume a single turbine.
- If the turbine type is missing, estimate it based on the relationship between hydraulic head and mean water flow at the station, using the turbine application chart.



Maximum turbine discharge: Retrieve or estimate the maximum design discharge for each turbine

- Retrieve data on the maximum turbine discharge for each turbine.

- If data is missing, derive a relationship between maximum turbine discharge and mean water flow using stations with available data, and use this relationship to estimate the maximum turbine discharge for the remaining plants based on the mean water flow.

$$k = \frac{Q_{\mathrm{t,max}}}{MQ} \leftrightarrow Q_{\mathrm{t,max}} = k \cdot MQ \quad \text{where}$$

$Q_{\mathrm{t,max}}$: maximum turbine discharge
MQ: mean water flow
k: scaling factor

Generalized turbine parameters: Estimate and calculate the four turbine parameters required by FORSA

- Assign the maximum efficiency of each turbine based on turbine type.
- Estimate the optimal turbine discharge and the zero-efficiency turbine discharge by multiplying the generalized turbine factors by the maximum turbine discharge.

Turbine type	Optimal discharge (%)	Zero-efficiency discharge (%)	Maximum efficiency (%)
Kaplan	82	7.0	93
Francis	95	9.5	94
Pelton	79	5.0	92

- Adjust the turbine parameters by accounting for additional efficiencies, such as generator efficiency.

6.1.2 Model scenarios

Model scenarios - Baseline scenario

Current environmental constraints: Create an environmental constraints scenario representing all constraints currently in place in the river system

- Retrieve data on existing environmental measures, such as minimum flow requirements or operational restrictions.

Potential proxies: If necessary, define river-system-specific proxies

- Define the purpose of the proxy, what it represents, and how it affects other stations and components of the system.
- Implement the proxy in FORSA.

Baseline scenario validation: Validate the constructed system.

- Validate inflow data by comparing the modeled mean water flow at the most downstream station with the reported mean water flow for the corresponding sub-catchment.
- If inconsistencies are identified, perform a station-by-station comparison of modeled and reported mean water flows to locate potential errors.
- If historical production data is available for some or all stations, compare it with modeled production to identify potential inconsistencies.

Model scenarios - Environmental constraints scenario(s)

VISS scenario: Construct an environmental constraints scenario based on proposed measures in the Swedish Water Information System (VISS).

- Identify all hydropower-related proposed measures associated with each station.
- Translate the proposed measures in VISS into model-compatible constraints in FORSA.
- For measures represented by minimum flow requirements in FORSA, calculate 10% of each station's mean water flow and allocate this value to each minimum-flow path. When minimum flows are required through more than one flow path, the requirements must be aggregated as hierarchical sums.
- For measures specified as environmentally adapted flows, model the station's minimum total discharge as 100% of the inflow. Note that this is only applied to stations without upstream regulation.
- Create the scenario in FORSA, modeling constraints as soft constraints where necessary to ensure that the system remains solvable.

HARO scenario: Modify the VISS scenario to align the total average production loss with the production loss specified by the HARO value allocated to the system.

- Calculate the average production loss in the original VISS scenario over multiple years and compare it with the HARO value for the system.
- Without changing the type of constraints, adjust the parameter values of all constraints in the scenario such that the resulting average production loss matches the HARO value.
  - If the average production loss is lower than the HARO value, modify the scenario in a manner that is expected to increase production losses, for example by uniformly increasing minimum flow requirements.

  - If the average production loss is higher than the HARO value, modify the scenario in a manner that is expected to reduce production losses, for example by uniformly decreasing minimum flow requirements.

RoR scenario: Modify the VISS scenario to represent a run-of-river hydropower system with a natural flow regime and no regulation capacity.

- Impose a minimum total discharge at all stations equal to 95% of the total inflow.
- Remove any strict regulation constraints that may conflict with the minimum-discharge requirement associated with the natural flow regime.

6.1.3 Flexibility metrics and analysis

Flexibility metrics

Production and Revenue: Analyze the relative change in production and revenue across scenarios.

Flexibility Factor: Calculate the Flexibility Factor for each scenario and analyze the relative change.

$$\mathrm{FF} = \frac{\pi^*}{\bar{\pi}} = \frac{\hat{I}/\hat{P}}{\bar{\pi}}$$

where
π^*: average achieved price
$\bar{\pi}$: average price
$\hat{I}$: total revenue
$\hat{P}$: total production

Average Ramp in Production and Amplitude Indicator: Calculate the Average Ramp in Production and Amplitude Indicator for each scenario and analyze the relative change.

$$\text{Average Ramp} = \frac{1}{T-1}\sum_{t=2}^{T}|P_{\mathrm{t}} - P_{\mathrm{t}-1}|$$

$$\text{Amplitude Indicator} = \frac{1}{T}\sum_{t=1}^{T}\left|P_{\mathrm{t}} - \bar{P}\right|$$

where
t: time step index
T: total number of time steps
P_{t}: production at time step t
$\bar{P}$: average production

High Value Production and High Value Share: Calculate the High Value Production and High Value Share for each scenario and analyze the relative change.

$$\text{High Value Production} = \sum_{t \in T:\ \pi_t > \tilde{\pi}} P_{\text{t}}$$

$$\text{High Value Share} = \frac{\sum_{t \in T:\ \pi_{\text{t}} > \tilde{\pi}} P_{\text{t}}}{\sum_{t \in T} P_{\text{t}}}$$

where

t: time step index
T: total number of time steps
P_{t}: production at time step t
π_{t}: price at time step t
$\tilde{\pi}$: median price

Flexibility analysis

Analysis of metrics: Compare and analyze the different metrics across scenarios over multiple years.

- **Flexibility Factor:** A decrease indicates that production has been shifted towards hours with lower electricity prices, resulting in a lower average achieved price relative to the average market price, while an increase indicates the opposite.
- **Average Ramp in Production:** A decrease indicates smaller hour-to-hour changes in production, while an increase indicates larger production changes between consecutive hours.
- **Amplitude Indicator:** A decrease indicates smaller deviations from the average production level, while an increase indicates larger deviations between production levels and the average production.
- **High Value Production:** A decrease indicates reduced production during hours when the electricity price is above the median price, while an increase indicates more production during such hours.
- **High Value Share:** A decrease indicates that a smaller share of total production occurs during hours with prices above the median, while an increase indicates the opposite.

6.2 Sensitivity analysis of input data

The modeling framework developed in this study involves several simplifying assumptions and parameter estimations, particularly related to the input data. Consequently, a sensitivity analysis was performed on some of the parameters subject to these simplifications.

For each parameter, the original system, hereafter referred to as the reference system, was modified by altering one parameter at a time and run for the years 2015–2024. The resulting metrics and their relative changes compared to the baseline of the modified system were then calculated. This approach allowed for a comparison of how environmental constraints affected the metrics in the modified system relative to the reference system.

Four sensitivity analyses were carried out. In the first analysis, all t_{flow} were set to 1 h. In the second and third analyses, all turbines were assumed to be of the Francis and Kaplan type, respectively. In the fourth analysis, the k-value used to estimate $Q_{\text{t,max}}$, was set to $k = 1.5$ instead of the original value of $k = 1.2$.

The results of the analyses are presented in the following sections, with each section describing the motivation for the selected parameter and providing a discussion of the corresponding results. The Francis and Kaplan analyses are discussed together, as they involve the same parameter change.

6.2.1 Flow time

As described in Section 5.1.1.3, the estimation of t_{flow} between stations is highly simplified. The approach does not account for the influence of lakes or reservoirs, river slope, or variations in riverbed material, all of which may affect flow velocities and travel times. Furthermore, the estimation relies on manual measurements, which are time-consuming and subject to measurement uncertainty.

To assess the potential impact of this simplification, a sensitivity analysis was conducted in which all t_{flow}-values between stations were uniformly set to 1 h. The resulting changes in the metrics for all scenarios are reported in Table A.16 in Appendix A.10.

Overall, the sensitivity analysis indicates that the influence of the t_{flow} representation on the results is limited. For the majority of metrics and scenarios, the differences between the reference and modified cases are negligible. The only deviations exceeding 2 pp relative to the reference system are observed in the HARO scenario, amounting to 2 pp for both the Amplitude Indicator and High Value Production, and in the RoR scenario, where a deviation of 3 pp is observed for High Value Production only.

These results suggest that the system outcomes are generally robust to variations in the assumed t_{flow}. Nevertheless, the underlying causes of the observed deviations are not fully understood. Further investigation is therefore required to determine whether the t_{flow} estimation can be further simplified without unintentionally affecting specific metrics.

6.2.2 Turbine type

As described in Section 5.1.3.2, the turbine type was used to estimate the turbine parameters, defining the efficiency curves of each turbine. Whenever the turbine type was unknown, the relationship between H and MQ at the station was used to derive the turbine type.

To assess the sensitivity of the system to the assumed turbine type, an analysis was conducted in which all stations in the system were uniformly assigned a Francis turbine configuration. A corresponding analysis was then performed in which all turbines were instead assigned a Kaplan turbine configuration.

The sensitivity analysis indicates that the assumed turbine type has a generally limited influence on the evaluated metrics across all scenarios. For most metrics, the differences between the reference system and the uniformly assigned Francis and Kaplan configurations are small, typically remaining within 1 pp.

Some larger deviations are observed for a limited number of metrics, but all observed changes remain within 3 pp. While these deviations are more dispersed than in the t_{flow} sensitivity analysis, their magnitudes remain modest and do not indicate a strong or systematic sensitivity of the system to the assumed turbine type. Detailed results of the sensitivity analysis are provided in Table A.17 Appendix A.10.

Given the marginal effects on the metrics, it could be argued that a single turbine type may be assigned to all stations where the turbine type is unknown. In the Swedish context, where Francis turbines are more common in small-scale hydropower, assigning Francis turbines in such cases could therefore be considered reasonable. This is also reflected in the Emån river case, where 11 out of 12 previously unknown turbines were identified as Francis turbines based on the relationship between H and MQ.

However, since H is a required input parameter for the modeled system in any case, and the MQ at all stations is needed for other input data estimations, using the relationship between these two variables to derive the most likely turbine type is not time-consuming and could therefore be argued that this step should be retained in the modeling framework.

6.2.3 k-value

As described in Section 5.1.3.3, $Q_{\text{t,max}}$ was estimated based on stations for which this data was available. These values were used to derive the k-value of the framework, defining the relationship between $Q_{\text{t,max}}$ and MQ. For the Emån case, a median value of $k = 1.2$ was obtained. However, as discussed in Section 2.2.1, a commonly used rule of thumb is $k = 1.5$.

Increasing the k-value increases $Q_{\text{t,max}}$ for all turbines with unknown data. The increase is proportional to the change in the k-value, as shown in Equation 6.1.

$$\Delta Q_{\text{t,max}} = \frac{1.5 - 1.2}{1.2} = 25\% \tag{6.1}$$

However, a 25% increase in $Q_{\text{t,max}}$ does not translate directly into predictable changes in the system-level metrics. A sensitivity analysis was therefore performed to assess the impact of the increased discharge capacity.

The results indicate that the influence of the assumed k-value on the evaluated metrics is very limited. Across all scenarios, the differences between the reference and modified cases are generally below 1 pp. Only a single deviation of 2 pp is observed for High Value Production in the RoR scenario. Overall, the effect of varying the k-value can therefore be considered insignificant for the present system. Detailed results of the sensitivity analysis are provided in Table A.18 in Appendix A.10.

However, this conclusion may not hold for all systems, as the impact of the estimation depends both on the number of turbines to which it is applied and on the types of power plants involved.

In the Emån system, the estimation approach was applied to 8 out of 37 power plants, affecting a total of 12 turbines. These plants span a range of sizes, as reflected by their differing MQ values, resulting in varying absolute increases in $Q_{\mathrm{t,max}}$. They also differ in V_{reg} and production amplitudes, which influence their ability to utilize the increased discharge capacity.

Furthermore, it is not possible to definitively determine which of the k-values is more accurate. Within the present framework, the original k-value is therefore considered more appropriate, as it is likely to better reflect site-specific conditions in the Emån system. However, in cases with limited or no data on $Q_{\mathrm{t,max}}$, the rule-of-thumb value $k = 1.5$ may be used as a complementary or alternative assumption.

6.2.4 Non-conducted sensitivity analyses

Several estimations included in the data-retrieval step of the framework were not subjected to sensitivity analysis due to time limitations.

One such example is the decision to separate inflow contributions into total and local components. This step was both time-consuming and subject to uncertainty, arising from measurement errors as well as manual data handling, similar to the uncertainties associated with the t_{flow} estimations. A simplified approach, in which inflows are assigned solely based on the closest upstream measurement point(s) for each station, could therefore be considered as an alternative to reduce processing time and the potential of human error. However, this would introduce a trade-off, as stations located downstream of another station within the same sub-catchment would have to be assigned zero local inflow in order to avoid double-counting of inflow contributions.

In addition to inflow partitioning, the sensitivity analysis of the t_{flow} estimations could also benefit from further testing using alternative assumptions. For instance, different cross-sectional area shapes or alternative flow depths could be evaluated to assess how sensitive the estimated t_{flow} are to these simplifications.

A similar structural assumption is made in the representation of reservoir geometry (see Section 5.1.2.1), where either the V_{reg} or h_{reg} is derived depending on which parameter is missing. The implications of this assumption depend on which parameter is derived. When the V_{reg} is derived, its value becomes directly dependent on the assumed reservoir geometry, whereas deriving the h_{reg} affects the operational range of H. Since the URL is fixed, changes in the h_{reg} determine the LRL and thereby influence the available H and the resulting production output. Consequently, alternative reservoir shapes that increase the V_{reg} are likely to be associated with higher values of flexibility metrics related to production shifting, such as the Flexibility Factor, High Value Production, and High Value Share, while shapes that increase h_{reg} may negatively affect total production.

6.3 Discussion

This section discusses the results and their limitations, and is divided into four parts corresponding to the main steps of the modeling framework, including a discussion regarding the FORSA model itself. In a final part, the usability of the resulting framework and implications of this study are discussed.

6.3.1 Off-the-shelf model

The structure of the modeling framework is to a large extent defined by the selected model, which determines the required input data, the generated outputs, and, consequently, the metrics that can be calculated.

FORSA exhibits several advantages, one of the most important being its original purpose of modeling entire river systems under environmental constraints, which makes it particularly well suited to the aim of this study. Furthermore, despite being a dynamic and non-linear model, its computational requirements remain moderate.

As demonstrated in this report, FORSA can be applied using exclusively open data, enabling the modeling of hydropower systems in the absence of detailed plant-level or historical production data. This is particularly beneficial in the context of the NAP. Although stations are assessed individually in court, both the collaboration process and the allocation of HARO values are conducted at the river-basin level. However, FORSA is not an open or freely available modeling tool, which limits both its use and the applicability of the proposed framework to users with a paid license.

As with any modeling tool, the underlying assumptions of the model impose limitations on the results and conclusions that can be drawn and must be considered when interpreting the findings. In the case of FORSA, the hourly temporal resolution of the model outputs prevents the quantification of certain aspects of hydropower flexibility and market values, such as grid and ancillary services operating at finer time scales. Furthermore, hydropower operation is optimized solely based on revenues from the day-ahead electricity market, implying that conclusions regarding flexibility and operational behavior are valid only within this market context. The use of exogenous electricity price signals means that the system is treated in isolation, and interactions with other generation assets or feedback effects across multiple systems are therefore not captured. Finally, the assumption of perfect foresight, whereby operational decisions are made with full knowledge of future conditions, differs from real-world operation and should be considered when interpreting and validating the results.

6.3.2 Input data

The modeling framework relies exclusively on open data, in order to simplify data retrieval and avoid dependence on proprietary or confidential information. This choice supports the development of a reproducible and transparent method that can be applied to other hydropower systems. However, although much of the input data was simplified, its retrieval and processing were nevertheless time-consuming. This raises the question of whether certain data inputs could be further simplified in order to reduce the time and effort required to construct the system representation.

Furthermore, reliance on highly detailed input data may be questionable depending on the quality of the underlying data. This may be the case for the flow time, which is estimated at an hourly resolution. Given that the inflow data are available only as daily average values, this temporal aggregation further supports the argument that the high spatial and temporal detail applied in the flow time estimation may not be necessary.

Similarly, the decision to divide inflows into total and local contributions was made to achieve a more detailed representation of the system. Considering that the SMHI Catchment and Hydrology database reports uncertainties on the order of 30–35%, it is unclear whether this additional level of disaggregation significantly improves the realism of the system representation. As noted in Section 6.2.4, the local contribution component was nevertheless retained in order to allocate inflow contributions to individual stations. However, since the results were ultimately analyzed at the system level rather than per station, this level of spatial detail may have been unnecessary.

These parameters could therefore potentially be derived using more automated or coarser methods, reducing the level of detail without necessarily compromising the representativeness of the relative scenario comparison.

Overall, a substantial share of the input data was estimated using simplified but supported assumptions in order to ensure reliance on openly available data. While this introduces additional uncertainty, the simplifications are considered acceptable, as the analysis focuses on relative differences between environmental scenarios rather than absolute values. The results are therefore expected to remain representative for comparative purposes, despite uncertainties in the underlying data.

Nevertheless, maintaining parameter values and a level of detail close to real conditions remains important for validation, and as it helps ensure a sufficiently realistic system representation and meaningful changes in the flexibility metrics.

6.3.3 Model scenarios

The VISS scenario was constructed to represent modern environmental conditions, motivated by VISS's systematic approach to identifying environmental measures in Swedish river systems. Although the proposed measures are often generic and require additional site-specific data for detailed implementation, VISS remains the most comprehensive open-access data source covering all Swedish water bodies. Furthermore, it is commonly used by the County Administrative Boards when proposing measures for individual hydropower stations within the NAP process, making it a relevant reference for this study.

A key limitation of the scenario analysis is that the scenarios are dominated by one type of environmental measure, namely minimum discharge requirements. This limits the diversity of model constraints considered and may therefore affect both the assessment of system impacts and the flexibility metrics derived from the model results. Other types of environmental measures could be represented through additional constraints, as discussed in Section 5.2.1, but were not included here since the scenarios were based on measures derived from VISS. While the predominance of minimum discharge requirements is specific to the case river Emån, the overall approach remains applicable to other river systems through the guidance on constraint implementation provided in Section 5.2.1.

A related limitation concerns the parameterization of environmental measures within the proposed framework. For the measure type considered in this study, the required threshold value is explicitly given as a minimum discharge requirement. Other types of environmental measures may, however, require additional parameter values or explicit limits that are not provided directly by the framework. If such measures are included, the user must therefore define appropriate values based on reasonable estimates, available data, and justified assumptions.

Note that the modeling framework is not limited to the proposed scenarios in this study. Other scenarios can be created depending on the knowledge and availability of case-specific data, as well as on the types of comparisons that are of greatest relevance for the system in question. This allows the framework to be adapted to different study objectives, for example by incorporating alternative operational assumptions, regulatory constraints, or combinations among these, depending on the focus and scope of the analysis.

6.3.4 Flexibility metrics and analysis

The flexibility metrics applied in the analysis step of the framework are established indicators from the literature, as described in Section 4.2, and were not newly developed for this study. The only exception is the modification of the Amplitude Indicator, for which the normalization was removed to enable clearer comparisons between scenarios within the same system. During the metric selection process, only metrics compatible with the hourly resolution of the FORSA output data were considered. Consequently, alternative approaches to quantifying hydropower flexibility at finer temporal resolutions may exist but fall outside the scope of the framework.

The selected metrics capture different and complementary aspects of hydropower flexibility. The Average Ramp in Production and the Amplitude Indicator reflect short-term operational flexibility and production variability, while the remaining metrics describe how production responds to electricity price signals. Taken together, the metrics enable flexibility to be analyzed from multiple perspectives.

The Average Ramp in Production and the Amplitude Indicator were included to broaden the analysis beyond the price–production relationship. However, since FORSA optimizes production to maximize revenue, these metrics do not necessarily represent the theoretically optimal values that could be achieved, but rather the values realized by the system under the given optimization objective. Nevertheless, as this optimization framework is applied consistently across all scenarios, the metrics still provide insight into which scenarios were able to reach more favorable values under identical external conditions, such as the same water inflows, electricity prices and system representation. By removing the normalization of the Amplitude Indicator, both metrics are expressed in absolute terms and can therefore be interpreted more intuitively, both on their own and relative to the baseline scenario, provided that the system representation is sufficiently realistic.

Among the production–revenue metrics, the Flexibility Factor and the High Value Share describe a similar characteristic, namely how production is distributed between periods of relatively high and low electricity prices. A key distinction lies in their respective reference prices. The Flexibility Factor relates the average achieved price to the average market price, whereas the High Value Share classifies production based on whether prices are above or below the median. As a result, extreme electricity prices can have a substantial influence on the Flexibility Factor, since both the average market price and the achieved price are sensitive to price magnitude.

In contrast, the High Value Share is unaffected by price magnitude, as the median depends solely on the ordering of prices.

In terms of interpretability, the Flexibility Factor may be considered less intuitive than the High Value Share. As a relatively new and not yet well-established index, it can be difficult to assess what constitutes a "high" or "low" value. The High Value Share, by contrast, is expressed as a percentage between 0 and 100%, which allows for more immediate interpretation. However, when the analysis focuses on relative differences between scenarios, both metrics can be regarded as similarly intuitive, since they are interpreted through changes relative to a common baseline rather than through their absolute values.

An increase in the Flexibility Factor or the High Value Share between scenarios could, when considered in isolation, be interpreted as an increase in flexibility. However, such an interpretation may be misleading, as these changes may coincide with a reduction in total production, including production during high-price periods. In such cases, the apparent increase in flexibility reflects a redistribution of a smaller production volume rather than an enhanced ability to respond to system needs.

For this reason, it is advantageous to assess these metrics in conjunction with High Value Production. Even if price-based flexibility indicators improve, a reduced production volume implies that less energy is available to be shifted or allocated, thereby limiting the total flexibility that the system can provide.

6.3.5 Usability of framework

The focus on small-scale hydropower in Sweden in this study, is derived from the comparatively limited attention given to small-scale hydropower in previous assessments and modeling studies. In addition, all hydropower plants in Sweden, regardless of size, are subject to the NAP, which highlights the need for analytical approaches specifically designed for small-scale hydropower systems, which constitute a large share of the total number of hydropower plants in Sweden. This choice directly limits the applicability of the results to other hydropower contexts. Regulatory frameworks, hydrological conditions, and operational practices differ across countries and between small- and large-scale hydropower systems. Consequently, the results are most relevant for Swedish small-scale hydropower operating under the NAP and may not be directly transferable to larger systems or to regions with different institutional or environmental conditions.

Beyond this limitation in scope and transferability, there are also limitations related to how the framework supports interpretation of the results. Specifically, the framework is better suited for comparing multiple scenarios and their relative changes with respect to a baseline than for interpreting the performance or implications of a single scenario in isolation. Even when relative changes in the metrics are considered, it remains difficult to draw solid conclusions about a system under one scenario alone. The framework is instead more effective for assessing how different scenarios relate to and differ from one another.

This limitation follows from both the chosen metrics and the simplifications made in the input data. Regarding the metrics, they can be argued to be insufficiently intuitive when interpreted on their own and are therefore better suited for evaluating relative changes between scenarios rather than absolute outcomes for a single scenario. An exception is the High Value Production metric. However, this metric relies on the baseline system being a reasonably accurate representation of reality in order to be meaningful in absolute production terms. If the input data do not adequately reflect the current system, the resulting production levels, and consequently the absolute changes in High Value Production, may not be realistic.

Another limitation that further makes the framework better suited for comparing scenarios rather than for interpreting an isolated scenario within a system is that potential future environmental scenarios are modeled using historical inflow and electricity price data. While these data provide a consistent basis for analysis, actual inflows and electricity prices are likely to differ under future climate conditions and electricity market structures. This discrepancy may influence the model outputs and the derived metrics, and consequently the conclusions drawn from the analysis. However, since all scenarios are evaluated using the same underlying assumptions and input data, the framework remains suitable for comparative analysis.

In addition to these assumptions regarding future conditions, the framework is also subject to limitations related to validation and benchmarking. As no directly comparable modeling frameworks currently exist for evaluating small-scale hydropower flexibility in this manner, the proposed framework could not be assessed through comparison with other similar methods. The only plausible comparison would have been against historical outcomes from the NAP processes, for example by comparing modeled production impacts with observed production losses following the implementation of environmental measures, for a specific catchment area. However, such comparisons were not pursued in this study.

Instead, the value of the framework lies primarily in its internal consistency, transparency, and ability to systematically explore relative differences between scenarios under controlled assumptions. These characteristics make the framework particularly suitable for exploratory and comparative analyses, while future work could focus on empirical validation as more data from implemented NAP measures become available.

Finally, this study is based on a case study of the Emån river system, and the discussion and conclusions regarding the flexibility metrics should therefore be interpreted within this specific context. To further validate the modeling framework and assess its applicability beyond this case, it should be applied to additional river systems encompassing a broader range of environmental measures. Such applications would also enable an assessment of the robustness of the framework, as the flexibility metrics may exhibit different responses under alternative hydrological, regulatory, and operational conditions.

7
Conclusions

The conclusions presented in this chapter are directly related to the research questions formulated in Section 1.2.

RQ1: What input data are required to model river systems in FORSA, and how can these data be retrieved or estimated using only open data sources?

This research question is addressed through the first step of the modeling framework. The main data categories identified are system network data, station data, and turbine data. The selection of data sources, as well as methods for estimating data that could not be retrieved directly from open data sources, are described in detail in Section 5.1 and summarized in Section 6.1.1.

RQ2: How can environmental measures under the NAP be translated into model parameters and scenarios?

Environmental measures were obtained from the VISS database, forming the basis for the model parameters and environmental scenarios. The complete approach is presented in Section 5.2 and summarized in Section 6.1.2, thereby addressing RQ2.

RQ3: What metrics can be derived from the model results, and how can these be used to assess the flexibility of small-scale hydropower?

The final research question is addressed in Section 5.3 and summarized in Section 6.1.3, where the flexibility metrics derived from the model results are defined and interpreted. The selected metrics are based on existing literature and capture different aspects of operational flexibility for the investigated hydropower system.

All research questions have been answered within the scope of this study through the developed modeling framework.. As a final conclusion, this framework provides a structured and transparent approach for assessing how environmental measures influence the operational flexibility of small-scale hydropower systems. By combining open data sources with systematic estimation methods and defined flexibility metrics, it enables consistent scenario analysis and supports decision-making within the NAP process. This study is therefore particularly relevant to stakeholders involved in the NAP process, including policymakers, hydropower plant owners, and consultancy firms. Its main contribution lies in its explicit focus on hydropower flexibility, an aspect for which evaluation approaches remain limited within the field.

Bibliography

[1] Kalmarkusten, *Finsjö övre kraftverk*, 2026. [Online]. Available: https://www.kalmarkusten.se/platser/finsjo-ovre-kraftverk/. (Accessed: Jun. 11, 2026).

[2] Havs- och vattenmyndigheten, “Förslag till nationell plan för omprövning av vattenkraft,” Tech. Rep., 2019.

[3] Sveriges Regering, “Regeringens proposition 2017/18:243,” 2018.

[4] Energimyndigheten, *Vattenkraft*, 2024. [Online]. Available: https://www.energimyndigheten.se/forskning-och-innovation/forskning/elsystem/vattenkraft/. (Accessed: Mar. 25, 2026).

[5] Energimyndigheten, Svenska kraftnät, and Havs- och vattenmyndigheten, “Vattenkraftens reglerbidrag och värde för elsystemet,” Tech. Rep., 2016. [Online]. Available: www.energimyndigheten.se.

[6] Havs- och vattenmyndigheten, “Strategi för åtgärder inom vattenkraften,” 2014. [Online]. Available: https://www.havochvatten.se/data-kartor-och-rapporter/rapporter-och-andra-publikationer/publikationer/2014-07-04-strategi-for-atgarder-inom-vattenkraften.html.

[7] European Commission, *Water Framework Directive*. [Online]. Available: https://environment.ec.europa.eu/topics/water/water-framework-directive_en.

[8] S. Mathisen, B. Mo, A. Helseth, J. Bladh, and J. Funkquist, “Measuring the Impact of Environmental Constraints on Hydropower Flexibility,” in *International Conference on the European Energy Market, EEM*, vol. 2022-September, IEEE Computer Society, 2022. DOI: 10.1109/EEM54602.2022.9921047.

[9] L. E. Schäffer, A. Adeva-Bustos, T. H. Bakken, A. Helseth, and M. Korpås, *Modelling of Environmental Constraints for Hydropower Optimization Problems – a Review*. IEEE, 2020. DOI: 10.1109/EEM49802.2020.9221918.

[10] H. Ek Fälth, “What can hydropower deliver in electricity systems? Operational limits, modeling approaches, and system implications of environmental regulation,” Ph.D. dissertation, May 2026. DOI: 10.63959/CHALMERS.DT/5860.

[11] S. Thapa, T. Magee, and E. Zagona, “Factors That Affect Hydropower Flexibility,” *Water (Switzerland)*, 2022. DOI: 10.3390/w14162563.

[12] Y. Wang, T. Levin, J. Kwon, and E. Baker, “The value of hydropower flexibility for electricity system decarbonization,” *Energy Reports*, 2025. DOI: 10.1016/j.egyr.2025.02.019.

[13] H. Ek Fälth, N. Mattsson, L. Reichenberg, and F. Hedenus, "Trade-offs between aggregated and turbine-level representations of hydropower in optimization models," *Renewable and Sustainable Energy Reviews*, 2023. DOI: 10.1016/J.RSER.2023.113406.

[14] H. Ritchie and P. Rosado, "Electricity Mix," *Our World in Data*, Jul. 2020. [Online]. Available: https://ourworldindata.org/electricity-mix. (Accessed: May 7, 2026).

[15] H. Ritchie, M. Roser, and P. Rosado, "Renewable energy," *Our World in Data*, 2020. [Online]. Available: https://ourworldindata.org/renewable-energy. (Accessed: Apr. 13, 2026).

[16] Svenska kraftnät, *Elstatistik*, 2026. [Online]. Available: https://www.svk.se/om-kraftsystemet/kraftsystemdata/elstatistik/. (Accessed: Apr. 15, 2026).

[17] Å. Killingtveit, "Hydropower," *Managing Global Warming: An Interface of Technology and Human Issues*, pp. 265–315, Jan. 2019. DOI: 10.1016/B978-0-12-814104-5.00008-9.

[18] R. Amano and W. W. Peng, "Fundamentals of Turbomachinery : Theory and Applications," 2026. [Online]. Available: https://app.knovel.com/kn/resources/kpFTTA0007/toc.

[19] R. Pichs Madruga et al., "Renewable Energy Sources and Climate Change Mitigation : Special Report of the Intergovernmental Panel on Climate Change," 2012. [Online]. Available: https://www.ipcc.ch/report/renewable-energy-sources-and-climate-change-mitigation/.

[20] SMHI, *Vattenföring*. [Online]. Available: https://www.smhi.se/kunskapsbanken/hydrologi/vattenforing.

[21] Vattenregleringsföretagen, *Vattenhushållning*. [Online]. Available: https://www.vattenreglering.se/. (Accessed: Apr. 15, 2026).

[22] Energiforsk, "Hållbar vattenkraft i framtidens energisystem," 2025. [Online]. Available: https://energiforsk.se/media/34080/2025-1082-hallbar-vattenkraft-i-framtidens-energisystem-slutrapport-fran-haven-projektet.pdf.

[23] J. Bladh and J. Funkquist, "Högvärdesproduktion och högvärdeskvot," 2026. [Online]. Available: https://energiforsk.se/media/x0aj4ywm/2026-1170-hogvardesproduktion-och-hogvardeskvot.pdf.

[24] Tennessee Valley Authority; SVG version by Tomia, *File:Hydroelectric dam.svg*. [Online]. Available: https://commons.wikimedia.org/w/index.php?curid=3302749. (Accessed: Jun. 9, 2026).

[25] IREDA, *Sectors - Hydro Energy*, 2025. [Online]. Available: https://www.ireda.in/hydro-energy. (Accessed: Jun. 9, 2026).

[26] S. Dixon and C. Hall, "Hydraulic Turbines," in *Fluid Mechanics and Thermodynamics of Turbomachinery*, Elsevier, 2014, pp. 361–418. DOI: 10.1016/B978-0-12-415954-9.00009-7.

[27] H. Alvarez, *Energiteknik*. Studentlitteratur, 2006, vol. 1.

[28] S. Öberg, L. Göransson, H. Ek Fälth, U. Rahmlow, and F. Johnsson, "Evaluation of hydropower equivalents in electricity capacity expansion models," [Online]. Available: `https://ssrn.com/abstract=5013603`.

[29] L. Vinogg and I. Elstad, *Mechanical Equipment*. Norwegian University of Science and Technology, 2003.

[30] S. Engström, *Små vattenkraftverk*. 1983, p. 19.

[31] C. Söderberg, *Småskalig vattenkraft : projektering, konstruktion, drift*. 2005.

[32] Kungliga Ingenjörsvetenskapsakademien, "Elektrifieringen - så river vi barriärerna," Tech. Rep., 2025. [Online]. Available: `https://www.iva.se/publicerat/rapport-elektrifieringen--sa--river-vi-barriarerna/`.

[33] Svenska kraftnät, "Att kartlägga de konsekvenser för elsystemet som omprövning av vattenkraften medför m.m," 2023. [Online]. Available: `https://www.svk.se/495ad4/siteassets/2.utveckling-av-kraftsystemet/systemansvar-o-elmarknad/vattenkraftsel/slutrapport-20230926-nap-vattenkraft.pdf`.

[34] Energimyndigheten, "Vattenkraftens reglerförmåga och ny reglerklassindelning," Tech. Rep., 2026, ER 2026:12. [Online]. Available: `https://www.energimyndigheten.se/nyhetsarkiv/2026/ny-reglerklassindelning----for-vattenkraften/`.

[35] M. Huber, D. Dimkova, and T. Hamacher, "Integration of wind and solar power in Europe: Assessment of flexibility requirements," *Energy*, vol. 69, pp. 236–246, 2014. DOI: `10.1016/j.energy.2014.02.109`.

[36] P. D. Lund, J. Lindgren, J. Mikkola, and J. Salpakari, *Review of energy system flexibility measures to enable high levels of variable renewable electricity*, 2015. DOI: `10.1016/j.rser.2015.01.057`.

[37] *Voltage Regulation in Hydroelectric Power Generation*. [Online]. Available: `%7Bhttps://datacalculus.com/en/blog/hydroelectric-power-generation/hydroelectric-control-room-operator/voltage-regulation-in-hydroelectric-power-generation%7D`. (Accessed: May 6, 2026).

[38] P. Kundur, "Definition and Classification of Power System Stability IEEE/CIGRE Joint Task Force on Stability Terms and Definitions," *EEE Transactions on Power Systems*, 2004. DOI: `10.1109/TPWRS.2004.825981`.

[39] H. Ek Fälth, F. Hedenus, L. Reichenberg, and N. Mattsson, "Through energy droughts: Hydropower's ability to sustain a high output," *Renewable and Sustainable Energy Reviews*, 2025. DOI: `10.1016/j.rser.2025.115519`.

[40] B. Malm Renöfält, Å. Widén, R. Jansson, and E. Degerman, "Identifiering av påverkan, åtgärdsbehov och åtgärdspotential i vattendrag påverkade av vattenkraft," 2017. [Online]. Available: `https://energiforsk.se/rapporter/identifiering-av-paverkan-atgardsbehov-och-atgardspotential-i-vattendrag-paverkade-av-vattenkraft-2017-429/`.

[41] Naturskyddsföreningen, *Porlande bäckar och brusande älvar – värdet i strömmande vatten*, 2023. [Online]. Available: https://cdn.naturskyddsforeningen.se/uploads/2023/09/27103831/Porlande-backar-och-brusande-alvar-Naturskyddsforeningen.pdf.

[42] S. Riekkola, A. Hassan, and M. Pettersson, "Disproportionate Costs Under EU Water Law: The Swedish Approach to Hydropower," *Water 2026, Vol. 18*, 2026. DOI: 10.3390/W18070794.

[43] P. Tomczyk, P. Willems, and M. Wiatkowski, "Comparative analysis of changes in hydromorphological conditions upstream and downstream hydropower plants on selected rivers in Poland and Belgium," *Journal of Cleaner Production*, 2021. DOI: 10.1016/J.JCLEPRO.2021.129524.

[44] Havs- och Vattenmyndigheten, *Towards sustainable hydropower in Sweden*, 2019. [Online]. Available: https://www.havochvatten.se/en/eu-and-international/towards-sustainable-hydropower-in-sweden.html. (Accessed: Apr. 20, 2026).

[45] EU, *Europaparlamentets och rådets direktiv 2000/60/EG*, 2000. [Online]. Available: https://eur-lex.europa.eu/resource.html?uri=cellar:5c835afb-2ec6-4577-bdf8-756d3d694eeb.0011.02/DOC_1&format=PDF.

[46] Havs- och vattenmyndigheten, "Havs- och vattenmyndighetens föreskrifterom klassificering och miljökvalitetsnormer avseende ytvatten," Tech. Rep., 2019. [Online]. Available: https://www.havochvatten.se/vagledning-foreskrifter-och-lagar/foreskrifter/register-vattenforvaltning/klassificering-och-miljokvalitetsnormer-avseende-ytvatten-hvmfs-201925.html.

[47] Vattenmyndigheterna, Länsstyrelserna, and Havs- och vattenmyndigheten, *VISS - VattenInformationsSystem för Sverige*, 2024. [Online]. Available: https://viss.lansstyrelsen.se/About.aspx. (Accessed: May 6, 2026).

[48] European Environment Agency, *Freshwater pollution and ecosystems*. [Online]. Available: https://www.eea.europa.eu/en/analysis/publications/zero-pollution/ecosystems/freshwater-pollution-and-ecosystems.

[49] European Commission, "WFD and Hydromorhological Pressures," Tech. Rep., 2006. [Online]. Available: https://circabc.europa.eu/sd/a/68065c2b-1b08-462d-9f07-413ae896ba67/HyMo_Technical_Report.pdf.

[50] Sveriges riksdag, *Vattenförvaltningsförordning (2004:660)*, 2004. [Online]. Available: https://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/vattenforvaltningsforordning-2004660_sfs-2004-660/#K4.

[51] Sveriges riksdag, *Miljöbalk (1998:808)*, 1998. [Online]. Available: %7Bhttps://www.riksdagen.se/sv/dokument-och-lagar/dokument/svensk-forfattningssamling/miljobalk-1998808_sfs-1998-808/%7D.

[52] Regeringen, "Nationell plan för moderna miljövillkor," 2020. [Online]. Available: https://www.havochvatten.se/download/18.1bd43926172bdc4d64881cc0/1708959747462/regeringsbeslut-nationell-plan-moderna-miljovillkor.pdf.

[53] Havs- och vattenmyndigheten, *Vägledning om samverkan inför prövning enligt nationella planen - Vattenkraftverk och dammar*, 2021. [Online]. Available: https://www.havochvatten.se/arbete-i-vatten-och-energiproduktion/vattenkraftverk-och-dammar/vagledning-om-samverkan-infor-provning-enligt-nationella-planen.html#Omsamverkan. (Accessed: Apr. 27, 2026).

[54] Havs- och vattenmyndigheten, *Omprövning enligt NAP i domstolen*, 2020. [Online]. Available: https://www.havochvatten.se/arbete-i-vatten-och-energiproduktion/vattenkraftverk-och-dammar/omprovning-enligt-nap-i-domstolen.html.

[55] T. Brown, J. Hörsch, and D. Schlachtberger, "PyPSA: Python for power system analysis," *Journal of Open Research Software*, vol. 6, no. 1, 2018, ISSN: 20499647. DOI: 10.5334/jors.188.

[56] A. Helseth, B. Mo, A. L. Henden, and G. Warland, "Detailed long-term hydrothermal scheduling for expansion planning in the Nordic power system," *IET Generation, Transmission and Distribution*, 2018, ISSN: 17518687. DOI: 10.1049/iet-gtd.2017.0903.

[57] DHI, *MIKE HYDRO Basin*. [Online]. Available: https://www.dhigroup.com/technologies/mikepoweredbydhi/mike-hydro-basin. (Accessed: Jun. 8, 2026).

[58] E. Gabor, E. Beilicci, and R. Beilicci, "Advanced Hydroinformatic Tools for Modelling of Reservoirs Operation," *IOP Conference Series: Materials Science and Engineering*, 2019. DOI: 10.1088/1757-899X/471/4/042002.

[59] DHI, "MIKE HYDRO Basin User Guide," 2026. [Online]. Available: https://manuals.mikepoweredbydhi.help/latest/Water_Resources/MIKEHydro_Basin_UserGuide.pdf.

[60] USACE Hydrologic Engineering Center, *Introduction to HEC-RAS*, 2026. [Online]. Available: https://www.hec.usace.army.mil/confluence/rasdocs/rasum/6.1/introduction-to-hec-ras. (Accessed: Jun. 8, 2026).

[61] Vattenkraftens Miljöfond, *Beppe*. [Online]. Available: https://vattenkraftensmiljofond.se/verktyg/produktionsbegransningar/modeller-for-berakning-och-vardering-av-produktionsbegransning/beppe/. (Accessed: Jun. 8, 2026).

[62] *Älvbyrån*. [Online]. Available: https://www.alvbyran.se/.

[63] S. Mathisen, T. Aronsen, L. E. Schäffer, M. Majaneva, and K. Lund Bjørnås, "Measuring economic flexibility of hydropower relative to environmental sustainability," *Energy Reports*, vol. 15, 2026. DOI: 10.1016/j.egyr.2025.108977.

[64] Energimyndigheten, *Flexibilitet i energisystemet*, 2025. [Online]. Available: https://www.energimyndigheten.se/energisystem-och-analys/energisystem-och-analys/flexibilitet-i-energisystemet/.

[65] V. Aubin, A. Helseth, and M. Korpås, "Do we have to choose between the ecosystems and the energy transition? Environmental trade-offs with operation of Norwegian hydropower," *Renewable Energy*, 2025. DOI: 10.1016/j.renene.2025.122595.

[66] SMHI, *Vattenwebb: Regleringar*. [Online]. Available: https://vattenwebb.smhi.se/regulations/. (Accessed: May 6, 2026).

[67] SMHI, *Vattenwebb: Damm- och sjöregister*. [Online]. Available: https://vattenwebb.smhi.se/svarwebb/. (Accessed: May 6, 2026).

[68] SMHI, *Vattenwebb : Modelldata per område*. [Online]. Available: https://vattenwebb.smhi.se/modelarea/. (Accessed: Apr. 10, 2026).

[69] Lantmäteriet, *Min Karta*. [Online]. Available: https://minkarta.lantmateriet.se/. (Accessed: Apr. 10, 2026).

[70] Länsstyrelsen Jönköping, *Nulägesbeskrivning inom NAP Emån*. [Online]. Available: https://www.lansstyrelsen.se/jonkoping/miljo-och-vatten/atgarder-och-verksamheter-i-vatten/dammar-och-vattenkraftverk/nationell-plan-for-moderna-miljovillkor-for-vattenkraftverk/nulagesbeskrivning-inom-nap-eman.html.

[71] *Emån - vattenkraft.info - Vattenkraften i Sverige*. [Online]. Available: https://vattenkraft.info/?where=vattendrag&what=Em%C3%A5n&bifl=on. (Accessed: May 13, 2026).

[72] L. Jönköpings and L. Kalmar, "Nulägesbeskrivning för Emåns avrinningsområde Regional NAP-samverkan i prövningsgrupperna 74_1, 74_2, 74_3 och 74_4," [Online]. Available: https://www.lansstyrelsen.se/download/18.2f8110451975d2f3bc14dd66/1750254279073/Allm%C3%A4n%20del%20(3).pdf.

[73] Länsstyrelsen Jönköping and Norconsult, "Mindre vattenkraftverks bidrag till elnätets stabilitet," 2026. [Online]. Available: https://www.lansstyrelsen.se/download/18.55b414119c934f54864f3c7/1772455455712/Mindre%20vattenkraftverks%20bidrag%20till%20eln%C3%A4tets%20stabilitet%20(3704-2024-24.1).pdf.

[74] Vatteninformationssystem Sverige, *Åtgärdskategori Miljöanpassade flöden*, 2015. [Online]. Available: https://viss.lansstyrelsen.se/Measures/EditMeasureType.aspx?measureTypeEUID=VISSMEASURETYPE000827. (Accessed: May 24, 2026).

A
Additional Data and Results

This appendix presents supplementary material supporting the modeling and analysis of the hydropower system. The material consists primarily of underlying input data used in the model setup, together with detailed results from the model output.

A.1 Inflow

Table A.1: Summary of all stations where local inflow contributions were considered in the inflow data. Upstream area refers to the catchment area upstream of the station for which inflow data are included, while total area refers to the total area of the sub-catchment. Fraction refers to the ratio of upstream to total area and represents the share of inflow data allocated to the station.

Station	**subID**	**Upstream area** (km^2)	**Total area (km^2)**	**Fraction (%)**
Gärdeskvarn	2209	15.56	20.34	76
Borrsjön	2344	6.12	10.24	60
Åsle kvarn	2344	1.12	10.24	11
Storesjön	2606	1.26	9.96	13
Flugeby	2444	21.63	36.58	59
Sjunnen	2444	4.09	36.58	1
Spexhultasjön	2858	3.13	11.50	27
Bodanässjön	2771	0.52	5.90	9
Klinte	2617	21.53	60.68	35
Brunnshult	2617	26.38	60.68	43
Axelfors	2617	4.57	60.68	8
Bruksgården	2429	19.28	87.71	22
Ädelfors	2429	10.91	87.71	12
Kvillsfors	2431	8.96	32.15	28
Enegrenen	2657	8.39	44.32	19
Boanäs	2582	0.46	1.10	41
Strömsberg nedre	2270	10.34	12.03	86
Bruzaholm	2974	38.14	39.70	96
Hjälten	2866	14.66	124.46	12
Högebro	2866	95.33	124.46	77
Hulingen	2407	3.23	37.15	9
Ljusholms kvarn	2009	18.64	22.56	83
Högsby	1919	27.19	65.00	42
Finsjö övre	1916	8.16	10.02	81
Finsjö nedre	1916	0.91	10.02	9
Jungnerholmarna	1880	4.74	20.51	23
Karlshammar	1901	17.49	19.10	92

Table A.2: Summary of inflow allocation for hydropower stations in the Emån river system, including SubIDs for total and local contributions, local inflow fractions where applicable, and upstream inflows subtracted.

Station	subID (Total)	subID (Local)	Local fraction	Upstream stations to be subtracted
Rya kvarn	2171	–	–	–
Gärdeskvarn	2196 2149	2209	0.76	Rya kvarn (1 total)
Borrsjön	–	2344	0.60	–
Åsle kvarn	–	2344	0.11	–
Holms kvarn	2231	–	–	–
Prinsfors	2422	–	–	–
Storesjön	2736	2606	0.13	–
Haga	2606	–	–	Storesjön (1 total + 1 local)
Mela kvarn	2406	–	–	Gärdeskvarn (2 total + 1 local) Borrsjön (1 local) Åsle kvarn (1 local) Holms kvarn (1 total) Prinsfors (1 local) Haga (1 total)
Ekenässjön	2537	–	–	–
Flugeby	2514	2444	0.59	–
Sjunnen	–	2444	0.11	–
Holsby kvarn	2444	–	–	Mela kvarn (1 total) Ekenässjön (1 total) Flugeby (1 total + 1 local) Sjunnen (1 local)
Spexhultasjön	2836	858	0.27	–
Bodanässjön	2806	2771	0.09	Spexhultasjön (1 total + 1 local)
Södra Vixen	2845	–	–	–
Norra Vixen	2914	–	–	Södra Vixen (1 total)
Värnedammen	2752	–	–	Bodanässjön (1 total + 1 local) Norra Vixen (1 total)
Klinte	–	2617	0.35	–
Brunshult	–	2617	0.43	–
Axelfors	–	2617	0.08	–
Aspö	2509	–	–	Värnedammen (1 total) Klinte (1 local) Brunshult (1 local) Axelfors (1 local)
Bruksgården	2414	2429	0.22	–

Station	subID (Total)	subID (Local)	Local fraction	Upstream stations to be subtracted
Ädelfors	–	2429	0.12	–
Turefors	2429	–	–	Holsby kvarn (1 total) Aspö (1 total) Bruksgården (1 total + 1 local) Ädelfors (1 local)
Kvillsfors	2443	2431	0.28	–
Stora Bellen	2751	–	–	–
Enegrenen	–	2657	0.19	–
Boanäs	2604	2582	0.41	Stora Bellen (1 total) Enegrenen (1 local)
Snickeradammen	2582	–	–	Boanäs (1 total + 1 local)
Pauliströms bruk	–	–	–	–
Järnforsen	2393	–	–	Turefors (1 total) Kvillsfors (1 total + 1 local) Snickeradammen (1 total)
Flen	2642	–	–	–
Kvarnstugan	2462	–	–	Flen (1 total)
Strömsberg nedre	2184 2278	2270	0.86	–
Saljen	2276	–	–	Strömsberg (2 total + 1 local)
Tobro	2289	–	–	Saljen (total)
Säljen	2019	–	–	–
Höghultström	2073	–	–	Säljen (1 total)
Björneström	2167	–	–	Höghultström (1 total)
Mörtefors	–	–	–	–
Hjorteström	2226	–	–	Björneström (1 total)
Viserumssjön	2232	–	–	Hjorteström (1 total)
Eksebo	2186	–	–	–
Gårdveda	2311	–	–	Tobro (1 total) Viserumssjön (1 total) Eksebo (1 total)
Bruzaholm	2865	2974	0.96	–
Hjälten	2974 2992	2866	0.12	Bruzaholm (1 total + 1 local)
Högebro	2966	2866	0.77	–
Hällefors	2780 2674	–	–	Hjälten (2 total + 1 local) Högebro (1 total + 1 local)
Hulingen	2564	2407	0.09	Hällefors (2 total)
Rosenfors	2407	–	–	Hulingen (1 total + 1 local)

Station	subID (Total)	subID (Local)	Local fraction	Upstream stations to be subtracted
Maren	2182	–	–	–
Elmteström	1878	–	–	–
Sadenhult	1995	–	–	Elmteström (1 total)
Ljussholms kvarn	1971 2048 1931	2009	0.83	Sadenhult (1 total)
Blankaström	2084	–	–	Järnforsen (1 total) Kvarnstugan (1 total) Gårdveda (1 total) Rosenfors (1 total) Maren (1 total)
Högsby	2033 1964 2034	1919	0.42	Blankaström (1 total) Ljussholms kvarn (3 total + 1 local)
Finsjö övre	2007 1919	1916	0.81	Högsby (2 total + 1 local)
Finsjö nedre	–	1916	0.09	–
Jungnerholmarna	1916	1880	0.23	Finsjö övre (2 total + 1 local) Finsjö nedre (1 local)
Skrika kvarn	1929	–	–	–
Karlshammar	1880 1913	1901	0.92	Jungnerholmarna (1 total + 1 local) Skrika kvarn (1 total)
Hammarsjön	2108	–	–	–
Emsfors	1886	–	–	Karlshammar (2 total + 1 local) Skrika kvarn (1total) Hammarsjön (1 total)

A.2 Flow time

Table A.3: Summary of data used to estimate water flow times between stations. SubIDs denote the sub-catchments between stations, with associated river length L_{sc}, width w_{sc}, cross-sectional area S_{sc}, mean flow MQ_{sc}, and resulting flow time $t_{\text{flow},sc}$.

From ↓ To	subID	L_{sc} (m)	w_{sc} (m)	S_{sc} (m^2)	MQ_{sc} (m^3/s)	$t_{flow,sc}$ (h)
Aspö ↓ Bruksgården	2429	3658	23	11.5	12.52	0.93

From ↓ To	**subID**	L_{sc} **(m)**	w_{sc} **(m)**	S_{sc} **(m²)**	MQ_{sc} **(m³/s)**	$t_{flow,sc}$ **(h)**
Axelfors ↓ Aspö	2617	4324	18	9.0	5.60	1.93
	2509	852	14	7.0	5.61	0.30
	2429	2788	69	34.5	12.52	2.13
	2617	4324	18	9.0	5.60	1.93
	2509	852	14	7.0	5.61	0.30
	2429	2788	69	34.5	12.52	2.13
Björneström övre ↓ Mörtefors	2167	850	2	1.0	1.27	0.19
Blankaströms ↓ Högsby	1919	9900	35	17.5	28.50	1.69
Boanäs ↓ Snickaredammen	2582	875	8	4.0	1.30	0.75
Bodanäsasjön ↓ Värnedammen	2771	5100	1	0.5	0.35	2.02
	2692	6000	1	0.5	1.02	0.81
	2685	7200	1	0.5	1.47	0.68
	2757	2653	5	2.5	1.46	1.26
	2713	22847	1	0.5	2.13	1.49
	2816	1396	5	2.5	2.14	0.45
	2827	1437	11	5.5	2.38	0.92
	2841	5500	26	13.0	4.14	4.79
	2752	7500	10	5.0	5.00	2.08
	2617	1116	21	10.5	5.60	0.58
Borrsjön ↓ Åsle kvarn	2344	615	1	0.5	0.10	0.88
Bruksgården ↓ Ädelfors	2429	2552	40	20.0	12.52	1.13
Brunnshult ↓ Axelfors	2617	2228	23	11.5	5.60	1.27
Bruzaholm ↓ Hjälten	2866	5600	1	0.5	1.72	0.45

From ↓ To	subID	L_{sc} (m)	w_{sc} (m)	S_{sc} (m^2)	MQ_{sc} (m^3/s)	$t_{flow,sc}$ (h)
Ekenässjön ↓ Flugeby	2537	10800	1	0.5	0.22	6.86
	2437	350	1	0.5	0.26	0.18
	2444	4722	20	10.0	6.21	2.11
	2537	10800	1	0.5	0.22	6.86
	2437	350	1	0.5	0.26	0.18
	2444	4722	20	10.0	6.21	2.11
Eksebo ↓ Gårdveda	2193	5200	1	0.5	0.29	2.50
	2252	3120	9	4.5	2.24	1.74
	2291	6500	12	6.0	4.11	2.63
	2315	3868	12	6.0	4.19	1.54
	2321	2470	15	7.5	4.22	1.22
	2362	2410	15	7.5	4.23	1.19
	2311	1410	40	20.0	4.27	1.83
	2193	5200	1	0.5	0.29	2.50
	2252	3120	9	4.5	2.24	1.74
	2291	6500	12	6.0	4.11	2.63
	2315	3868	12	6.0	4.19	1.54
	2321	2470	15	7.5	4.22	1.22
	2362	2410	15	7.5	4.23	1.19
	2311	1410	40	20.0	4.27	1.83
Elmteströms Kvarn ↓ Sadenhult	1933	4510	1	0.5	0.32	1.93
	1995	1150	1	0.5	0.73	0.22
	1971	673	1	0.5	0.82	0.11
Emsfors ↓ SEA	1838	4630	50	25.0	29.26	1.10
Enegrenen ↓ Boanäs	2657	10700	8	4.0	1.24	9.62
	2604	1150	8	4.0	1.29	0.99
	2582	605	10	5.0	1.30	0.65
	2657	10700	8	4.0	1.24	9.62
	2604	1150	8	4.0	1.29	0.99
	2582	605	10	5.0	1.30	0.65
Finsjö nedre ↓ Jungnerholmarna	1916	1905	35	17.5	28.76	0.32
	1880	688	40	20.0	28.87	0.13
Finsjö övre ↓ Finsjö nedre	1916	865	25	12.5	28.76	0.10

From ↓ To	subID	L_{sc} (m)	w_{sc} (m)	S_{sc} (m^2)	MQ_{sc} (m^3/s)	$t_{flow,sc}$ (h)
Flen ↓ Kvarnstugan	2551	7000	6,5	3.25	0.60	10.52
	2488	570	6,5	3.25	0.60	0.86
	2531	420	7	3.5	0.67	0.61
	2462	2620	7	3.5	0.69	3.69
Flugeby ↓ Sjunnen	2444	1761	37	18.5	6.21	1.46
Gårdveda ↓ Blankaströms	2351	4477	15	7.5	4.31	2.16
	2317	7600	13	6.5	4.38	3.13
	2286	16900	30	15.0	25.25	2.79
	2161	7400	30	15.0	25.67	1.20
	2084	5600	5	2.5	26.38	0.15
Gärdeskvarn ↓ Mela kvarn	2209	5800	9	4.5	1.03	7.03
	2296	7000	11	5.5	1.72	6.23
	2394	4579	9	4.5	2.20	2.60
	2403	1378	10	5.0	2.22	0.86
	2459	4739	11	5.5	4.16	1.74
	2554	1596	12	6.0	4.28	0.62
	2525	1836	14	7.0	4.44	0.80
	2525	2810	17	17.0	4.44	2.99
	2464	2050	10	15.0	4.54	1.88
	2455	555	16	32.0	4.55	1.09
	2453	1820	12	30.0	4.58	3.31
	2458	935	22	66.0	4.60	3.73
	2380	3775	18	63.0	5.72	11.54
	2406	1280	30	120.0	5.63	7.58
Haga ↓ Mela kvarn	2606	1363	1	0.5	0.46	0.42
	2545	3950	8	4.0	1.06	4.14
	2461	16700	10	5.0	1.67	13.89
	2459	4739	11	5.5	4.16	1.74
	2554	1596	12	6.0	4.28	0.62
	2525	1836	14	7.0	4.44	0.80
	2525	2810	17	17.0	4.44	2.99
	2464	2050	10	15	4.54	1.88
	2455	555	16	32	4.55	1.09

From ↓ To	subID	L_{sc} (m)	w_{sc} (m)	S_{sc} (m^2)	MQ_{sc} (m^3/s)	$t_{flow,sc}$ (h)
	2453	1820	12	30	4.58	3.31
	2458	935	22	66.0	4.60	3.73
	2380	3775	18	63.0	5.72	11.54
	2406	1280	30	120.0	5.63	7.58
Hammarsjön ↓ Emsfors	2113	1290	1	0.5	0.55	0.33
	2080	5700	1	0.5	0.59	1.35
	2052	1400	1	0.5	0.65	0.30
	1984	10100	3	1.5	0.71	5.91
	1932	2070	1	0.5	0.72	0.40
	1886	2300	60	30	29.16	0.66
Hjorteström ↓ Viserumssjön	2223	220	1	0.5	1.87	0.02
	2232	2060	4	2.0	1.91	0.60
	2234	875	9	4.5	1.91	0.57
Hjälten ↓ Högebro	2866	15000	10	5.0	1.72	12.09
Holms kvarn ↓ Mela kvarn	2309	14100	1	0.5	0.91	2.15
	2380	2930	8	4.0	5.72	0.57
	2406	1280	30	15.0	5.63	0.95
Holsby kvarn ↓ Aspö	2444	224	24	12.0	6.21	0.12
	2429	2788	69	34.5	12.52	2.13
Hulingen ↓ Rosenfors	2407	9400	13	6.5	4.63	3.67
Hällefors ↓ Hulingen	2675	12056	12	6.0	3.89	5.16
	2629	3744	15	7.5	3.94	1.98
	2564	5500	15	7.5	4.33	2.65
	2407	3600	13	6.5	4.63	1.40
Högebro ↓ Hällefors	2866	5200	10	5.0	1.72	4.19
	2790	5200	12	6.0	1.96	4.41
	2780	12200	15	7.5	3.08	8.25
Höghultsström ↓ Björneström	2167	9932	4	2.0	1.27	4.35
Högsby ↓ Finsjö övre	1919	16500	30	15.0	28.50	2.41
	1916	7000	35	17.5	28.76	1.18

From ↓ To	**subID**	L_{sc} **(m)**	w_{sc} **(m)**	S_{sc} **(m²)**	MQ_{sc} **(m³/s)**	$t_{flow,sc}$ **(h)**
Jungnerholmarna ↓ Karlshammar	1880	13385	40	20.0	28.87	2.58
	1901	4860	50	25.0	29.40	1.15
Järnforsen ↓ Blankaströms	2423	25800	22	11.0	16.09	4.90
	2355	2040	18	9.0	16.10	0.32
	2330	1130	25	12.5	20.73	0.19
	2286	16900	30	15.0	25.25	2.79
	2161	7400	30	15.0	25.67	1.20
	2084	220	1	0.5	26.38	0.00
Karlshammar ↓ Emsfors	1901	1885	38	19.0	29.40	0.34
	1886	1907	28	14.0	29.16	0.25
Klinte ↓ Brunnshult	2617	3400	8	4.0	5.60	0.67
Kvarnstugan ↓ Blankaströms	2436	605	8	4.0	0.69	0.97
	2423	25800	22	11.0	16.09	4.90
	2355	2040	18	9.0	16.10	0.32
	2330	1130	25	12.5	20.73	0.19
	2286	16900	30	15.0	25.25	2.79
	2161	7400	30	15.0	25.67	1.20
	2084	4477	15	7.5	26.38	0.35
Kvillsfors ↓ Järnforsen	2431	7300	22	11.0	13.21	1.69
	2393	1220	25	12.5	14.79	0.29
Ljusholms kvarn ↓ Blankaström	2009	2515	8	4.0	1.27	2.19
	2033	1313	7	3.5	1.28	0.99
Maren ↓ Blankaströms	2134	5200	26	13.0	0.41	46.05
	2084	5600	5	2.5	26.38	0.15
Mela kvarn ↓ Flugeby	2406	351	28	14.0	5.63	0.24
	2444	5600	21	10.5	6.21	2.63
Mörtefors ↓ Hjorteström	2226	3620	10	5.0	1.87	2.69

From ↓ **To**	**subID**	L_{sc} **(m)**	w_{sc} **(m)**	S_{sc} **(m²)**	MQ_{sc} **(m³/s)**	$t_{flow,sc}$ **(h)**
Norra Vixen	2989	10315	1	0.5	0.40	3.62
↓	2871	3460	1	0.5	0.50	0.96
Värnedammen	2850	2914	1	0.5	0.53	0.77
	2841	5500	26	13.0	4.14	4.79
	2752	7500	10	5.0	5.00	2.08
	2617	1116	21	10.5	5.60	0.58
Pauliströms bruk	2519	11300	7	3.5	1.53	7.17
↓	2393	1250	20	10.0	14.79	0.23
Järnforsen						
Prinsfors	2512	1022	1	0.5	0.22	0.65
↓	2461	13773	10	5.0	1.67	11.46
Mela kvarn	2459	4739	11	5.5	4.16	1.74
	2554	1596	12	6.0	4.28	0.62
	2525	1836	14	7.0	4.44	0.80
	2525	2810	17	17.0	4.44	2.99
	2464	2050	10	15.0	4.54	1.88
	2455	555	16	32.0	4.55	1.09
	2453	1820	12	30.0	4.58	3.31
	2458	935	22	66.0	4.60	3.73
	2380	3775	18	63.0	5.72	11.54
	2406	1280	30	120	5.63	7.58
Rosenfors	2407	1490	15	7.5	4.63	0.67
↓	2330	1130	25	12.5	20.73	0.19
Blankaströms	2286	16900	30	15.0	25.25	2.79
	2161	7400	30	15.0	25.67	1.20
	2084	3868	12	6.0	26.38	0.24
Rya kvarn	2171	776	1	0.5	0.36	0.30
↓	2109	4770	8	4.0	0.51	10.29
Gärdeskvarn	2196	2800	8	4.0	0.64	4.88
	2209	5400	7	3.5	1.03	5.09
Sadenhult	1971	6900	8	4.0	0.82	9.36
↓	2009	5500	1	0.5	1.27	0.60
Ljusholms kvarn						
Saljen	2292	1260	1	0.5	1.49	0.12
↓	2319	2145	10	5.0	1.52	1.96
Gårdveda	2289	3770	5	2.5	1.57	1.66

From ↓ To	subID	L_{sc} (m)	w_{sc} (m)	S_{sc} (m^2)	MQ_{sc} (m^3/s)	$t_{flow,sc}$ (h)
	2356	2400	15	7.5	1.68	2.97
	2329	4955	8	4.0	1.78	3.09
	2291	6500	12	6.0	4.11	2.63
	2315	3868	12	6.0	4.19	1.54
	2321	2470	15	7.5	4.22	1.22
	2362	2410	15	7.5	4.23	1.19
	2311	1410	40	20.0	4.27	1.83
Sjunnen ↓ Holsby kvarn	2444	3368	24	12.0	6.21	1.81
Skrika kvarn ↓ Karlshammar	1901	4770	50	25.0	29.40	1.13
Snickaredammen ↓ Pauliströms bruk	2582	210	8	4.0	1.30	0.18
Spexhultasjön ↓ Bodanässjön	2836	6	1	0.5	0.10	0.01
	2858	6700	1	0.5	0.24	3.92
	2806	1633	1	0.5	0.29	0.79
	2771	377	1	0.5	0.35	0.15
Stora Bellen ↓ Enegrenen	2657	1700	1	0.5	1.24	0.19
Storesjön ↓ Haga	2606	6500	1	0.5	0.46	1.98
Strömsbergs nedre ↓ Saljen	2276	8100	1	0.5	1.49	0.76
	2270	1615	1	0.5	0.97	0.23
Säljen ↓ Höghultsström	2093	1270	1	0.5	0.53	0.33
	2098	1885	1	0.5	0.54	0.48
	2144	550	1	0.5	0.62	0.12
	2043	7900	5	2.5	0.94	5.81
	2073	1065	20	10.0	0.97	3.06
	2167	620	40	20.0	1.27	2.72
Södra Vixen ↓ Norra Vixen	2914	300	1	0.5	0.15	0.27

From ↓ To	subID	L_{sc} (m)	w_{sc} (m)	S_{sc} (m^2)	MQ_{sc} (m^3/s)	$t_{flow,sc}$ (h)
Turefors ↓ Kvillsfors	2429	300	19	9.5	12.52	0.06
	2431	1123	35	17.5	13.21	0.41
Viserumssjön ↓ Gårdveda	2234	80	9	4.5	1.91	0.05
	2252	3120	9	4.5	2.24	1.74
	2291	6500	12	6.0	4.11	2.63
	2315	3868	12	6.0	4.19	1.54
	2321	2470	15	7.5	4.22	1.22
	2362	2410	15	7.5	4.23	1.19
	2311	1410	40	20.0	4.27	1.83
Värnedammen ↓ Klinte	2617	7300	14	7.0	5.60	2.53
Åslekvarn ↓ Mela kvarn	2344	1520	1	0.5	0.10	2.16
	2320	5800	1	0.5	0.39	2.07
	2296	7000	11	5.5	1.72	6.23
	2394	4579	9	4.5	2.20	2.60
	2403	1378	10	5.0	2.22	0.86
	2459	4739	11	5.5	4.16	1.74
	2554	1596	12	6.0	4.28	0.62
	2525	1836	14	7.0	4.44	0.80
	2525	2810	17	8.5	4.44	1.49
	2464	2050	10	5.0	4.54	0.63
	2455	555	16	8.0	4.55	0.27
	2453	1820	12	6.0	4.58	0.66
	2458	935	22	11.0	4.60	0.62
	2380	3775	18	9.0	5.72	1.65
	2406	1280	30	15.0	5.63	0.95
Ädelfors ↓ Turefors	2429	14000	20	10.0	12.52	3.11

Table A.4: Total flow time between stations.

From	→ To	Flow time (h)
Aspö	Bruksgården	1
Axelfors	Aspö	9
Björneström övre	Mörtefors	0
Blankaströms	Högsby	2
Boanäs	Snickaredammen	1
Bodanäsasjön	Värnedammen	15
Borrsjön	Åsle kvarn	1
Bruksgården	Ädelfors	1
Brunnshult	Axelfors	1
Bruzaholm	Hjälten	0
Ekenässjön	Flugeby	18
Eksebo	Gårdveda	25
Elmteströms kvarn	Sadenhult	2
Emsfors	SEA	1
Enegrenen	Boanäs	23
Finsjö nedre	Jungnerholmarna	0
Finsjö övre	Finsjö nedre	0
Flen	Kvarnstugan	16
Flugeby	Sjunnen	1
Gårdveda	Blankaströms	9
Gärdeskvarn	Mela kvarn	52
Haga	Mela kvarn	54
Hammarsjön	Emsfors	9
Hjorteström	Viserumssjön	1
Hjälten	Högebro	12
Holms kvarn	Mela kvarn	4
Holsby kvarn	Aspö	2
Hulingen	Rosenfors	4
Hällefors	Hulingen	11
Högebro	Hällefors	17
Höghultsström	Björneström	4
Högsby	Finsjö övre	4
Jungnerholmarna	Karlshammar	4
Järnforsen	Blankaströms	9
Karlshammar	Emsfors	1
Klinte	Brunnshult	1
Kvarnstugan	Blankaströms	11

From	→ **To**	**Flow time (h)**
Kvillsfors	Järnforsen	2
Ljusholms kvarn	Blankaström	3
Maren	Blankaströms	46
Mela kvarn	Flugeby	3
Mörtefors	Hjorteström	3
Norra Vixen	Värnedammen	13
Pauliströms bruk	Järnforsen	7
Prinsfors	Mela kvarn	47
Rosenfors	Blankaströms	5
Rya kvarn	Gärdeskvarn	21
Sadenhult	Ljusholms kvarn	10
Saljen	Gårdveda	18
Sjunnen	Holsby kvarn	2
Skrika kvarn	Karlshammar	1
Snickaredammen	Pauliströms bruk	0
Spexhultasjön	Bodanässjön	5
Stora Bellen	Enegrenen	0
Storesjön	Haga	2
Strömsbergs nedre	Saljen	1
Säljen	Höghultsström	13
Södra Vixen	Norra Vixen	0
Turefors	Kvillsfors	0
Viserumssjön	Gårdveda	10
Värnedammen	Klinte	3
Åslekvarn	Mela kvarn	23
Ädelfors	Turefors	3

A.3 Reservoir data

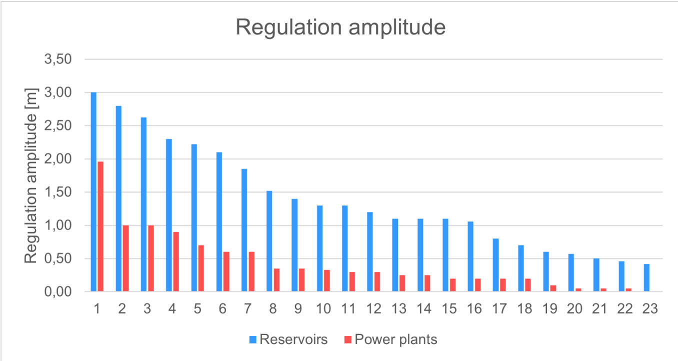


Figure A.1: Regulation amplitude for stations with available data, ordered by magnitude and grouped into regulation reservoirs and reservoir power plants.

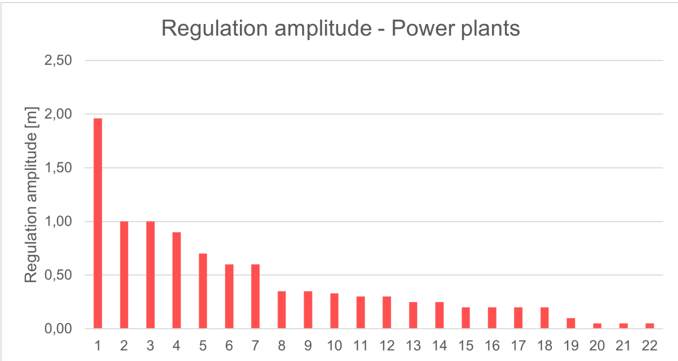


Figure A.2: Regulation amplitude for reservoir power plants with available data, ordered by magnitude.

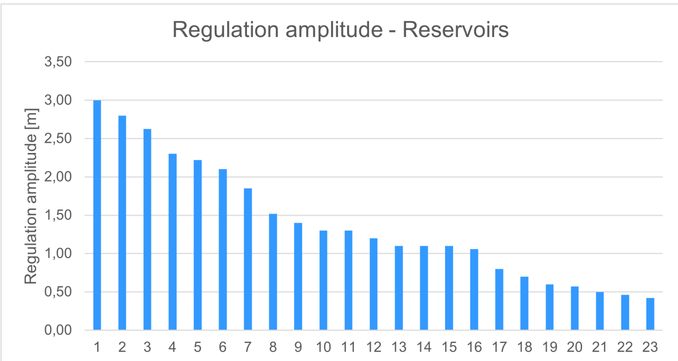


Figure A.3: Regulation amplitude for regulation reservoirs with available data, ordered by magnitude.

A.4 FORSA efficiency curves

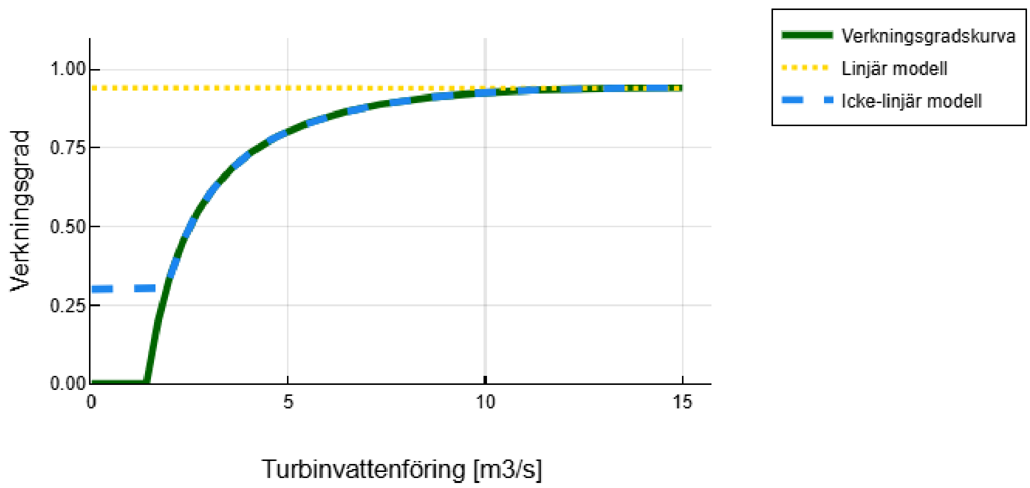


Figure A.4: Efficiency curve for the Francis turbine at the Klinte power plant. The y-axis shows the efficiency (%) and the x-axis shows the turbine discharge (m^3/s). The green line represents the efficiency curve calculated using the four turbine parameters, while the blue dashed line shows the turbine operation curve, including the 30% efficiency threshold at which the turbine starts operating.

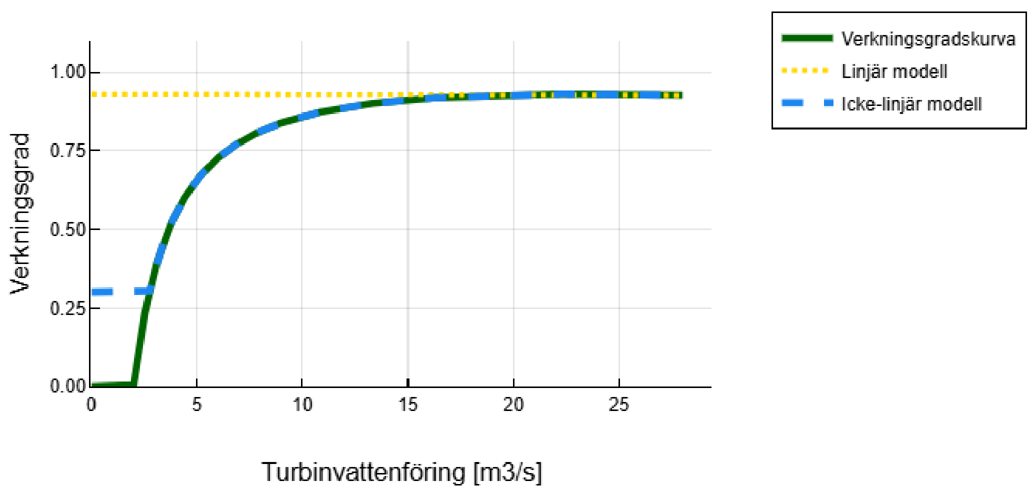


Figure A.5: Efficiency curve for the Kaplan turbine at the Finsjö nedre power plant. The y-axis shows the efficiency (%) and the x-axis shows the turbine discharge (m^3/s). The green line represents the efficiency curve calculated using the four turbine parameters, while the blue dashed line shows the turbine operation curve, including the 30% efficiency threshold at which the turbine starts operating.

A.5 Turbine configuration

Table A.5: Stations where turbine type could not be obtained through open-source data, and where the relationship between hydraulic head and mean river discharge was used. The table also provides the SubID for the sub-catchment where the MQ data was retrieved for each station.

Station	$\boldsymbol{H_{\max}}$ **(m)**	**subID**	$\boldsymbol{MQ}$ **(m³/s)**	**Turbine type**
Björneström övre	4.4	2167	1.27	Francis
Bruzaholm	5.0	2974-2994	0.48	Francis
Gärdeskvarn	4.0	2196+2149	0.84	Francis
Holms kvarn	3.0	2231	0.64	Francis
Högebro	9.0	2866	1.72	Francis
Högsby	9.8	1964+2033+2034	27.79	Kaplan
Ljusholms kvarn	3.0	2048+1971+1931	1.16	Francis
Rosenfors	3.5	2407	4.63	Francis
Rya kvarn	4.0	2171	0.36	Francis
Skrika kvarn	3.6	2184+2278	0.89	Francis
Åslekvarn	6.4	2344	0.10	Francis

A.6 Maximum turbine discharge

Table A.6: Summary of stations for which maximum turbine discharge data are available. SubIDs denote the sub-catchments used to derive the mean flow, MQ, at each station, together with the corresponding k-value obtained from the relationship between maximum turbine discharge and mean flow.

Station	Maximum turbine discharge (m^3/s)	SubID	MQ (m^3/s)	k-value
Jungerholmarna	6.00	1916	28.76	0.21
Axelfors	1.30	2752	5.00	0.26
Finsjö övre	14.00	1919+2007	28.71	0.49
Holms kvarn	0.40	2231	0.64	0.63
Kvarnstugan	0.60	2462	0.69	0.87
Gärdeva	4.00	2311	4.27	0.94
Holsby kvarn	6.00	2444	6.21	0.97
Finsjö nedre	28.00	1919+2007	28.71	0.98
Gärdeskvarn	0.85	2196+2149	0.84	1.01
Rosenfors	5.00	2407	4.63	1.08
Haga	0.50	2606	0.46	1.10
Pauliströms bruk	1.45	2582	1.30	1.12
Kvillsfors	15.00	2429+2443	13.01	1.15
Turefors	15.00	2429	12.52	1.20
Ådelfors	14.50	2444+2509+2414	11.98	1.21
Aslekvarn	0.12	2344	0.10	1.23
Bruksgården	15.00	2444+2509+2414	11.98	1.25
Aspö	15.00	2444+2509	11.82	1.27
Blankaströms	34.00	2084	26.38	1.29
Ljussholms kvarn	1.50	2048+1971+1931	1.16	1.29
Järnforsen	20.00	2393	14.79	1.35
Flugeby	10.00	2406+2437+2514	5.97	1.67
Hogsby	50.00	1964+2033+2034	27.79	1.80
Högerbo	4.00	2866	1.72	2.32
Brunnshult	14.00	2752	5.00	2.80
Prinsfors	0.57	2422	0.20	2.87
Klinte	15.00	2752	5.00	3.00

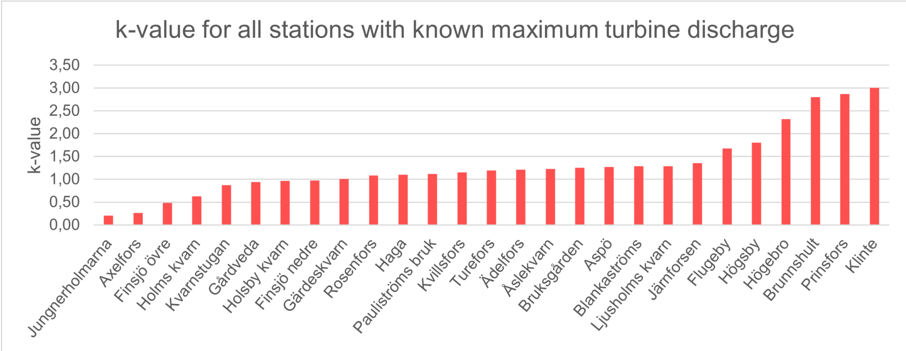


Figure A.6: k-values for stations with available maximum turbine discharge data, based on Table A.6 and ordered by magnitude.

A.7 Baseline scenario

Table A.7: Summary of all current environmental constraints, all identified as minimum water flow constraints through either fish passage or spillways, included in the baseline scenario for Emån. Note that all minimum discharge constraints were modeled as soft constraints.

Station	**Fish passage (m^3/s)**	**Spillways (m^3/s)**
Aspö		1.40
Axelfors		0.05
Blankaströms	1.50	0.20
Bruksgården		0.25
Brunnshult	0.05	0.20
Emsfors	4.50	
Finsjö nedre	0.50	0.90
Flugeby		0.50
Gårdveda		0.05
Högebro		0.03
Karlshammar	4.00	
Klinte		0.20
Paulistöms bruk		0.03
Saljen		0.30
Sjunnen		0.50
Storesjön		0.06
Turefors		0.35
Värnedammen		1.40

A.8 HARO iterations

Table A.8: Relative changes in production (%) across scenarios and simulated years. The simulation for the HARO 20% scenario in 2020 was infeasible and therefore no result is reported for that year.

Year	VISS	HARO 15%	HARO 17%	HARO 20%
2015	-1.5	-15.8	-18.0	-21.2
2016	-18.7	-27.1	-30.3	-34.7
2017	-16.0	-24.0	-27.2	-31.8
2018	-12.1	-17.7	-29.7	-22.5
2019	-16.4	-24.2	-27.1	-31.2
2020	-12.0	-17.6	-19.7	-
2021	-12.5	-18.8	-21.4	-25.1
2022	-16.5	-23.6	-26.1	-29.7
2023	-8.4	-12.4	-14.0	-16.3
2024	-19.6	-14.3	-16.4	-19.0
Average	**-13.3**	**-19.5**	**-22.0**	**-25.7**

A.9 Output data and flexibility metrics

A.9.1 Average output data

Table A.9: Changes relative to the baseline-scenario for key parameters and flexibility metrics. All values represent averages for the period 2015–2024.

Metric	VISS	HARO	RoR
Production (%)	-14	-22	-17
Revenue (%)	-12	-21	-28
Flexibility Factor (%)	1	2	-13
Average Ramp in Production (%)	-9	-17	-78
Amplitude Indicator (%)	-2	-5	-11
High Value Production (%)	-14	-24	-36
High Value Share (%-units)	0	1	-15

A.9.2 Electricity price data

Table A.10: Mean and median electricity prices (SEK/MWh) in the electricity price region SE3 for the years 2015–2024.

Year	Mean	Median
2015	206	216
2016	278	258
2017	301	289
2018	458	461
2019	405	406
2020	221	174
2021	672	517
2022	1379	994
2023	589	438
2024	409	292

A.9.3 Production and revenue

Table A.11: Total annual production (GWh), and average hourly production (MWh/h), for all scenarios for the years 2015–2024, including the average.

	Total production				Average production			
Year	Baseline	VISS	HARO	RoR	Baseline	VISS	HARO	RoR
2015	117	105	96	100	13	12	11	11
2016	76	62	53	60	9	7	6	7
2017	89	75	65	69	10	9	7	8
2018	100	88	80	81	11	10	9	9
2019	89	75	65	69	10	9	7	8
2020	105	92	84	97	12	10	10	11
2021	111	97	88	97	13	11	10	8
2022	85	71	63	69	10	8	7	8
2023	132	121	114	115	15	14	13	13
2024	120	109	101	102	14	12	11	12
Average	101	88	79	81	12	10	9	9

Table A.12: Total annual revenue (MSEK), and average hourly production (SEK/h), for all scenarios for the years 2015–2024, including the average.

Year	Total revenue Baseline	VISS	HARO	RoR	Average hourly revenue Baseline	VISS	HARO	RoR
2015	29	27	25	24	3341	3044	2822	2706
2016	24	20	17	16	2723	2239	1943	1840
2017	30	26	22	22	3441	2918	2535	2493
2018	46	39	36	34	5205	4503	4073	3865
2019	41	34	30	30	4667	3932	3431	3398
2020	30	26	23	22	3453	3002	2666	2461
2021	100	91	85	41	11425	10432	9662	4639
2022	177	147	129	98	20109	16782	14696	11183
2023	109	104	100	90	12398	11855	11352	10181
2024	76	72	68	61	8658	8181	7768	6899
Average	66	59	54	44	7542	6689	6095	4966

A.9.4 Flexibility Factor

Table A.13: Flexibility Factor for all scenarios for the years 2015–2024, including the total average.

Year	Baseline	VISS	HARO	RoR
2015	1.2	1.2	1.2	1.2
2016	1.1	1.2	1.2	1.0
2017	1.1	1.1	1.1	1.0
2018	1.0	1.0	1.0	0.9
2019	1.1	1.1	1.1	1.1
2020	1.3	1.3	1.3	1.0
2021	1.3	1.4	1.4	0.9
2022	1.5	1.5	1.5	1.0
2023	1.4	1.5	1.5	1.3
2024	1.6	1.6	1.7	1.5
Average	1.3	1.3	1.3	1.1

A.9.5 Average Ramp in Production and Amplitude Indicator

Table A.14: Average Ramp in Production (MWh) and Amplitude Indicator (MWh), for all scenarios for the years 2015–2024, including the average.

	Average Ramp in Production				**Amplitude Indicator**			
Year	**Baseline**	**VISS**	**HARO**	**RoR**	**Baseline**	**VISS**	**HARO**	**RoR**
2015	1.4	1.4	1.3	0.3	7.6	7.8	1.3	0.3
2016	1.6	1.4	1.2	0.3	5.7	5.2	1.2	0.3
2017	1.6	1.5	1.4	0.3	6.1	5.7	1.4	0.3
2018	1.4	1.2	1.0	0.3	7.9	8.1	1.0	0.3
2019	1.4	1.3	1.1	0.3	6.1	6.0	1.1	0.3
2020	1.7	1.5	1.4	0.4	8.4	8.3	1.4	0.4
2021	1.8	1.8	1.7	0.3	6.8	6.9	1.7	0.3
2022	1.9	1.7	1.4	0.3	7.7	7.3	1.4	0.3
2023	1.6	1.5	1.4	0.4	7.4	7.9	1.4	0.4
2024	1.6	1.5	1.5	0.5	8.9	9.0	1.5	0.5
Average	1.6	1.5	1.3	0.3	7.2	7.1	1.3	0.3

A.9.6 High Value Production and High Value Share

Table A.15: High Value Production (GWh) and High Value Share (%), for all scenarios for the years 2015–2024, including the average.

	High Value Production				**High Value Share**			
Year	**Baseline**	**VISS**	**HARO**	**RoR**	**Baseline**	**VISS**	**HARO**	**RoR**
2015	87	81	76	69	74	77	79	69
2016	41	32	27	19	54	52	51	327
2017	63	53	45	38	70	71	70	55
2018	39	31	26	21	39	35	33	26
2019	65	55	48	43	73	73	73	63
2020	67	58	51	51	64	62	61	52
2021	75	67	60	25	68	69	69	37
2022	64	53	47	37	75	75	741	53
2023	96	92	88	75	73	76	78	66
2024	96	89	83	71	80	82	82	70
Average	67	59	53	42	66	66	66	50

A.10 Sensitivity analysis

A.10.1 Flow time

Table A.16: Relative change in metrics for all scenarios for the reference system and the modified system. The modified system represents a system in which all flow times have been set to 1 hour.

	VISS		**HARO**		**RoR**	
Metric	Ref	Mod	Ref	Mod	Ref	Mod
Production (%)	-13	-14	-22	-23	-17	-18
Revenue (%)	-12	-12	-21	-22	-28	-29
Flexibility Factor (%)	1	1	2	2	-13	-13
Average Ramp in Production (%)	-8	-8	-17	-18	-78	-79
Amplitude Indicator (%)	-1	-2	-5	-7	-11	-12
High Value Production (%)	-13	-14	-24	-26	-36	-39
High Value Share (pp)	0	0	-1	-1	-15	-16

A.10.2 Turbine type

Table A.17: Relative change in metrics for all scenarios for the reference system and the modified systems. The modified systems are systems in which all turbine types have been set to either Francis (F) or Kaplan (K)

	VISS			**HARO**			**RoR**		
Metric	Ref	F	K	Ref	F	K	Ref	F	K
Production (%)	-13	-13	-12	-22	-23	-22	-17	-19	-18
Revenue (%)	-12	-12	-11	-21	-21	-22	-28	-29	-28
Flexibility Factor (%)	1	2	2	2	2	2	-13	-13	-12
Average Ramp in Production (%)	-8	-8	-8	-17	-17	-15	-78	-78	-78
Amplitude Indicator (%)	-1	-1	2	-5	-5	-4	-11	-8	-9
High Value Production (%)	-13	-14	-13	-24	-24	-22	-36	-38	-37
High Value Share (pp)	0	0	0	-1	-1	0	-15	-15	-15

A.10.3 k-value

Table A.18: Relative change in metrics for all scenarios for the reference system and the modified system. The modified system represents a system in which all unknown maximum turbine discharges have been estimated with a scaling factor of $k = 1.5$.

	VISS		**HARO**		**RoR**	
Metric	Ref	Mod	Ref	Mod	Ref	Mod
Production (%)	-13	-13	-22	-22	-17	-18
Revenue (%)	-12	-12	-21	-21	-28	-29
Flexibility Factor (%)	1	2	2	2	-13	-13
Average Ramp in Production (%)	-8	-8	-17	-17	-78	-78
Amplitude Indicator (%)	-1	-2	-5	-5	-11	-9
High Value Production (%)	-13	-13	-24	-24	-36	-38
High Value Share (pp)	0	1	-1	-1	-15	-15

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