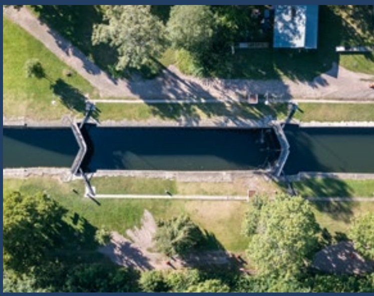



Book on Dams

The Swedish Experience




This book has been developed by Svenska kraftnät as part of our mission to promote dam safety in Sweden. In its development, we have had significant support from SwedCOLD and its network, which has contributed with information and images. We have also received financial support from Energiforsk's dam safety program.

"We have finally arrived in Gothenburg" - Welcome to the 91st ICOLD Annual Meeting!

Dear colleagues,

When you open this book, we have finally arrived at the **91st ICOLD Annual Meeting** in **Gothenburg, June 2023**. It has been a long journey, but we are thrilled that the event is finally here and that we, on behalf of the Swedish National Committee of ICOLD, SwedCOLD, can welcome you to Gothenburg.

We proudly present the Book on Swedish Dams to introduce you to Sweden, our nature resources and the development and use of dams of different purposes. In this way we seek to highlight the vital role of the Swedish hydropower and mining industries in the country's economy and energy supply. We hope you will enjoy the book!

On behalf of SwedCOLD, we would also like to thank everyone who contributed to the book.

During the week of the ICOLD Annual Meeting, we hope to meet you at our workshops, short courses on current topics, technical excursions to dams in the region, social events and the SwedCOLD symposium "Management for Safe Dams". The symposium will have more than 100 presentations and cover six themes and their application to various dam types and purposes, including hydropower, flood control, irrigation, levees, and mine tailings.

Once again, we welcome you to the 91st ICOLD Annual Meeting and wish you a productive and enjoyable time in Gothenburg.

Best regards,

Maria Bartsch
President of SwedCOLD,
past Vice-President of ICOLD

Anders Isander
Lead of Local Organizing Committee,
past President of SwedCOLD

A word from the editors

This book is being published in conjunction with ICOLD's 91st annual meeting, organized by SwedCOLD. The book is primarily aimed at conference attendees who are well-versed in dams but curious about Sweden and our dams. We also believe that professionals working with dams and water resources, students, and general technology enthusiasts with knowledge about Sweden will find the book interesting. We hope it will contribute to knowledge exchange and discussions as well as promote Sweden and dam engineering.

Central to the book is the concluding annex, which presents around 40 dams that their owners have selected. These dams are significant to Sweden for various reasons, and they provide a natural selection of examples that illustrate the development of dams in the country.

With the support of these dams, maps, pictures and timelines, we aim to tell the story of Swedish dams. The book utilizes both a historical and a geographical perspective. Firstly, it introduces ICOLD and SwedCOLD and gives a background on Sweden's industrial history, focusing on the development of the hydropower and mining industries. Then, it delves into Sweden's geography, natural resources and climate. Following these introductory chapters, the focus shifts to Swedish dams and their industry. From the construction of the first large dams at the beginning of the last century, through the fast hydropower development during the 50s-70s, and the development of the Swedish framework for dam safety, to the present-day challenges with managing an ageing dam portfolio, raising tailings dams and constructing levees for flood protection.

We would like to express our gratitude to all the colleagues who have contributed with information and images - without you, this book would not have been possible. One of the challenges with describing the historical development in general terms is that it forces us to simplify complex events and decisions. The history of Sweden's dams is no exception. We have tried to balance presenting these structures' technical details and historical context while acknowledging the limitations of summarizing such a vast and diverse field. Any errors or shortcomings are our own responsibility.

We hope that you will find this book both interesting and informative. Moreover, we are confident that you will enjoy the many pictures of Sweden's beautiful nature and dams.

Sincerely,
Rikard Hellgren and Maria Bartsch
Dam Safety Specialists, Svenska kraftnät.
May 2023

Dalkarlsdammen, Garpenberg. Photo: Svenska kraftnät.

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1. SwedCOLD and ICOLD

Älvkarleby hydropower facility. Photo: Svenska kraftnät.

1. SwedCOLD and ICOLD

The longstanding relationship between ICOLD and the Swedish dam safety community via the Swedish national committee of ICOLD, SwedCOLD, has been of exceptional significance to the Swedish dam industry.

Sweden was among the first members of ICOLD as early as 1931 and hosted the first-ever ICOLD Congress in 1933. This chapter presents the history of SwedCOLD, focusing on the collaboration with ICOLD and the events SwedCOLD has organized. Since Swedish participation has been driven by topics relevant to us, this chapter also provides a glimpse of the upcoming chapters.

1928: The Birth of ICOLD

The constituitive meeting of the International Commission on Large Dams is held in Paris. Six nations were represented: France, USA, Italy, Romania, the UK and Switzerland.

1931: Sweden joins ICOLD, 1st Executive Meeting in London

The first Executive Meeting is held in London in 1931. This is also the year when Sweden becomes a member of ICOLD. At this point, ICOLD consists of thirteen members.

1933: 1st Congress and 3rd Executive Meeting in Stockholm and Trollhättan, Sweden

ICOLD's 1st Congress and 3rd Executive Meeting is held in Stockholm, with nineteen members in attendance. A five-day tour of Sweden and several hydropower facilities followed the congress.

1934: Formation of the Swedish Committee on Large Dams - SwedCOLD

Although a member of ICOLD, Sweden is still missing a formal national committee. This changes now in 1934, as the Swedish Committee on Large Dams is formed.

1948: The 3rd Congress and 15th Executive Meeting in Stockholm, Sweden

The ICOLD 3rd Congress is held in Stockholm, including a banquet with nearly 400 seated guests, a big event after the long war.

1981: The 49th Executive Meeting in Stockholm, Sweden

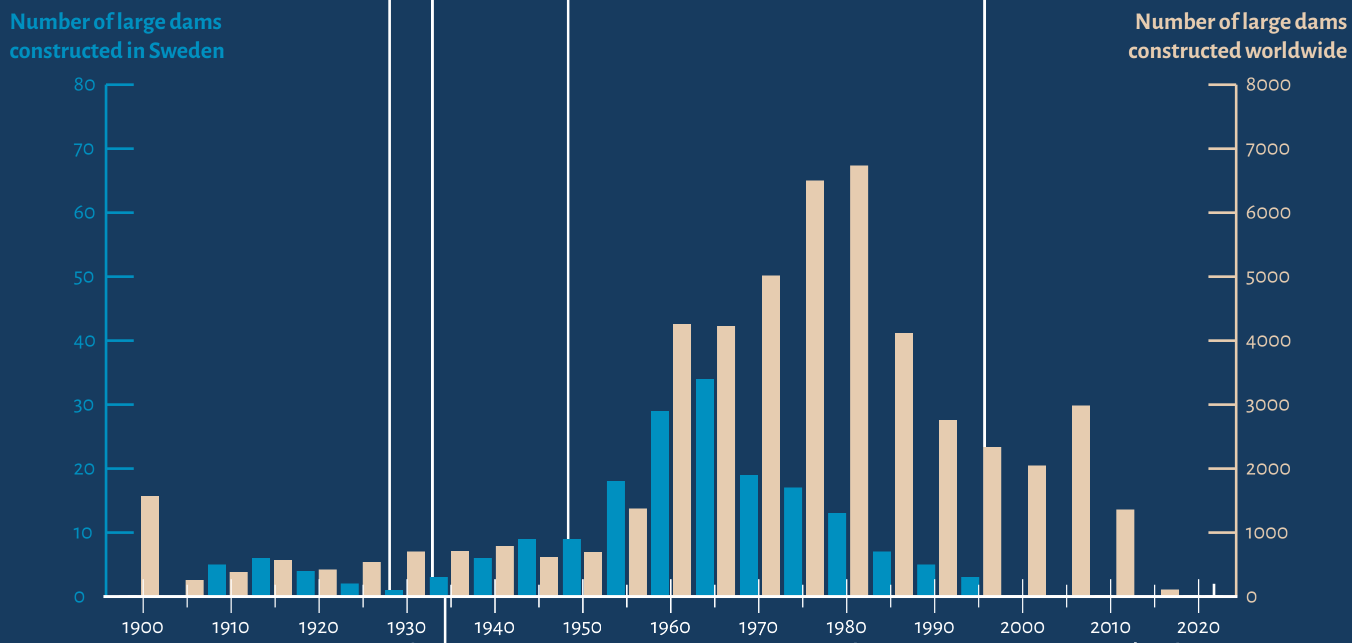
1996: European ICOLD club Symposium in Stockholm, Sweden

The theme of the symposium was repair and upgrading of dams: concrete dams, embankment dam and floods.

2013: European club of ICOLD in Stockholm, Sweden

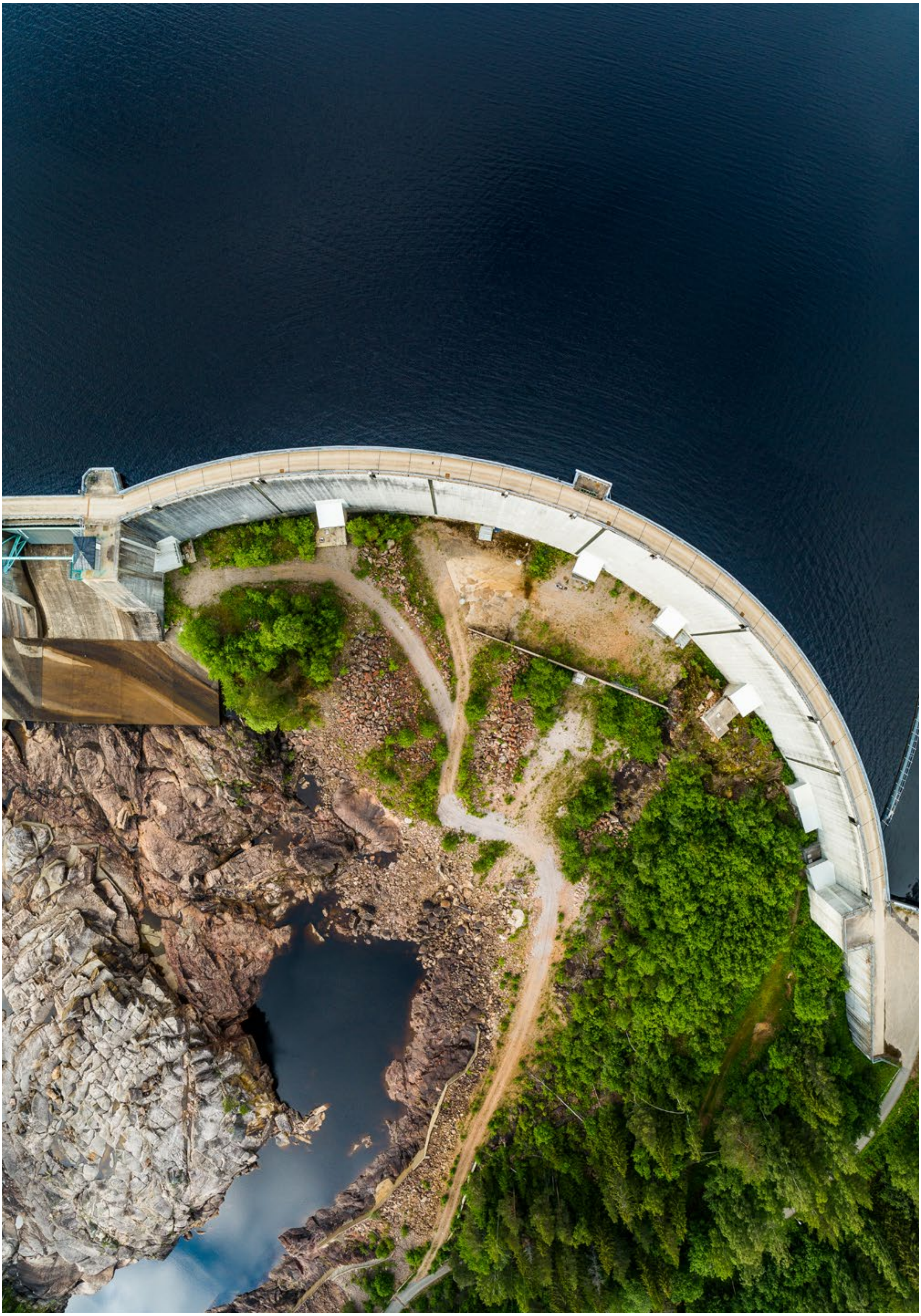
Workshop on the theme: Accidents and incidents – What can we learn?"

2017: 14th International Benchmark Workshop on Numerical Analysis of Dams in Stockholm, Sweden



Source: ICOLD World Register of Dams.

Krokströmmen dam. Photo: Svenska kraftnät.



The formation of ICOLD

ICOLD is historically connected to the World Energy Congress (WEC), formerly the World Power Conference (WPC). In 1924, the WPC was established to facilitate discussions on current and future energy issues. Two years later, at a WPC section meeting, attendees discussed the possibility of forming an international organization to exchange experiences regarding the construction of large dams. The following year, an invitation was extended from the French government to interested states to participate in forming an international committee on large dams.

While a committee had already been created in France, the WPC's central office in London believed that an independent committee for large dams would mean duplication of effort. This situation created a disagreement on the connection between the dam commission and the WPC. Lengthy discussions were held on the status of the dam commission in relation to the WPC. A compromise was eventually reached, and in July 1928, la Commission Internationale des Grands Barrages (the French name of the International Commission on Large Dams) was constituted following the guidelines drawn up by the French committee. The dam commission's meetings would be held simultaneously with the WPC or other conferences with a similar program.

In 1930, the International Commission on Large Dams (ICOLD) became an independent organization within the World Power Conference. The dam commission's first executive meeting was held in London in 1931. At that time, Sweden participated in the meeting represented by the Swedish Consul General in London, even though it formally joined ICOLD a few days after the meeting.

The meeting also decided that ICOLD's first congress would be held in Stockholm in 1933, in conjunction with the World Power Conference's congress. Sweden was initially represented in ICOLD by its national committee for the World Power Conference. It was first in 1934, that the Swedish national committee for ICOLD was established. The Swedish State Power Board through Chief Engineer, Axel Ekvall, served as Sweden's first delegate in ICOLD and SwedCOLD's first chairman from 1934 to 1940.

ICOLDs 1st Congress and 3rd Executive Meeting, Stockholm and Trollhättan 1933

By the time of ICOLD's third executive meeting and its first congress in Stockholm in 1933, the number of member countries had grown to 19. During this executive meeting, four issues were raised, two of which would not be realized until many years later.

- The first issue was forming a special committee on concrete issues, which became one of ICOLD's foremost tasks for many years.
- The second issue was the establishment of an international dam register, and although its plans were extensive, it was never implemented as originally intended. The first edition of the international dam register in its current form was not published until 1964, over 30 years later.
- The third issue was the creation of an international dam dictionary, which was started soon after the executive meeting but was delayed by World War II. The first edition of the dam dictionary was not published until around 1950.
- The fourth issue raised at the meeting was a proposal that ICOLD and the International Congress of Navigation should act as godparents to a new international committee, which later became the International Association for Hydraulic Research (IAHR).

The congress was followed by a five-day study tour made by train that ended in Trollhättan, where over 100 engineers, many accompanied by their partners, visited several sites, including Lilla Edet (see Annex 1) and other hydroelectric power stations in Göta älv. A Technical Excursion, of this year's annual meeting will follow in the footsteps of the previous generation of ICOLD engineers and visit the hydropower plant Lilla Edet once again. The dam is currently undergoing reconstruction, with the spillways being reconstructed. This visit will provide an opportunity to learn more about the reconstruction project, which is planned to be completed by the end of 2025. The hydropower plants in Göta Älv remain important and play a critical role in regulating the water level and outflow of Sweden's – as well as western Europe´s – largest lake, Vänern.

The formation of SwedCOLD and its early focus on concrete

Concrete was an essential material used in the construction of large high dams in Sweden, which were priamry built as either concrete dams or diaphragm embankments with a central concrete core, read more about the development of Swedish dams in Chapter 4.1. However, extensive damage and leakage discovered on many of these concrete dams in Sweden in the 1920s resulted in early research into the design and composition of concrete for hydraulic structures. These research efforts paved the way for international cooperation on concrete research. When SwedCOLD was established in 1934, cement issues dominated the committee's activities for several years. They formed a Subcommittee on Special Cements for Large Dams in ICOLD and were instrumental in hosting The International Cement Congress in Stockholm in July 1938, submitting a Swedish report to the interim international cement committee and forming a special committee for cement issues.

SwedCOLD

Through SwedCOLD, the Swedish National Committee of ICOLD, Sweden has been a member of ICOLD since 1931. The National Committee is organized as an Executive Committee with representatives from dam owners in the hydropower and mining industry, consultants, contractors, industry organizations, and the national dam safety regulator. Today, the Executive Committee consists of 27 members, including co-opted members, and represents 19 financing companies. SwedCOLD is connected to a large network of professionals who work with dams through its Expert network and its network for young engineers.

SwedCOLD's main objectives are to provide a national forum for information and discussion of important matters concerning dams, to contribute to knowledge transfer and development within dam engineering, and to contribute to ICOLD through participation in technical committees, annual meetings and congresses.

SwedCOLD's Expert Network

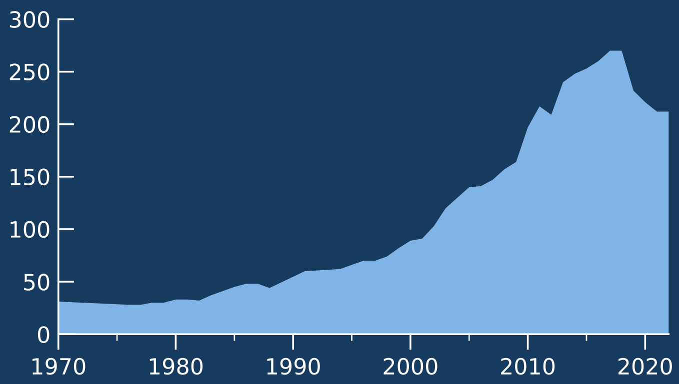
SwedCOLD's Expert network for dam professionals has existed for over 50 years and today has more than 200 members. The Executive Committee approve applications to the Expert Network upon request, and it is a requirement for all members of the Expert Network to have several years of relevant expertise in the field. Additionally, all members of the Executive Committee are also members of the Expert Network. Twice a year SwedCOLD organizes a well attended symposium devoted to selected topics in the field of dams. SwedCOLD also publishes a newsletter, host workshops and arrange site visits to dam projects.

SwedCOLD's Newsletter is a publication released twice a year in connection with the organization's symposia. The newsletter provides updates on the latest developments and news related to dams and dam engineering and SwedCOLD's activities and events.

SwedCOLD's leadership positions from the organization's foundation to the present day

NAME	CHAIR	SECRETARY	VICE CHAIR	VICE CHAIR, ICOLD
Axel Ekwall	1934–1940	–	–	–
Ragnar Kjellberg	–	1957–1983	1946–1956	–
Gösta Westerberg	1940–1957	–	–	1946–1949
Tore Nilsson	1957–1973	1949–1956	–	1962–1965
Väinö Wanhainen	1973–1978	–	–	–
Sven-August Hultin	1978–1989	–	–	–
L. Klöfver	–	1984–1989	–	–
Jan Eurenius	–	1990–1996	–	–
Urban Norstedt	1990–2002	–	2003–2005	–
Gunnar Sjödin	2003–2009	1997–2002	–	–
Lars Hammar	2012–2017	–	1999–2002	–
Maria Bartsch	2017–2023	2003–2007	2008–2017	2007–2010
Ylva Helmfrid Schwartz	–	2008–2011	–	–
Anders Isander	2009–2011	–	–	–
Anders Söderström	–	2012–2019	–	–
Per Elvnejd	–	–	2018–2023	–
Finn Midböe	–	2021–2023	–	–

Number of members in SwedCOLD's Expert network



Number of members in SwedCOLDs expert network, from 1970 to today.

SwedCOLD's Biannual Dam Symposia

SwedCOLD hosts two symposia annually that attract significant attendance. These symposia focus on selected topics related to dams, and the topics covered during these spring and autumn meetings since 1997 can be found in the table.

YEAR	SPRING MEETING	AUTUMN MEETING
2022	Flood adaptation and climate – experiences from projects	Lessons learned from accidents and incidents
2021	Operation and emergency preparedness (digital)	Safety management and dam safety assessment
2020	Cancelled (covid-19)	Dam measurements - purpose, analysis, and evaluation (digital)
2019	RIDAS* 2019 and environmental adaptation	Modern monitoring and investigation methods, as well as RIDAS*
2018	Spillways	Dam safety and environmental adaptations
2017	Risk management and discharge safety	Dams and foundation
2016	Management of aging concrete dams and power stations	Embankment dams, measures, implementation issues, and Energiforsk's dam safety program
2015	Development in dam safety	Renewal of facilities, dams, and power stations
2014	Operational dam safety: Human – Technology – Organization	New regulations in dam safety and current technical issues
2013	Development of condition monitoring in a long-term perspective. – Why do dam safety reviews and condition monitoring	Incidents and emergency preparedness for dam failures
2012	Large projects in existing dams	EU directives concerning dams and current concrete issues
2011	Hydraulic modelling and design flood determination	Dam safety and safety management systems
2010	New construction methods for dams	Dam monitoring and management of measurement data
2009	Discharge safety and information on peer reviews of dam safety	Dams under extreme loads
2008	Dam safety development in Sweden	Sediment traps – experiences and examples. Report from ICOLD committees.
2007	Climate and vulnerability investigations, dam breach experiments, reporting from DSIG and ICOLD committees	New technology and tailing dams
2006	Concrete dams and climate	Measures to enhance dam safety

**RIDAS is the title of the Swedenergy's Guidelines for Dam Safety.*

YEAR	SPRING MEETING	AUTUMN MEETING
2005	Discharge safety and debris	WCD and current tailings dam issues
2004	Embankment dams – safety-enhancing measures, theory, and practice	Instrumentation and monitoring of dams
2003	Preparedness for dam breaches	The role of authorities – in Sweden and other countries
2002	Concrete and RCC dams and Report from ICOLD committees	Operational dam safety; Human – Technology – Organization
2001	Pros and cons of dam construction	Dr Sims, discharge safety, the authority's view on dam safety
2000	RIDAS* and dam safety reviews	Climate issues – now and in the future
1999	Instrumentation and monitoring of dams	Risk analysis for dam safety
1998	Power plants and dams in China and other countries	Embankment dams – Incidents and floods – Significance of dams
1997	Sinkholes in Bennett Dam, investigations and repairs	Insurance issues for dam facilities

View from SwedCOLD Symposium, 2021.

Photo: Svenska kraftnät.

The symposium in Stockholm led to the formation of the International Union of Testing and Research Laboratories for Materials and Structures (known as RILEM). RILEM has since become an leading international organization in construction materials and structures. The discussions at the symposium also led to the establishment of a research program on cement and concrete, which the Swedish Cement Association funded. This program and the symposium's success eventually led to the establishment of the Swedish Cement and Concrete Research Institute (CBI) in 1947. The institute, later renamed the Swedish Cement and Concrete Institute, has since played a crucial role in developing the Swedish cement and concrete industry.

The 3rd Congress and 15th Executive Meeting in Stockholm, Sweden

The Swedish committee continued to work tirelessly despite international cooperation being canceled due to the war. The main issue was still cement, but also cost comparison for different types of dams. In 1946, the ICOLD resumed its international cooperation. The Swedish committee proposed that ICOLD hold its first congress after the war in Stockholm in the summer of 1948, which the committee accepted after much discussion. The committee faced challenges with a short timeline and scarce resources. Although the arrangements were not comparable to later congresses, attendees were happy to be there after the long war. The congress was an opportunity to renew old friendships and make new ones, regardless of past wartime alliances.

During the congress, the participants were taken on a 5-day long journey via two train sets from Stockholm through the Indalsälven and Ångermanälven rivers up to Harsprånget in northern Sweden. They then traveled south via industries in central Sweden and once again visited Trollhättan, where the closing meeting was held.

An increased focus on rock engineering

During the rapid expansion of Swedish hydropower in the 1950s, rock engineering became a critical aspect of the Swedish hydropower industry. The combination of geological conditions and the shape of the rivers often required the construction of long intake tunnels and underground facilities in connection with the large dams. In the early 1950s, the Swedish committee attempted to expand ICOLD's activities to include underground works. However, it took several attempts before the Subcommittee on Underground Works in connection with Hydroelectric dams was established in 1957. The committee's primary goal was to study technical issues related to underground works in connection with dams, such as rock reinforcement methods, water permeability reduction, and the general properties of rocks that can affect the construction and building of dams and tunnels.

In 1965, the committee was renamed the Committee on Foundations of Large Dams and on Underground Works, with a new scope to study the connections between foundations and incidents and accidents at high dams. The failure of the French arch dam Malpasset in 1959, where defects in the rock foundation at the left abutment of the dam were one of the more significant causes, was a decisive factor in this change.

SwedCOLD and ICOLDs' changed focus

In 1967, ICOLD became independent from the WPC. This coincided with a shift from ICOLD's initial focus on promoting advances in the planning, design, construction, operation, and maintenance of large dams and their associated civil works, to addressing subjects of current concern such as dam safety, performance monitoring, reanalysis of older dams and spillways, effects of aging, and environmental impact. This was achieved by creating several new subcommittees, including dam safety, monitoring, aging, calculation analysis, and environmental impact. In the 1970s and beyond, numerous additional subcommittees were established and more recently new subjects include cost studies at the planning and construction stages, harnessing international rivers, information for the public at large, and financing.

As ICOLD's activities continued to expand, Sweden's focus on dam construction began to shift. The construction of dams in Sweden slowed down in the 1970s, leading to a greater emphasis on national collaboration and participation in development projects in other countries. In 1978, it was decided to hold yet another ICOLD annual meeting in Sweden, which took place in Stockholm in 1981. By this time, ICOLD's activities had become so extensive that they cannot be easily summarized. Some of the highlights of the activities outside the meeting included a lunch reception hosted by the City of Stockholm at City Hall and the official dinner at the Opera Terrace. The meeting was a great success, and the attendees appreciated the event. This was also the last time until this year that Sweden organized a worldwide ICOLD meeting.

In the 1980s, the hydropower industry in Sweden entered a period of dam operation and maintenance that continues to this day. During this period, some deficiencies in construction and design were discovered, necessitating the reinforcement, modernization, or reconstruction of many dams. Sweden has since hosted several ICOLD events related to dam safety. In 1996, the European ICOLD Club Symposium on the theme of repair and upgrading of dams, including concrete dams, embankment dams, and floods, was held in Stockholm.
In 2013, the European Club of ICOLD hosted a workshop in Stockholm on the theme "Accidents and Incidents - What Can We Learn?"

The 14th ICOLD International benchmark workshop

The latest big ICOLD event in Sweden was the 14th ICOLD International Benchmark Workshop on numerical analysis of dams, held in Stockholm in 2017. Every two years, ICOLD's Technical Committee A organizes an international benchmark workshop on numerical analysis of dams with the goal of sharing knowledge and experience within dam safety, planning, design, construction, and operation and maintenance of dams. The 14th Benchmark Workshop addressed the current challenges in the design and maintenance of existing dams and featured four predefined themes: cracking of a concrete arch dam due to seasonal temperature variations, static and seismic analysis of an arch-gravity dam, embankment dam behavior prediction of arching and cracking potential, and risk analysis for concrete dams. In addition, an open theme allowed participants to present their topics and projects within the field of numerical analysis of dams.

The workshop aimed to improve the understanding of the current challenges in the design and maintenance of existing dams through the exchange of experience on using numerical modeling for design, performance evaluation, and safety assessment of dams. On the third day of the workshop, a technical tour was arranged to explore the scenic areas around the Dalälven River, located north of Stockholm. The lower parts of the river are considered the birthplace of Swedish hydropower and feature several hydropower facilities dating back to the early 20th century. As part of the tour, participants visited the hydraulic laboratory of Vattenfall Research and Development in Älvkarleby, which offered a unique opportunity to observe advanced testing and measurement techniques used in the design and operation of dams. During this year's annual meeting, again, a studytour is arranged to the hydraulic laboratory and the hydropower facility in Älvkarleby.

ICOLD board and national representatives on ICOLD General Assembly in Ottawa, 2019.

ICOLD

The International Commission On Large Dams (ICOLD) is a non-governmental international organization that focuses on dam engineering. It provides a platform for member countries to exchange knowledge and experience related to dams. ICOLD is made up of over 100 member countries. Any independent country can become a member by constituting a National Committee consisting of individuals competent in dam-related matters.

ICOLD is directed by the General Assembly, which includes representatives from all member countries and officers of the commission. The Board is responsible for managing the commission's affairs and consists of the President, six Vice Presidents, Secretary-General, and Treasurer. Officers are elected for a three-year mandate, which is non-renewable except for the Secretary-General and Treasurer.

The Central Office of ICOLD is located in Paris and is responsible for managing and organizing ICOLD activities. The Technical Committees, Administrative Committees, and Special Committees are appointed by the Commission to carry out its work. The official languages of ICOLD are French and English.

Mission statement

ICOLD leads the profession in setting standards and guidelines to ensure that dams are built and operated safely, efficiently, economically, and are environmentally sustainable and socially equitable.

ICOLD is assisting nations to prepare to meet the challenges of the 21st century in the development and management of the world's water and hydropower resources.

ICOLD technical committees

Today, ICOLD operates within about 35 technical committees, including ad-hoc committees and regional clubs in Asia, America, Africa, and Europe. Sweden is represented in almost half of them.

ICOLD General Assembly 2019. Photo: Maria Bartsch.

	ICOLD TECHNICAL COMMITTEES (2023)	SWEDISH REPRESENTATIVE
A	Computational Aspects of Analysis Design of Dams	X
B	Seismic Aspects of Dam Design	
C	Hydraulics for Dams	X
D	Concrete Dams	X
E	Embankment Dams	X
F	Engineering Activities with the Planning Process for Water Resources Projects	
G	Environment	X
H	Dam Safety	X
HWS	Historical Water Structure (Water Heritage)	
I	Public Safety Around Dams	X
J	Sedimentation of Reservoirs	
K	Integrated Operation of Hydropower stations and Reservoirs	
L	Tailings Dams and Waste Lagoons	X
LE	Levees	
M	Operation, Maintenance and Rehabilitation of Dams	X
N	Public Awareness and Education	
O	World Register of Dams and Documentation	
P	Cementet Material Dams	
Q	Dam Surveillance	X
RE	Resettlement Due to Reservoirs	
S	Flood Evaluation and Dam Safety	X
T	Prospective and new Challenges for Dams and Reservoir in the 21st Century (Ad hoc-kommitté)	
TRS	Tropical Residual Soils	
U	Dams and River Basin Management	
V	Hydromechanical Equipment	X
Y	Climate change	X
Z	Capacity Building and Dams (Ad hoc-kommitté)	
	Young Professionals Forum (YPF)	X
	ICOLD Board	
	Regional Club Asia (APG)	
	Regional Club Americas (INCA)	
	Regional Club Africa (ARC)	
	Regional Club Europe (EURCOLD)	X

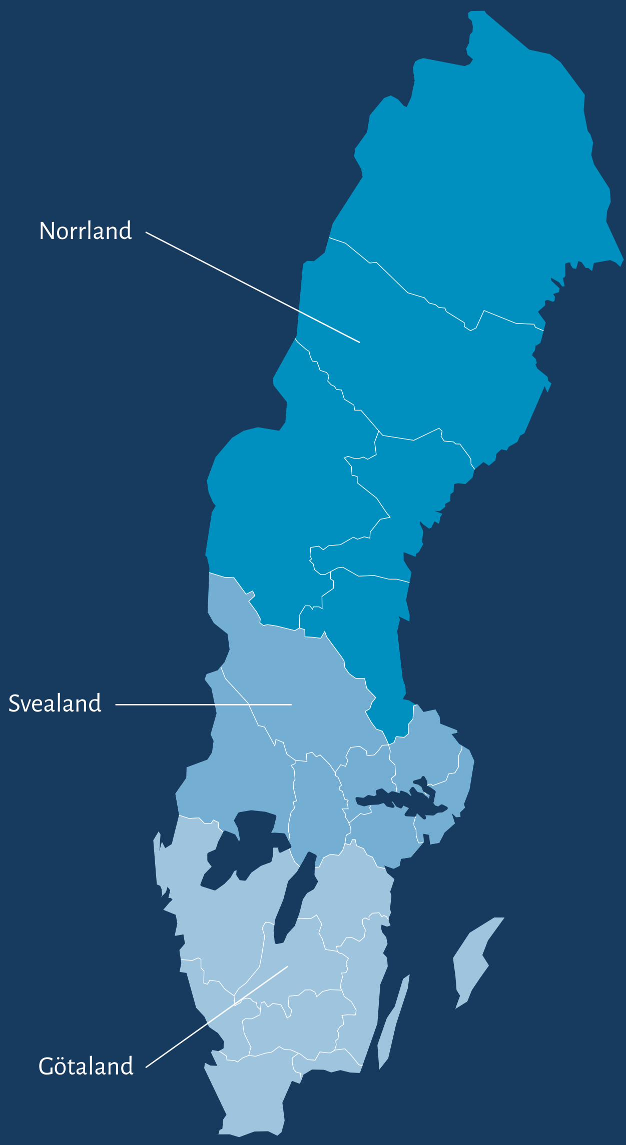
2.
Sweden in brief

Sveg hydropower dam. Photo: Svenska kraftnät.

2. Sweden in brief

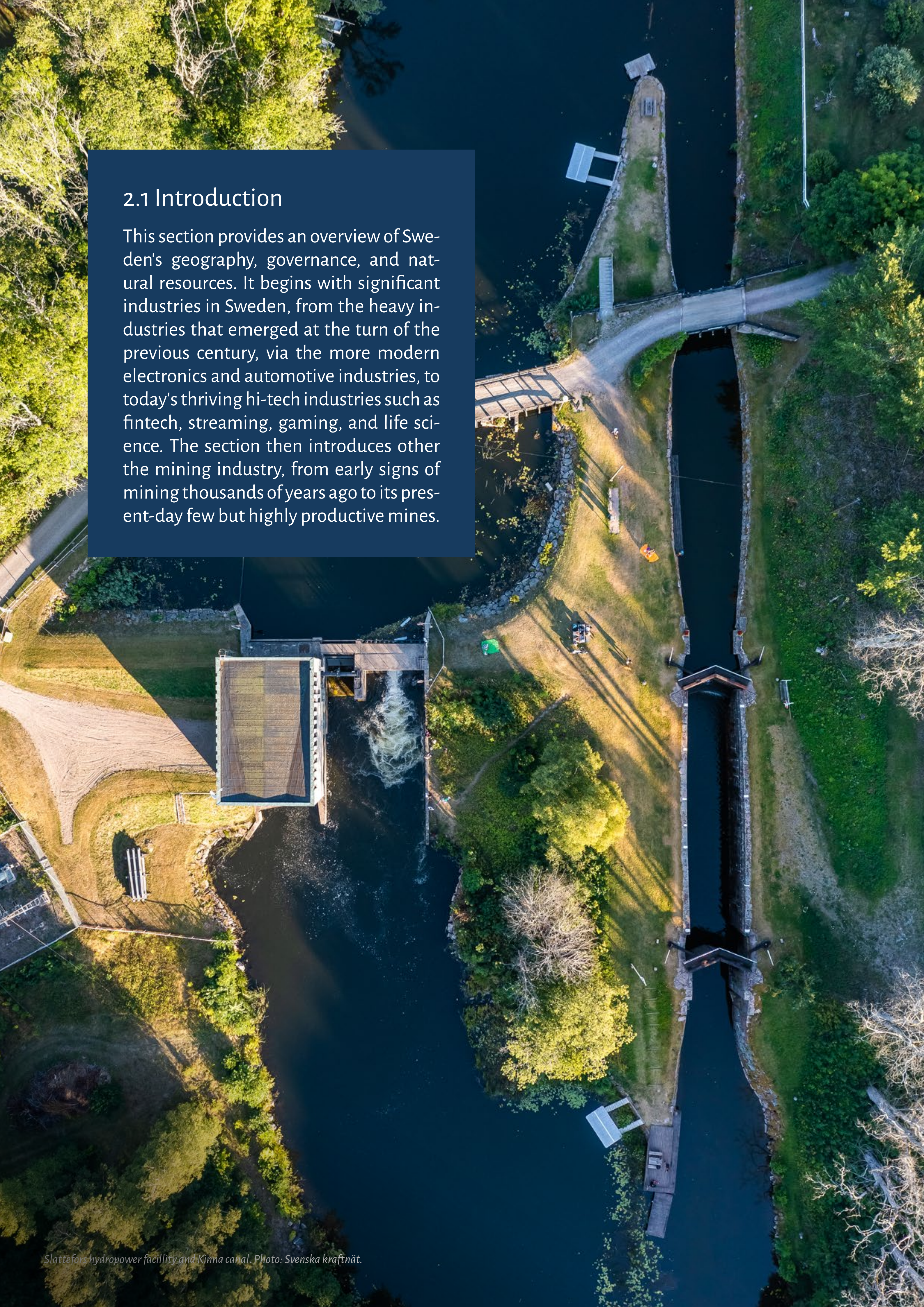
This chapter provides a brief overview of Sweden.

First, it introduces the country's geography, governance, and natural resources. Then, two sections follow that describe how these resources were utilized in the electrification and industrializing of Sweden, transforming it from a poor agricultural nation into a modern economy. These two sections have an emphasis on the development of the mining and hydropower industries, respectively.


Norrland
Svealand
Götaland

2.1 Introduction

This section provides an overview of Sweden's geography, governance, and natural resources. It begins with significant industries in Sweden, from the heavy industries that emerged at the turn of the previous century, via the more modern electronics and automotive industries, to today's thriving hi-tech industries such as fintech, streaming, gaming, and life science. The section then introduces other the mining industry, from early signs of mining thousands of years ago to its present-day few but highly productive mines.



Slattefors hydropower facillity and Kinna canal. Photo: Svenska kraftnät.

Basics

Sweden is situated in northern Europe on the Scandinavian Peninsula, with borders to Norway to the west and Finland to the northeast. With an area of 450,000 km², Sweden is the fifth largest country in Europe and the 55th largest country globally. Sweden has a 3200 km long coastline with the Baltic Sea and the Gulf of Bothnia to the east and the Öresund, Kattegatt, and Skagerrak straits to the west. Sweden has maritime borders with Denmark, Germany, Poland, Russia, Lithuania, Latvia, and Estonia. You can travel from Sweden to Denmark by car and train via the Öresund bridge. The Scandinavian mountain chain runs along the border to Norway in the west. Almost 10 % of Sweden's area is lakes and rivers. The largest lake is Lake Vänern, with a surface area of 5,650 km², making it the largest lake in the European Union..

Lands and population

The lands of Sweden, Götaland, Svealand, and Norrland (literally "Northland"), are the country's three traditional and historical regions. This division originates from the founding of Sweden, when Götaland, the land of the Geats, merged with Svealand, the land of the Swedes. Each land consists of several provinces, but the lands and the 25 provinces have no administrative function. Götaland is the southernmost and most densely populated part, Svealand is the central part with the administrative center in the capital Stockholm, and Norrland is the rural northern part that makes up 60 % of the land area but only 10 % of the population. Stockholm, Gothenburg (Göteborg), Malmö, and Uppsala are the four largest cities.

Governance

Sweden is a constitutional monarchy, which means that The King (or Queen) is the country's Head of State with duties regulated by law. The legislature and the supreme decision-making body of Sweden are the Riksdag. The Riksdag appoints The Government that governs Sweden and is the driving force in the process of legislative change. The Government consists of the Prime Minister and other cabinet ministers. Each ministry is responsible for several government agencies tasked with applying the laws and carrying out the activities the Riksdag and the Government decided on. Every year the Government issues appropriation directions for the government agencies. These set out the objectives of the agencies' activities and how much money they have available to them. Sweden has been a member of the European Union (the EU) since 1995.

Although Sweden counts as a unitary state, the governance is highly decentralized. Sweden is divided into 21 counties, each with a county administrative board and county council. The Government appoints the county administrative board, which acts as the local Government. It is, for example, the county administrative board that is responsible for dam safety supervision. The regional electorate elects the county council, and its primary responsibility is the public health care system and public transportation. At the local level, Sweden has 290 municipalities. Each municipality has an elected assembly, the municipal council, which takes decisions on municipal matters.

Stockholm - a city on islands. Photo: Maria Bartsch.

Natural resources

Sweden is a country rich in natural resources that have contributed significantly to its economic development over the years. With vast forested lands, mineral deposits, and ample water supplies, Sweden has built a thriving, globally competitive economy.

Forestry is one of the major natural resources in Sweden and has been a cornerstone of the country's economy for centuries. Sweden has over 23 million hectares of forest land, accounting for roughly 70% of its total land area. The economy of pre-19th century Sweden was dominated by the use of these vast forested lands providing wood for construction and fuel.

In the early 20th century, forestry was still a major contributor to Sweden's economy, accounting for up to 10% of its GDP. However, as other industries, such as manufacturing and services, grew, forestry's share of GDP declined. Today, forestry accounts for around 1.3% of Sweden's GDP. However, the forest industry is still one of Sweden's largest employers, providing jobs for over 70,000 people. Sweden is the world's largest exporter of sawn timber and the second-largest exporter of pulp and paper products.

One of Sweden's most important natural resources is iron ore, which has been mined in the country since the Middle Ages. During the 18th century, Sweden became a significant producer of minerals, particularly iron ore, copper, and gold. Sweden's mining industry begins to develop, with iron ore being one of the country's primary mineral resources. The industry expands significantly during the 19th century, with copper and gold also becoming significant resources. The mining industry has since seen significant fluctuations in its share of Sweden's GDP over the past century. During the mid-20th century, mining accounted for around 6% of Sweden's GDP, driven largely by iron ore exports. However, as the global economy shifted towards manufacturing and services, mining's share of GDP declined. Today, the industry contributes around 0.3% of the country's GDP. Read more about the history and development of the mining industry in Sweden in the next section and the dams used within the mining industry in Chapter 4.2.

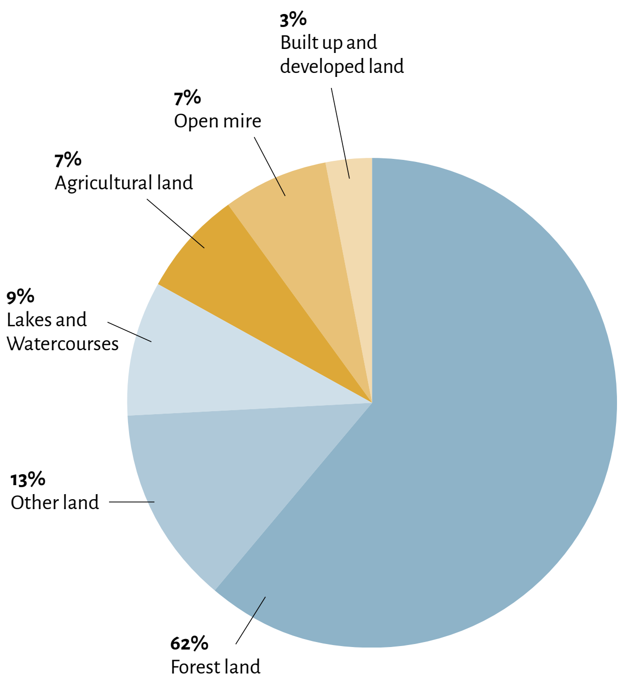
The largest iron ore deposits are found in the northern part of the country, particularly in the Kiruna region, where the state-owned company LKAB operates some of the world's most advanced and efficient mines. Iron ore is used in steel production, a crucial material for construction, machinery, and transportation.

Agriculture has played a crucial role in Sweden's economy for centuries, with early farmers relying on traditional techniques like slash-and-burn agriculture and crop rotation. However, the agricultural revolution of the late 18th century was a turning point for Sweden's economic growth and entrepreneurship. This revolution introduced large-scale and technically advanced methods of cultivating land, resulting in increased productivity for the agricultural sector. While this meant that some of the labor force became redundant, it also allowed individuals to move and work in the early industries.

The introduction of modern agricultural techniques such as crop rotation, fertilizers, and mechanization during the 19th century's industrialization period further revolutionized Swedish agriculture. This led to increased productivity and efficiency, making it possible for agriculture to keep up with the changing times. At the turn of the 20th century, over 50% of the Swedish population worked in the agricultural sector. Today, agriculture accounts for approximately 1% of Sweden's GDP, with the industry primarily focused on crop production and livestock breeding. Most farms in Sweden are large-scale operations, and the country's agricultural sector is characterized by specialization and technological innovation. Swedish agriculture is mainly located in the south and central parts of the country, with the provinces of Skåne, Östergötland, and Västra Götaland having the most fertile land. Common crops include wheat, barley, and rye, while cows and pigs are raised for meat and dairy products.

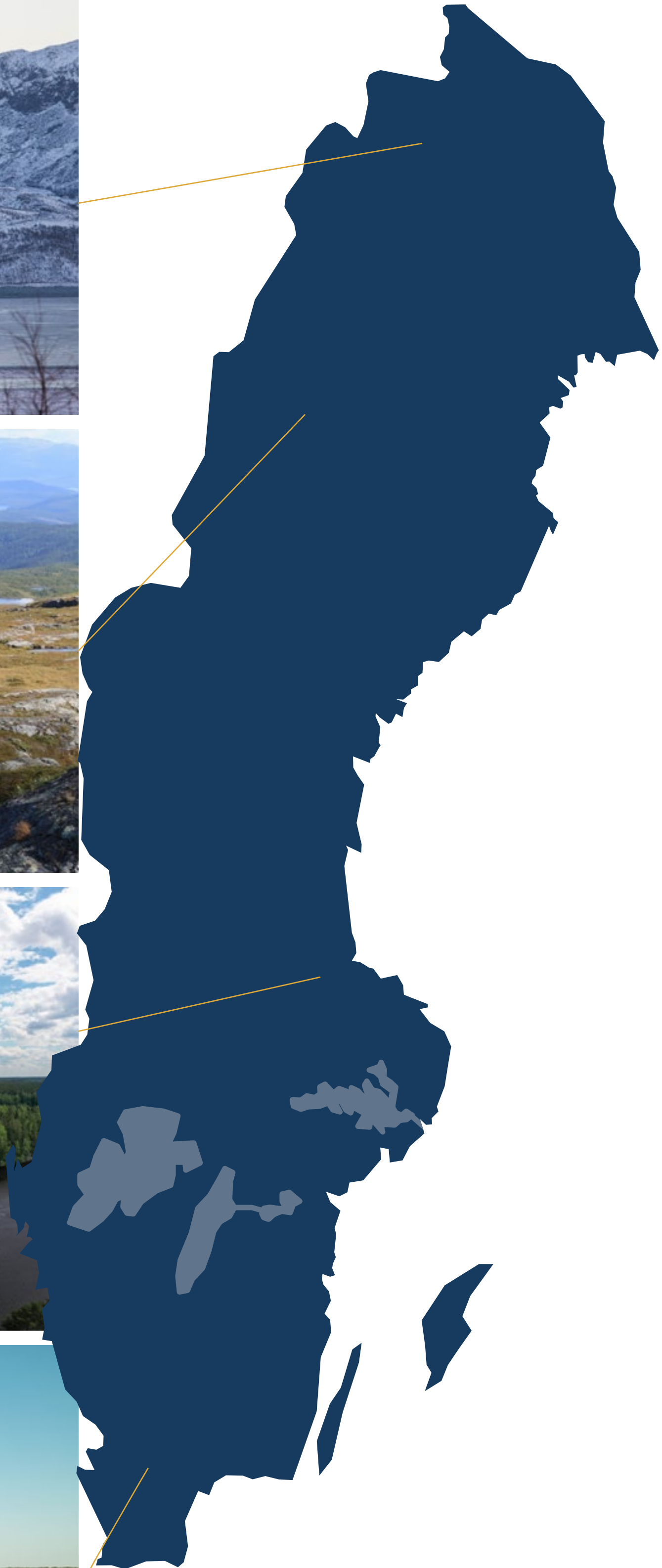
Sweden has over 100,000 lakes and more than 24,000 islands. These extensive water resources have also been critical in the country's electrification. Hydropower was another key natural resource that helped to drive Sweden's industrial development in the early 20th century. The country's many rivers and lakes provided an abundant source of renewable energy that was used to power factories and other industrial facilities.

Land and water areas







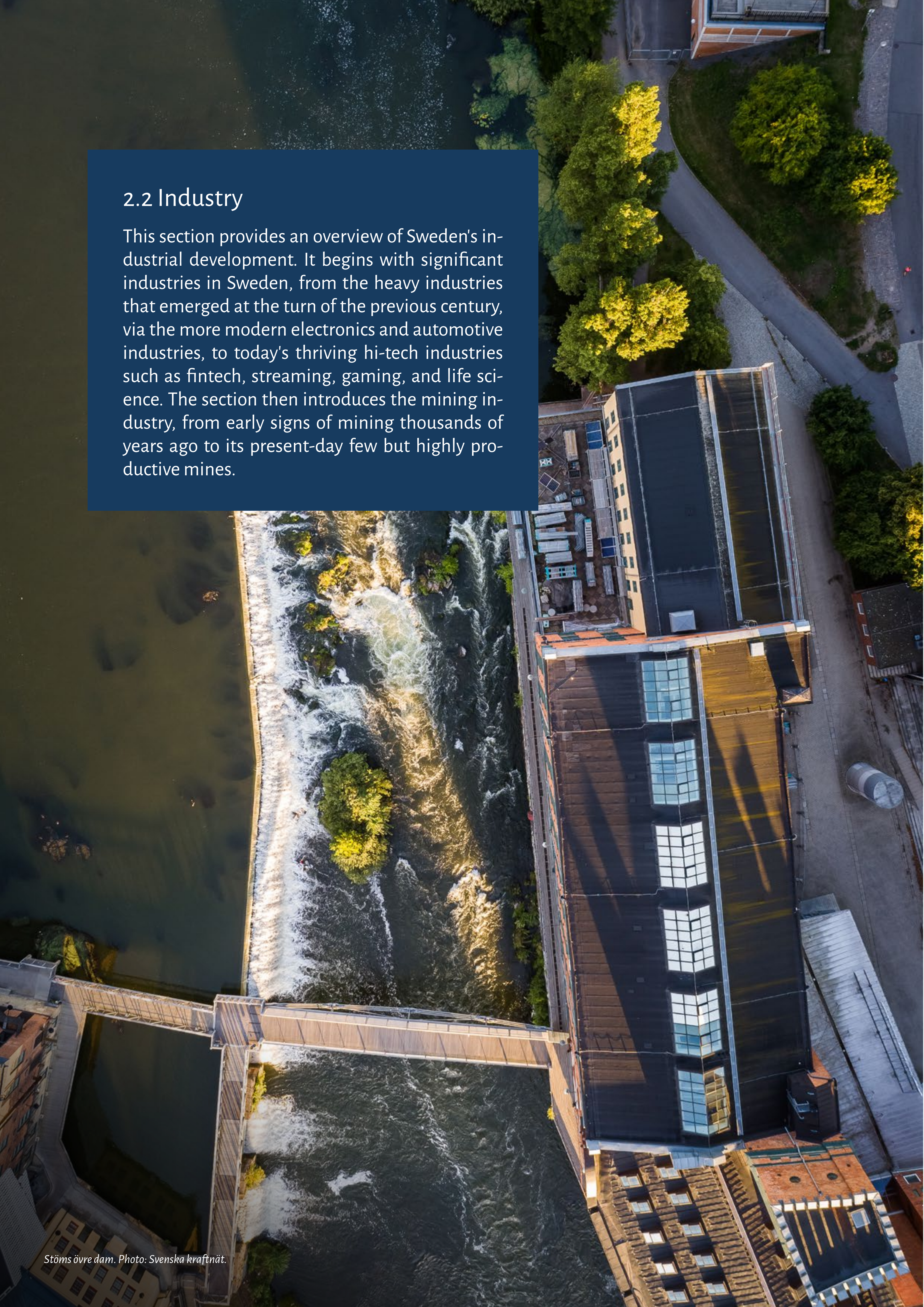


Longest north–south distance	**1 572 km**
Longest east–west distance	**499 km**
Land area incl. lakes and rivers	**447 500 sq km**
Population density	**23,5 pers./sq km**

Photos: Svenska kraftnät.

2.2 Industry

This section provides an overview of Sweden's industrial development. It begins with significant industries in Sweden, from the heavy industries that emerged at the turn of the previous century, via the more modern electronics and automotive industries, to today's thriving hi-tech industries such as fintech, streaming, gaming, and life science. The section then introduces the mining industry, from early signs of mining thousands of years ago to its present-day few but highly productive mines.



Stöms övre dam. Photo: Svenska kraftnät.

Industrialization

Sweden experienced significant economic growth during the first half of the 20th century, ultimately becoming one of the world's wealthiest nations by 1970. Two major events, coupled with Sweden's natural resources, were decisive in initiating this transformation: the free trade movement throughout Europe during the later part of the 18th century and the Second Industrial Revolution, which began in the 1890s, marked a shift from steam engines to electric and combustion engines in the industrial production process. These resources were instrumental in developing key industries such as steel production, paper and pulp manufacturing, and energy production.

The steel industry was particularly important to Sweden's economy in the early 20th century. The country's vast iron ore deposits enabled it to become one of the world's leading producers of steel. Companies such as AB SKF and Sandvik AB were founded during this time and became prominent players in the global market for industrial products. By the 1920s, Sweden was exporting large quantities of steel to countries around the world.

The paper and pulp industry also played a significant role in Sweden's economy in the early 20th century. The country's abundant forests provided a ready supply of raw materials for paper and pulp production. Companies such as SCA and Stora Enso were founded during this time and became leading producers of paper and pulp products. Sweden is still one of the world's leading producers of paper and pulp products, and the industry remains an important part of the country's economy.

The telecommunications industry began to develop in the late 20th century, with companies such as Ericsson and Telia becoming prominent players in the global market. The Swedish government invested heavily in research and development during this time, with a focus on developing a skilled workforce and promoting entrepreneurship.

The electronics industry also emerged in Sweden in the mid-20th century, with companies such as Electrolux and ABB becoming key players in the global market. These companies produced a range of consumer and industrial products, including appliances, electronics, and automation systems. Today, Sweden is home to a thriving electronics industry, with companies such as Axis Communications and Autoliv leading the way in video surveillance and automotive safety.

The automotive industry has been an important part of Sweden's economy since the early 20th century, with companies such as Volvo and Saab becoming well-known global brands. The country has a long history of automotive engineering and design, and today it is at the forefront of research and development in areas such as electric and autonomous vehicles. Companies such as Volvo Cars and Scania (owned by the Volkswagen Group) are leading the way in sustainable transportation solutions.

During the 1990s, Sweden's economy faced a major banking crisis and a sharp recession. However, the country recovered quickly due to its strong social welfare system and commitment to economic reform. The government implemented policies such as deregulation, privatization, and tax reforms to increase competitiveness and attract foreign investment.

Sweden's economy has also been impacted by globalization, with the country becoming increasingly integrated into the global economy. The country is a European Union (EU) member but has chosen not to adopt the Euro currency. Instead, Sweden has maintained its own currency, the Swedish krona, which has allowed the country to maintain greater control over its monetary policy.

In recent years, Sweden has continued to focus on innovation and technology to drive economic growth. The country has become a leader in areas such as sustainable energy, life sciences, and gaming. Sweden is home to several successful startups, such as Spotify, Klarna, and iZettle, which have achieved global success in the music streaming, fintech, and payments industries. The gaming industry in Sweden is also thriving, with companies such as King (creator of Candy Crush) and Mojang (creator of Minecraft) being based in the country.

Today, Sweden's economy is characterized by high innovation, productivity, and competitiveness. The country's economy heavily depends on exports, particularly in manufacturing, information and communications technology, and life sciences. Sweden has also made significant progress in promoting sustainable development, focusing on reducing carbon emissions and transitioning to a green economy.

Photo: Svenska kraftnät.

Mining

The history of mining in Sweden dates back over 2000 years, with evidence of metal work dating as far back as the 5th century. The still-operational Garpenberg mine, for example, is mentioned in records from the 14th century and the oldest known mine in Sweden, Lapphyttan, operated between 1150 and 1225. The early iron ore production took place in the in Bergslagen area in the central region of the country, where there were ample resources for iron works including iron-bearing rocks, fast-flowing rivers, and wood-rich forests. Over time, the process of extracting iron from ore advanced, and by the 16th century, the Swedish State took control of iron production to accelerate the transition from pig iron (crude iron) to bar iron. This led to Sweden becoming one of the world's leading producers of iron, with exports representing 70% of total Swedish exports in 1750.

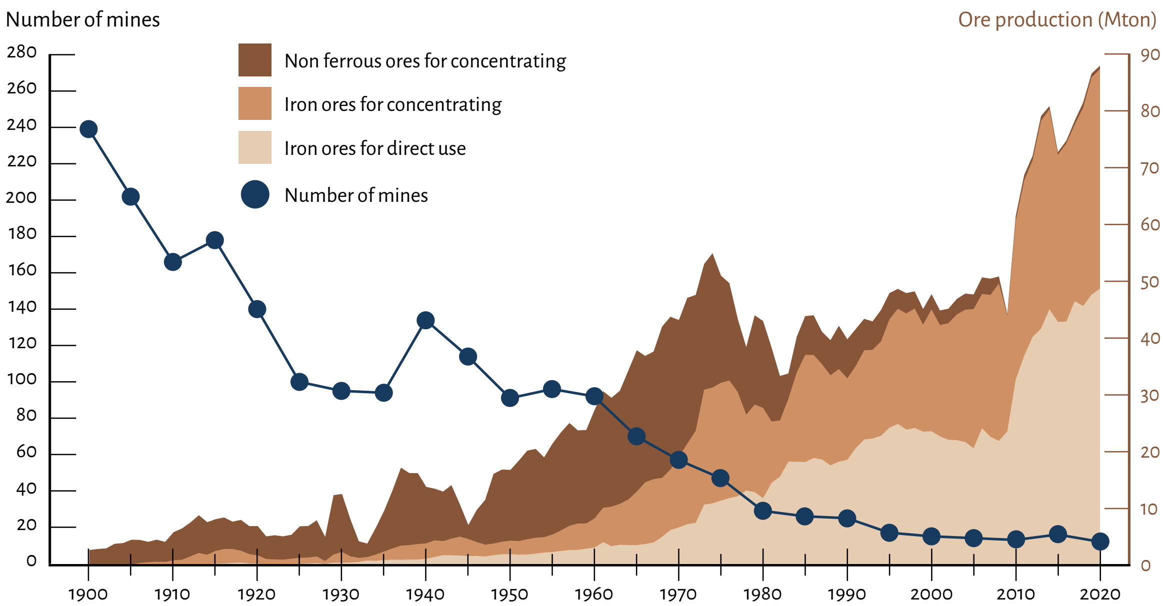
Today, the primary iron mining in Sweden takes place in the Norrbotten region in the far north of the country. This region's iron-rich content was known about as early as 1660, but it wasn't until the construction of a railroad between Luleå on the Swedish East coast and Narvik in Norway in the late 19th century that profitable iron ore production could occur. This led to the formation of the state owned mining company LKAB in 1890 and the region has been the backbone of Swedish iron production ever since.

As the mining industry progressed, so did the methods and technologies used. The number of active mines has decreased over the years, but the overall production rate has increased and become more automated. In 1910, the annual ore production from around 240 metal mines was nearly 5 million tons, while in 1960, production had increased to over 25 million tons from around 100 mines. Today, only 13 mines are in operation, but they have an annual production of about 90 million tons of ore. These mines produce, depending on the ore type, between 0.25% and 1.9% of the world's ore which equates to 11-89% of the European production.

The extraction of ore from the various Swedish mine sites involves both open-pit and underground operations. Once mined, the ore is transported to a processing plant where it is crushed, milled, and processed according to the particular type of ore. The waste product, known as tailings, generated at each processing plant, is to some extent used to refill the mine and the rest is deposited in a tailings management facility. This approach ensures the safe disposal of waste materials and reduces the impact of mining on the environment.

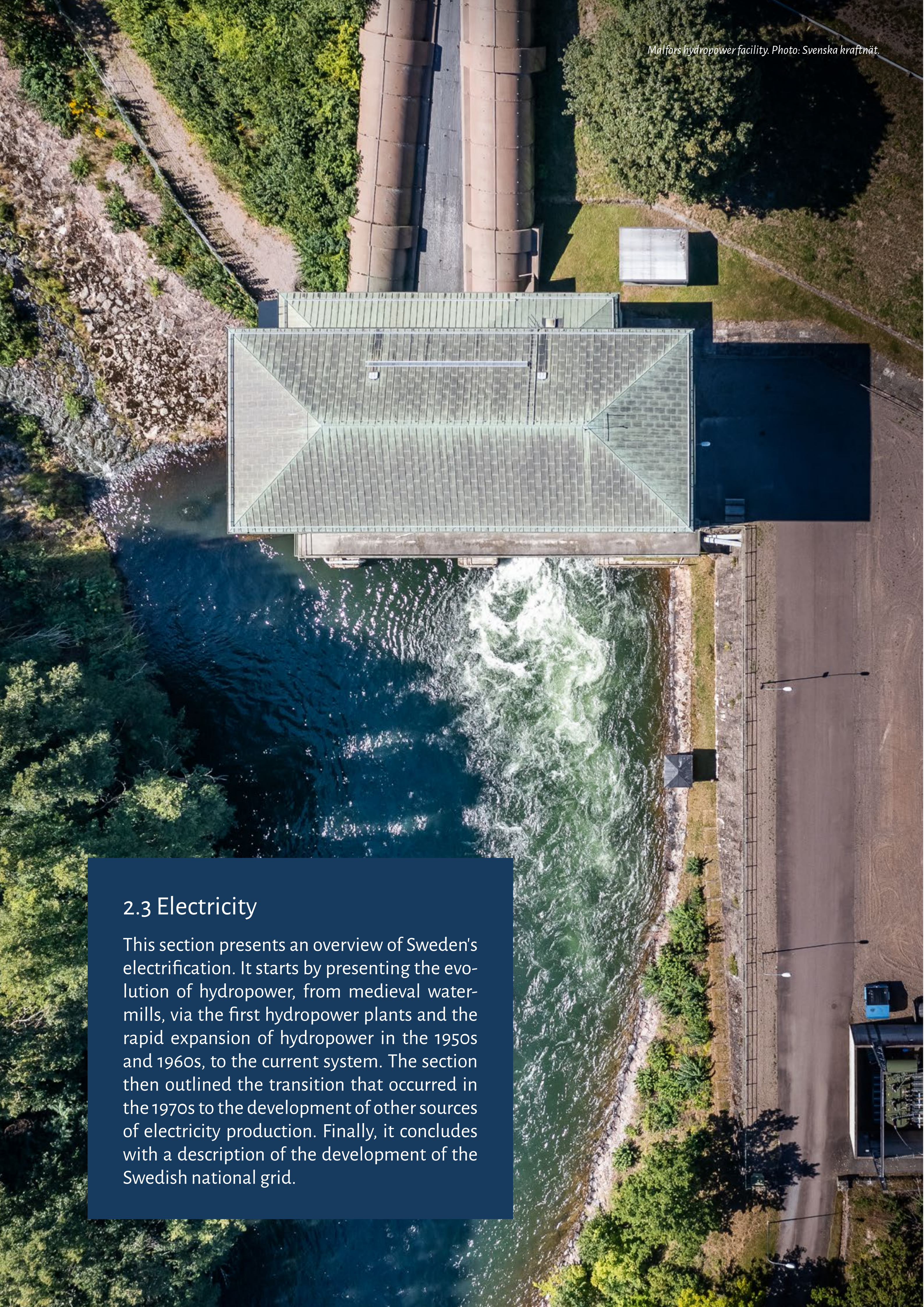
After this brief overview of Sweden's mining history, please refer to Chapter 4.2, which focuses on tailings management, including the design, construction, and operation of dams and facilities for this purpose.

Evolution of the Swedish mining industry from 1900 to present day. The number of mines (blue line) and the total production in million tons (brown) are shown



Björkdalsgruvan gold mine. Photo: Maria Bartsch.

Garpenberg Tailings management facility. Photo: Svenska kraftnät.



Malfors hydropower facility. Photo: Svenska kraftnät.

2.3 Electricity

This section presents an overview of Sweden's electrification. It starts by presenting the evolution of hydropower, from medieval watermills, via the first hydropower plants and the rapid expansion of hydropower in the 1950s and 1960s, to the current system. The section then outlined the transition that occurred in the 1970s to the development of other sources of electricity production. Finally, it concludes with a description of the development of the Swedish national grid.

Hydropower

The earliest examples of hydropower facilities in Sweden are watermills from medieval times. These mills used water-wheels to harness the power of flowing water and were often built adjacent to watercourses. The mining and hydropower industries were closely intertwined, and early mines were often powered by hydropower. During the 18th century, water wheels became Sweden's industry's dominant power source. Water facilitated the use of heavier and heavier machinery such as saws, hammers, stamping machines, and lathes. However, as the generated energy could not be transported, the power had to be used close to the water. To overcome this problem, mechanical systems were used for power transmission. In Sweden, the flatrod system (also known as the Konstgång or Stånggång), which was developed in Germany during the 16th century, became popular.

Development of hydroelectric power stations

By the 19th century, hydropower's relative importance in Sweden had decreased. Steam engines emerged as an alternative power source in the 18th century, quickly reducing the industry's need for hydropower while gas and kerosene lighted streets and buildings. However, after the development of tools and means of transmitting electricity over long distances, the electrification of Sweden began in the 1880s. Already in 1882, the first Swedish hydroelectric power station was put into operation. This marked the beginning of a rapid expansion in the size and number of hydropower stations. The early plants were primarily small-scale plants located near streams and rivers to power small industries and cities. Among the first large dams built for Hydropower were Knäred, Hylte, Porjus, and Älvkarleby were among the first large dams built for hydropower, and all of them are presented more in detail in Annex 1. However, it took until after the Second World War for the large-scale development of hydropower to start, and the annual addition of hydropower reached its peak during the 1950s and 1960s.

Local natural conditions greatly influenced the layout and design of the hydropower stations. You can read more about the natural conditions in Sweden in Chapter 3. The majority of Swedish hydropower is located in the rivers of northern Sweden. The rather flat water courses and wide river valleys that are typical of Swedish rivers seldom offer any natural sites for high dams. This, combined with relatively good geological conditions, meant that underground localization of the power station, combined with long tunnels, was often more economical than constructing several dams and stations along the river. As a result moderate heads, low dams, and long tunnels and canals normally characterize Swedish hydropower stations.

The outcome is a considerable number of underground hydropower stations were constructed, and most of the largest power stations are of this type. Whenever conditions allowed, the underground power station was located at a large depth near the dam, and the water was bypassed to the river through a tailrace tunnel. Head raise tunnels were used when this was not possible, or to interconnect tributaries by tunnels and convey the water to a joint station. Choosing an unlined tunnel with a larger cross-sectional area was usually deemed more economically beneficial than a smaller concrete-lined tunnel. Therefore, the tunnels are normally unlined and reinforced only where the rock is poor. Every turbine usually has a separate intake with trash racks and gates and a separate penstock. In stations with a headrace tunnel, there might be a special underground intake structure between this and the vertical or inclined penstock.

Ludvika Gammelgård, Östanberghjulet by Holger.Ellgaard is licensed under CC BY-SA 3.0

The Flatrod system

The flatrod system was a mechanical system used in the mining industry to transfer the power generated by a water wheel over short distances. The system consisted of a series of flat, horizontal rods connected by joints and bearings, and supported by wooden or metal frames. These rods could transmit power from the water wheel to other machines or pumps nearby.

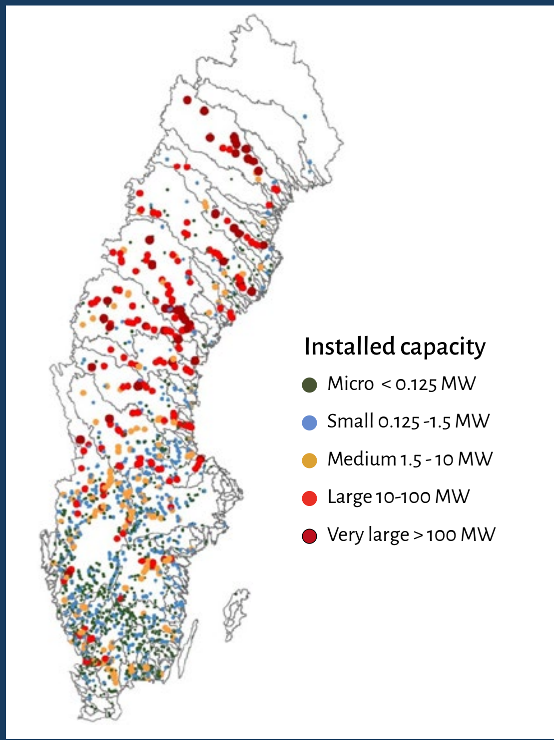
The Polhem wheel, named after its inventor Christopher Polhem, was an improvement of the flatrod system. It was an advanced system of gears that allowed for the efficient transfer of power over longer distances, and it was widely used in Sweden during the 18th century.

The Polhem wheel consists of a large gear driven by a water wheel, and a series of smaller gears transmitted power to other machines or equipment located at a distance. The system was highly adaptable and could be configured to meet the specific needs of different applications, making it a popular choice for various industries, including mining, sawmilling, and textile production.

Halt of further hydropower development

In the 1970s, the total annual production had surpassed 60 TWh. At this time, the gross theoretical hydro potential in Sweden based on topography and runoff data was estimated to 200 TWh per year, of which only 130 TWh per year were deemed technically possible and 95 TWh per year economically feasible to develop. However, the protection of the rivers Vindelälven, Kalixälven, Piteälven, and Torne älv from hydropower development, announced by the government in the 1970s, marked the beginning of the end of large-scale hydropower development in Sweden. The most economically profitable falls were already developed, and additional hydroelectric plants were completed at a decreasing rate during the 1970s and 1980s. From 1980 onwards, the annual production from hydropower has fluctuated between 60 and 80 TWh (dry and wet years); see plot on the page 36.

Today, Sweden has approximately 2100 hydroelectric power plants with a total installed capacity of 16,200 MW. About 200 hydroelectric power plants are large-scale or very large-scale, with an installed capacity of over 10 MW. These large-scale hydroelectric power plants account for 96% of the installed capacity and 94% of the annual power production.



The best conditions in Sweden for large-scale hydropower are found in the northern part. Here, the landscape falls slowly from the mountains in the west to the Gulf of Bothnia in the east. Many of the rivers are up to 500 km long and the difference in level between the reservoirs at the source and the mouth can be more than 500 m.

The Olidan power plant in River Göta älv was the Swedish state's first hydropower project (91 MW). For a long time, the state had plans to build hydroelectric power stations in the large rivers. However, there were concerns that there wouldn't be demand for all electricity produced. In 1909, The State Power Board was formed. In 1910, the first four of thirteen turbines were put into operation, ten of which are still in operation. Photo: Svenska kraftnät.

Photo: Svenska kraftnät.

Porjus hydropower facility

Over the years, increasing the installed capacity in existing power stations has also been common. In the early stage of hydropower development, power stations were designed to handle flow rates up to the mean annual flow of the river, resulting in significant discharge through spillways. The hydropower system utilizes regulation reservoirs, and modern stations are designed for short-term regulation and peak load production. For example, Porjus power station was initially constructed with a design flow of 80 m^3/s, corresponding to a factor of 0.3 between design flow and average runoff. Porjus was later expanded to a design flow of 340 m^3/s (factor of 1.24) in the 1940s and then further to a design flow of 1040 m/s (factor of 3.8) in the 1970s'. Porjus power plant is located below ground, on a site blasted out of the rock with the rated head of 59 m. Today, there are four units for electricity production: the active G11 and G12 in the new power plant, and U8 and U9, which are currently only used for research and development, in the old power plant from 1915.

Trängslet hydroppower facility - a long-term regulation reservoir in River Dalälven. Photo: Sten Bergström.

Untra hydro power facility - a short-term regulation reservoir in river Dalälven. Photo: Svenska kraftnät.

Schematic view of River Ljungan

Source: Vattenregleringsföretagen.

The Swedish Hydropower system

Similar topographic conditions and energy needs have led to a similar design structure in Sweden's major developed rivers. Most runoff occurs in spring, but energy demand is highest in winter with daily fluctuations. The major rivers feature large Long-term regulation reservoirs in the mountainous upper area, followed by a mix of small and medium-sized Short-term regulation reservoirs along the river.

Long-term regulation reservoirs

Large long-term regulating reservoirs are located at the upper portion of the river. These reservoirs are used to store water from season to season and even between years. The reservoirs capture the spring runoff from the mountain snowmelt, and when the electricity demand increases, this water can be released into the river and subsequently used by all hydro plants in the river.

Short-term regulation reservoirs

Small and medium-sized reservoirs along the river are used to meet the varying energy demand on weekly, daily, or even shorter time scales. These reservoirs provide the necessary flexibility for short-term energy needs.

Water regulation companies

Water regulation companies can be found in many of Sweden's major rivers that have been developed for hydroelectric power generation. These companies are jointly owned by all the hydropower producers in the river, and their purpose is to manage the shared interests of these producers. The responsibilities of the water regulation companies includes: overseeing the water management in the river, optimizing hydroelectric power production, monitoring hydrological conditions and making forecasts, as well as building, managing and operating the Long-term regulation reservoirs and their dam facilities.

Electricity production overall

When further expansion of hydropower was no longer sufficient to meet the growing demand for electricity, Sweden turned to other energy sources. In the late 1960s, the country began its nuclear power program, and in 1972, the first nuclear power plant, Oskarshamn 1, was completed. The program's success led to the construction of 12 nuclear power plants by the end of the 1970s, which produced about 40% of the country's electricity. Nuclear energy seemed to be a promising solution for Sweden's energy needs. Still, public concern over nuclear safety and environmental risks led to a decline in support for nuclear power, and no new reactors were built after the 1980s. Despite this, Sweden's six existing nuclear reactors still in operation continue to play a significant role in the country's electricity mix, producing around 30% as of 2020.

In recent decades, Sweden has increasingly turned to renewable energy sources, primarily wind power but also biomass and solar power. The country's first wind power plant was built in 1983, and today, Sweden has over 7,000 wind turbines with a total production of over 27 TWh during 2021. The country's largest wind power facility, the Markbygden wind farm, is expected to be completed in 2025 with around 1100 turbines and a capacity of up to 4000 MW. Markbygden is already the biggest wind farm in Europe and is on track to be one of the biggest onshore wind farms in the world.

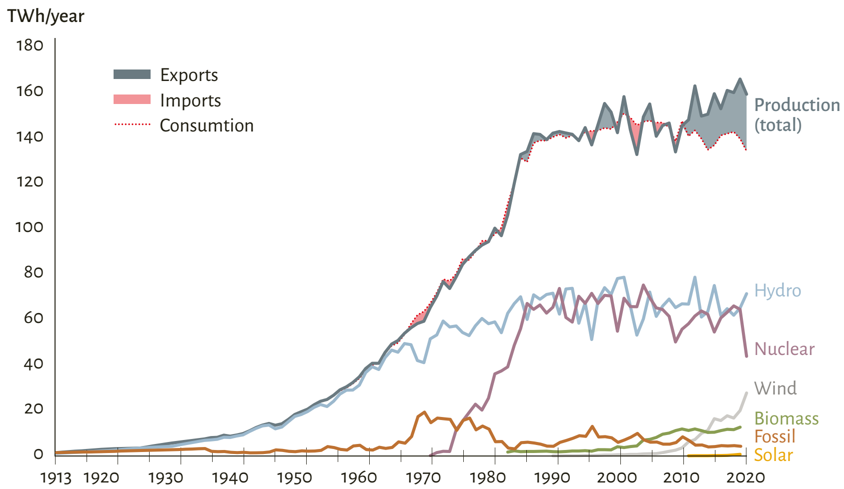
Biofuels currently account for a relatively small share of electricity production in Sweden. In 2020, approximately 12 TWh of biofuels were used for electricity production. However, biofuels have an overall significant role in Sweden's renewable energy mix, particularly for heating purposes. Over 50% of Swedish households are currently heated by biomass. This widespread use of biofuels for heating is not a recent development. The trend towards bioenergy in Sweden started in the 1970s when the country began searching for alternatives to fossil fuels due to their increasing costs and political instability. At that time, using wood for heating became an essential part of Sweden's energy mix. By the 1990s, biomass had become a significant renewable energy source in Sweden, and today biomass provides over 150 TWh of energy.

Finally, solar power has grown significantly recently, with several large-scale solar power plants being constructed. However, it still accounts for a small share of Swedish electricity production.

Sweden's total electricity production has increased significantly over the past century, from around 1,000 GWh in the 1920s to over 150,000 GWh in 2020. Per capita, electricity consumption has also increased, from around 300 kWh per person in 1920 to over 14,000 kWh per person in 2020.

Sweden's electricity demand is estimated to increase rapidly in the coming years, with some forecasts indicating a consumption that exceeds 300,000 GWh by 2045. This increase is primarily driven by the industry's transition in the face of climate change and the emergence of new electricity-intensive industries. This additional electricity consumption is not evenly distributed throughout the country, with the largest increase occurring in the northern parts of the country due to the electrification of the iron and steel industry.

Sweden electricity production



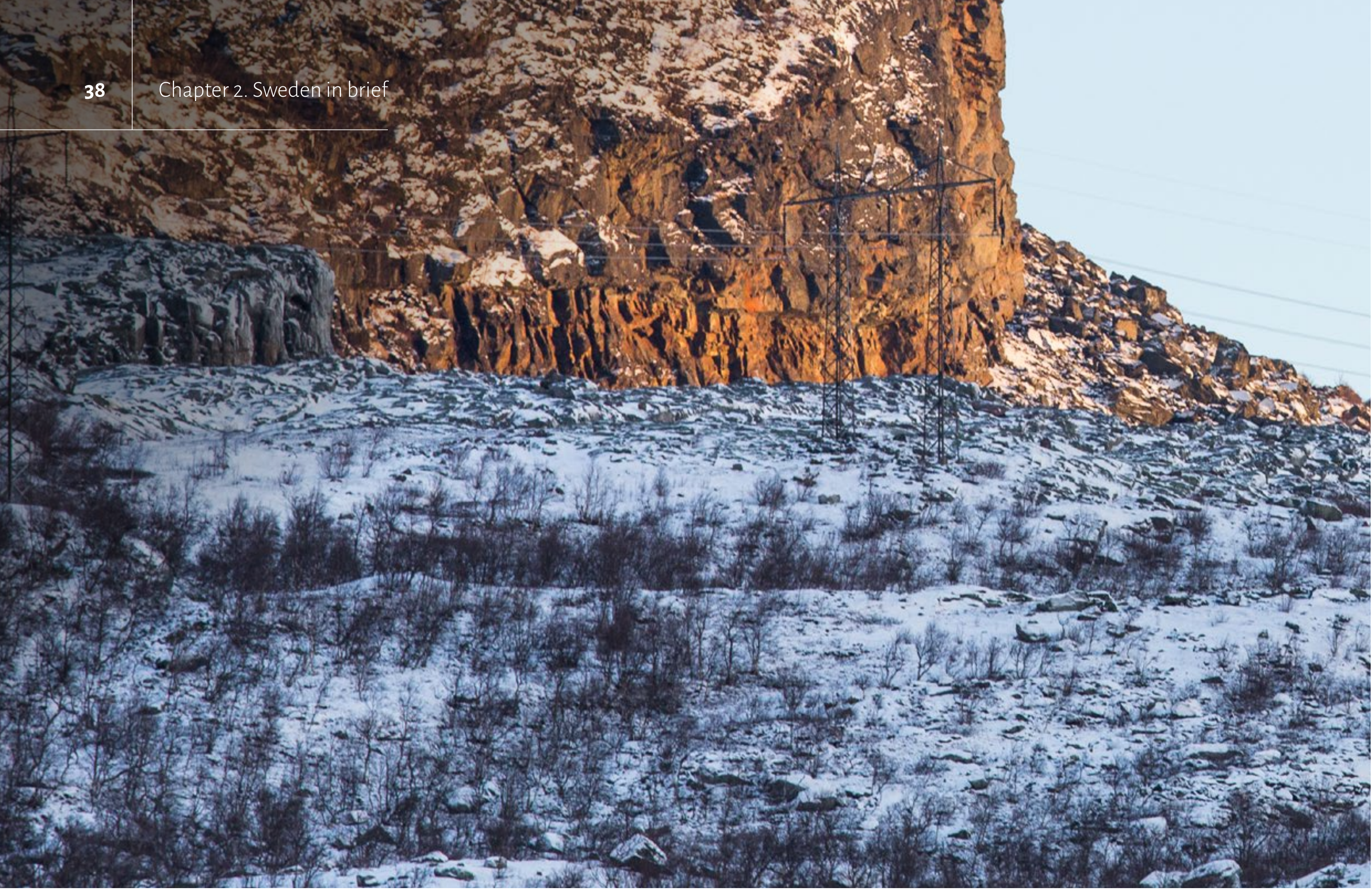
Source: SCB Statistik årsbok (1913–1969), Energimyndigheten (1970–2020), Electricity production in Sweden" by Kaj Tallungs, used under CC BY 4.0./ Changed color and axes types from original.

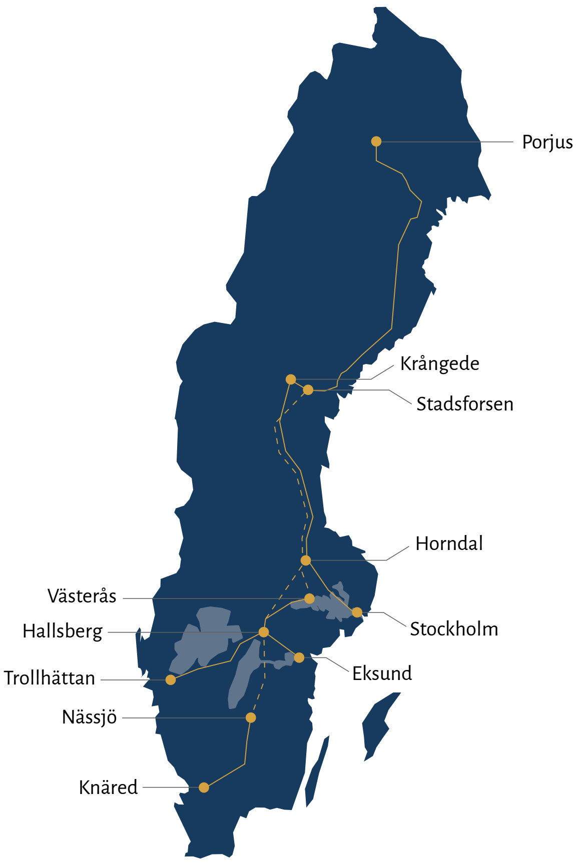
Energy supply and use in Sweden 2021, TWh

ENERGY SUPPLY, DOMESTIC	TWh
Biomass	151
Nuclear fuel	150
Crude oil and oil products	110
Hydropower	74
Wind power	27
Coal and coke	19
Natural gas, gasworks gas	12
Other fuel	14
Primary heat	5
Solar power	1
Import-export of electricity	-26
Total	**538**

Source: Energimyndigheten.

Photo: Svenska kraftnät.





The Swedish transmission network during the 1930s. Source: Vattenfall.

The national grid

In the early years of electrification, regional electric companies primarily built and operated Sweden's power grid. Vattenfall, which was founded in 1909 as a state-owned power producer with the original name the Royal Waterfall Board, quickly became one of the major players in the industry. Vattenfall played a key role in developing Sweden's transmission grid, which was initially built to connect Vattenfall's power stations to major cities and industries.

The different power companies initially had their own networks in geographically defined areas. Vattenfall had two extensive regional systems: Trollhättan and Älvkarleby. These two systems were connected in 1921 via Västerås using the so-called Western line, with record voltage of 130 kV at that time. This line formed what came to be known as the Central Block. However, in the early 1930s, there were still 15 more or less independent transmission networks in Sweden, and there were no lines between the northern part of Sweden and central Sweden.

To connect northern and central Sweden two major power lines were constructed in the 1920s and 1930s. The first, the Porjus-Boden-Stadsforsen power line, was completed in 1929 and was built to transmit electricity from the Porjus hydroelectric power plant in northern Sweden to the city of Boden, which is located approximately 70 kilometers to the east. From Boden, the line continued south to the Stadsforsen hydroelectric power plant. The second line was constructed in 1936 to transmit electricity from the Krångedefallen hydroelectric power plant on the Indalsälven river in northern Swe-

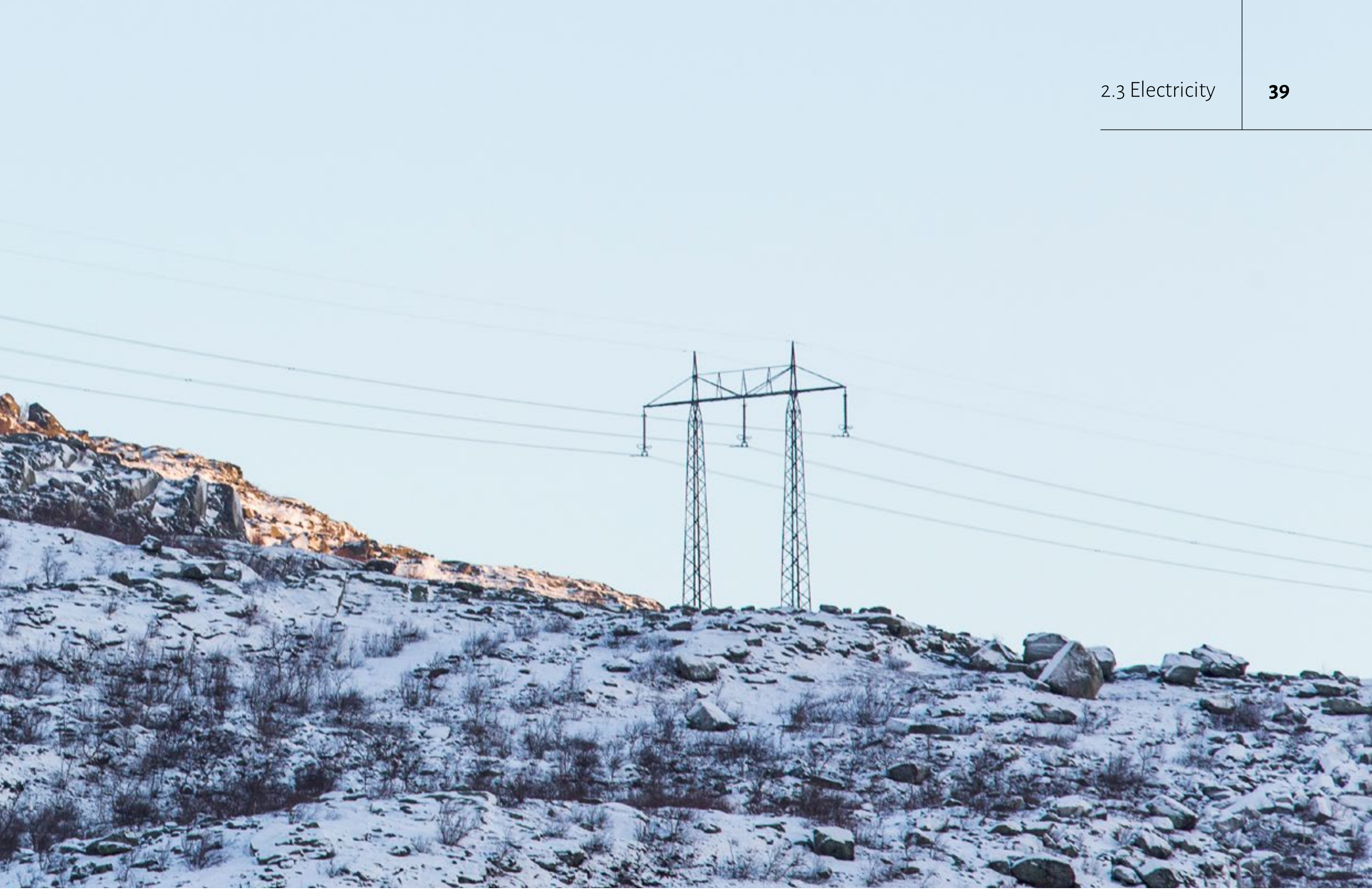


Photo: Svenska kraftnät.

den to the Horndal transformer station in the central part the country via Sweden's first-ever 220 kV transmission line. This transmission line also connected the Porjus-Boden-Stadsforsen line with southern Sweden. As a result, the entire power grid in Sweden was interconnected for the first time, stretching from Norrbotten in the north to Skåne in the south.

At this time, multiple companies aimed to construct transmission lines to connect Sweden's northern and central parts. However, a government investigation in the late 1930s led the power industry to collaborate. The complete grid was operated jointly for the first time in 1938.

After the war, Vattenfall and other power companies wanted to form a new joint venture to plan and expand the transmission network. However, the government opposed and instead, Vattenfall was given a monopoly in 1945 to build and own the 220 kV and 400 kV lines, and the other power companies could use the system through a trunk line agreement.

1945, the decision was made to construct the Harsprångslinjen, a major power line running 1000 kilometers between the hydroelectric power plants on the Lule River and Hallsberg in southern Sweden. The line was planned with a voltage of 380 kV to connect the northern and southern parts of Sweden's electricity grid.

Harsprångslinjen was critical in connecting the two parts of Sweden's power grid at a higher system voltage than the existing 132 kV lines. It was put into full operation in 1951, coinciding with the commissioning of the first two generators at the Harsprånget hydropower plant. It was the world's first high-voltage power line with a voltage of 400 kV and was put into operation in 1952.

By the end of the 1960s, there were six transmission lines from Indalsälven and southward. The transmission network underwent several expansions over the years, greatly improving Sweden's power grid's efficiency, reliability, and resilience. Today, there are 12 transmission lines connecting the north and south of Sweden, with the latest completed in 1989.

In the 1980s and 1990s, the Swedish government began deregulating the electricity sector, allowing for greater competition and private investment. As a preparation for the deregulation of the electricity market, Vattenfall became a limited liability company and in 1992 the transmission grid was separated and transferred to a newly formed agency, Svenska kraftnät. Today, Sweden's transmission grid is one of the most advanced and reliable in the world. The country has a highly interconnected transmission network, with high-voltage transmission lines stretching across the country and linking Sweden to neighboring countries. The grid, with a total length of over 15,000 kilometers, is still operated by Svenska kraftnät.

The transmission grid for electricity 2021

The Swedish transmission grid consists of about 16,000 km power lines, more than 175 transformer and switching substations as well as AC and HVDC interconnectors.

Svenska kraftnät’s activities

Our society is dependent on electricity. Svenska kraftnät is responsible for ensuring that Sweden has a safe, environmentally sound and cost-effective transmission system for electricity – today and in the future. We achieve this in the short term by monitoring the electrical system around the clock, and in the long term by building new power lines to meet tomorrow's electricity needs.

We are responsible for the national grid

The government has assigned Svenska kraftnät the task to maintain and develop the Swedish national grid for electricity. The national grid power lines transport electricity from wind, hydro and nuclear power stations to regional and local electricity networks, which in turn transmit the electricity on to the consumers.

We balance production and consumption in the electricity system

At all times, there must be a balance between the electricity produced and consumed in the electricity system. If the balance is disturbed we risk major disruptions in the grid with serious consequences. Svenska kraftnät is responsible for keeping this balance. Therefore, we work around the clock in our control rooms, where we monitor that the amount of produced and consumed electricity are the same.

We contribute to make sure electricity trading works smoothly

We have also been commissioned by the government to work to ensure that electricity trading can take place as smoothly as possible, and in free competition. This applies to trading both within the Nordic countries and with other European countries. In the EU, we are helping to create a single European electricity market.

We contribute to achieving energy and climate targets

Svenska kraftnät has an important role in Sweden's efforts to achieve the goals of energy and climate policy. We will develop energy efficient and environmentally sound solutions for the transmission of electricity on the national grid. We do this for example by conducting and supporting research in green technology.

The EU has set the goal that the share of renewable energy in the EU must be at least 27 percent in 2030. Svenska kraftnät facilitates the expansion of renewable energy by strengthening and expanding the national grid for electricity. For example, we are building new power lines to make it possible to connect new large wind farms to the national grid. That way those wind farms become part of Sweden's electricity supply.

We build new power lines

Connection of renewable energy is one of the reasons that we are currently reinforcing and expanding the grid at several locations in the country. Another reason is to promote competition in the electricity market where electricity is bought and sold. In order for the electricity market to operate more efficiently and with free competition, we are eliminating so-called "bottlenecks" in the Nordic electricity network and the networks that connect us with the rest of Europe. Bottlenecks are narrow passages in the network that we need to strengthen in order to transmit more electricity. Learn more about how we develop the grid.

We ensure that the electricity supply canhandle serious strains

Svenska kraftnät is Sweden's Authority of Electricity Contingency Planning. This means that we are working to ensure that electricity supply is prepared for extreme events that may pose serious strains on society. For example there may be large storms and fires, dam accidents and acts of terrorism. We make sure that measures are taken to enhance our preparedness, that there are trained professionals and that resources are available for repair work and communication equipment.

We promote dam safety

In the role as national dam safety authority, Svenska kraftnät acts for a future with safe dams and coordinated preparedness for dam failures. We contribute to national coordination and development through clear requirements, guidance and follow-up. We provide supervisory guidance to the county administration boards in matters of dam safety according to Chapter 11 in the environmental code. We promote capacity building through research, development, education and information in collaboration with stakeholders. We follow up the progress and report to the government annually.

We support and conduct research

Svenska kraftnät supports and conducts research and development that will enhance the reliability, efficiency and sustainability of the national grid. We also support research in dam safety. One of the research projects is about finding smart solutions for keeping the electricity balance when more wind power is connected to the power system. More wind power requires new solutions since the energy from wind power is weather dependent and cannot be stored.

Source: www.svk.se

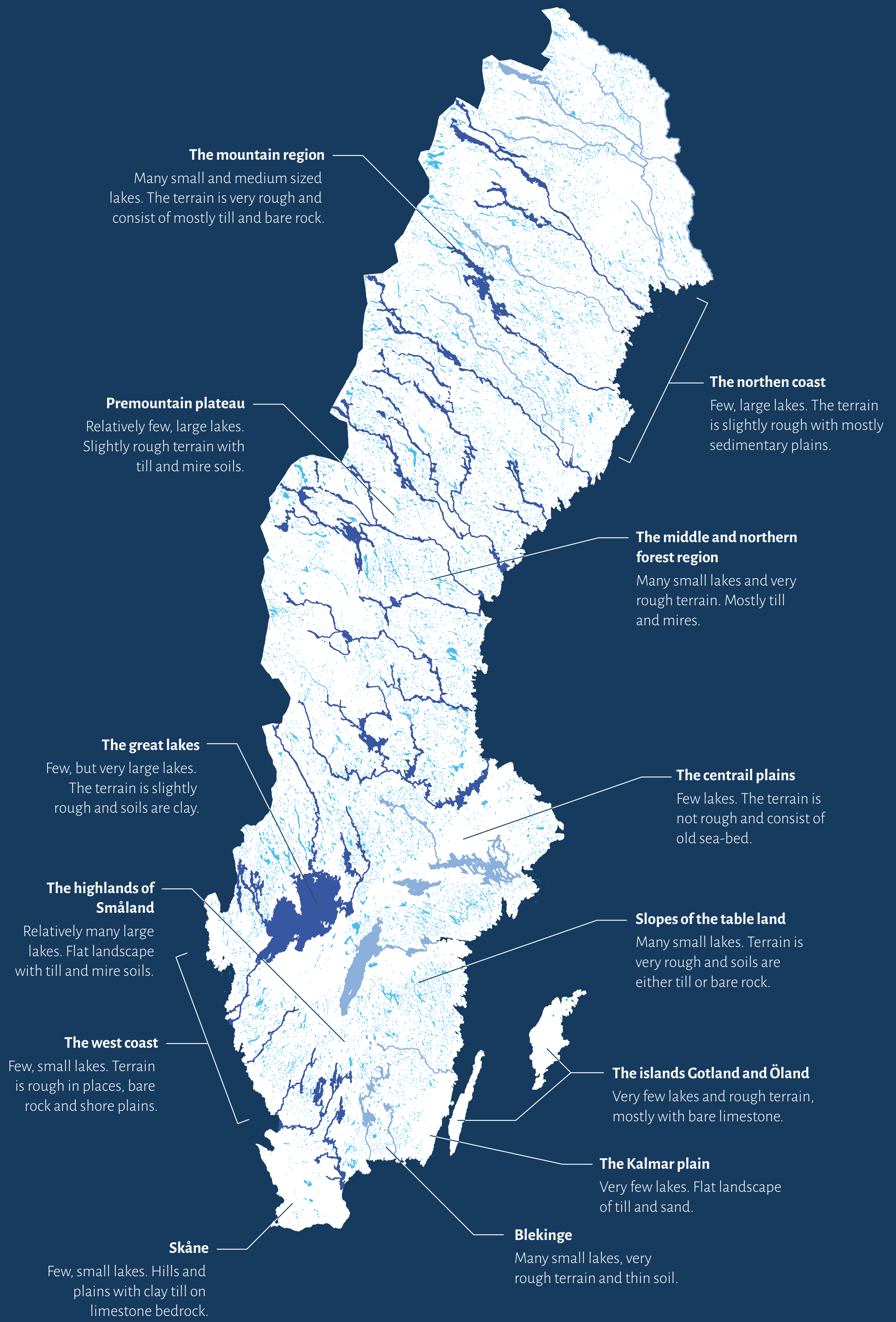
One of the dams at Lanforsen hydropower facility, River Dalälven.

3.
The nature

3. The nature

This chapter describes Swedish nature, water resources and climate.

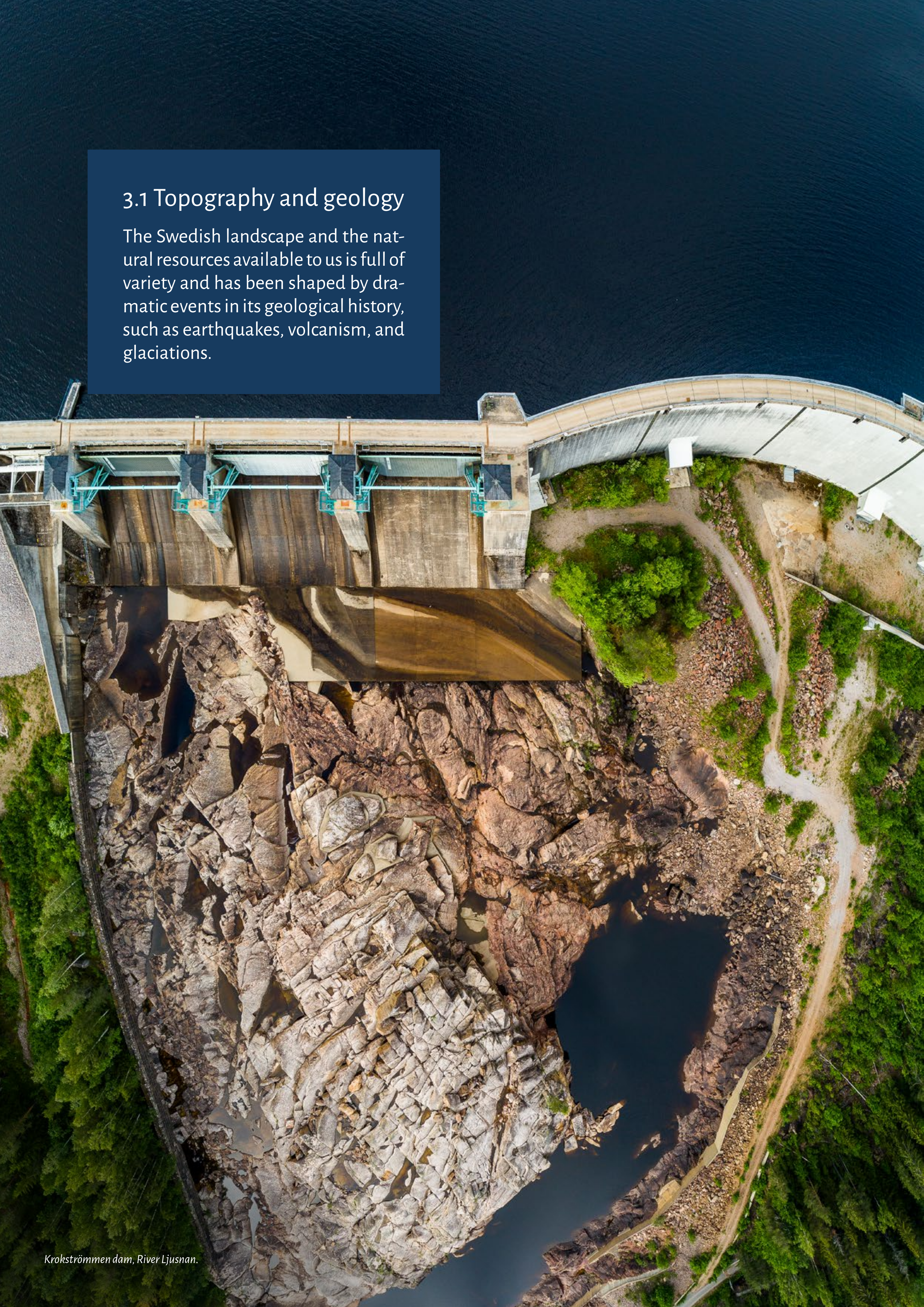
First Sweden's geology and traces of the latest ice age are introduced. After that, the focus shifts to today's landscape and climate, in particular water resources and their seasonal and regional variations. Observed climatologic trends are presented together with a brief overview of the milder and wetter conditions indicated by climate scenarios.



Characteristics of lakes and terrain. There are more than 100.000 lakes in Sweden covering 40.000 km², corresponding to more than 9% of the country. Source: Climate, Lakes and Rivers. National Atlas of Sweden, 1995.

3.1 Topography and geology

The Swedish landscape and the natural resources available to us is full of variety and has been shaped by dramatic events in its geological history, such as earthquakes, volcanism, and glaciations.



Krokströmmen dam, River Ljusnan.

Historical shaping of the landscape

The periods with inland ice and deglaciation have eroded the bedrock and in connection with that partially reshaped its surface, as well as moved and re-layered the previous weathered soils. Examples of such erosion forms are U-valleys and round outcrops. The material once picked up by the ice sheet was deposited mainly as moraine when the ice melted. Thus Sweden's most common soil type is till covering about 75 % of the landscape.

Geology

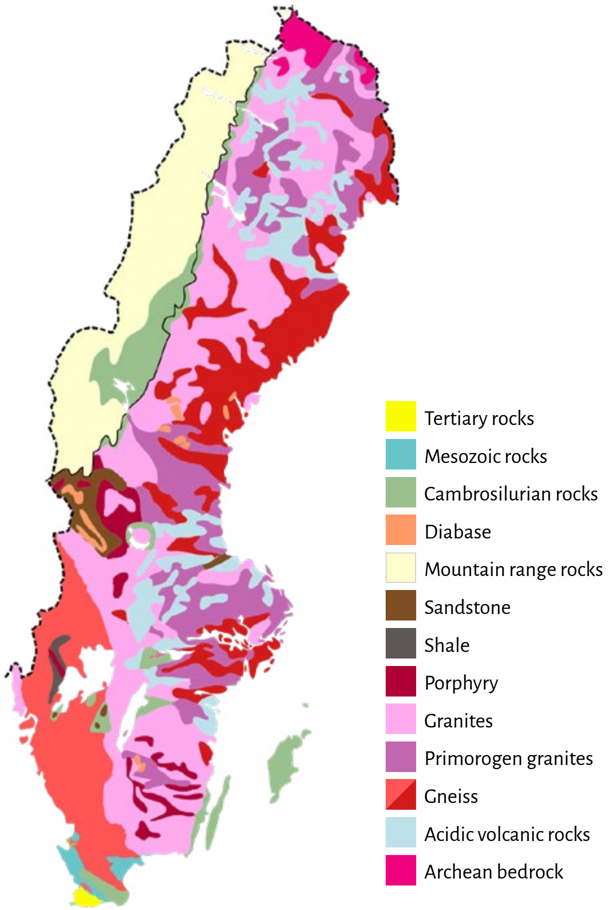
Sweden is part of an area of primordial rocks consolidated over hundreds of millions of years. The bedrock has since been exposed to several major changes in both pressure and temperature. Through this, the rock mass has been affected so that it has cracked open, folded and in some cases reconstituted. The most common rocks are gneiss and granite (pink to red in the bedrock map below) but the variety of rock types is large.

Sedimentary rocks such as sandstone and limestone mainly cover parts of Skåne in the very south, the great island Öland and Gotland in the Baltic sea but also the edge of the mountain chain "the Scandinavian mountains" in the north west as well as some minor parts of southern Sweden close to the great lakes (green color in the bedrock map).

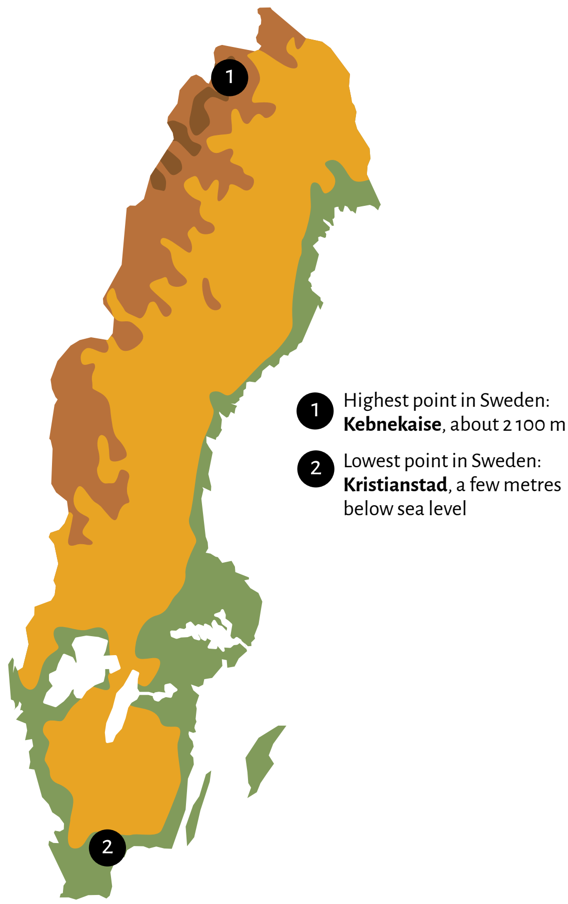
The mountain chain of today, forming the border to Norway, is the roots of an ancient heavily eroded mountain chain.

Sweden's highest point is **Kebnekaise**, about 150 km north of the Arctic Circle, at about 2100 m. The Kebnekaise massif has two peaks. The southern glaciated peak is traditionally said to be 2,111 meters, however the glacier is melting and therefore the summit is not as high as earlier. In 2019, for the first time, measurements showed the north peak at 2,097 m, that is free from ice, to be higher than the south peak.

The lowest elevation in Sweden is located in the former bay of **Lake Hammarsjön**, near **Kristianstad** at −2.41 m. The bay was drained in the 1860s to get more arable land for Kristianstad.



Simplified map of the bedrock of Sweden. Different types of gneiss and granite are the most common rock types. Source: SGU.



Simplified elevation map of Sweden.

Winter in Sarek and Padjelanta national parks, catchment area of River Luleälv. Photo: Uno Kuoljok.

Quaternary geology

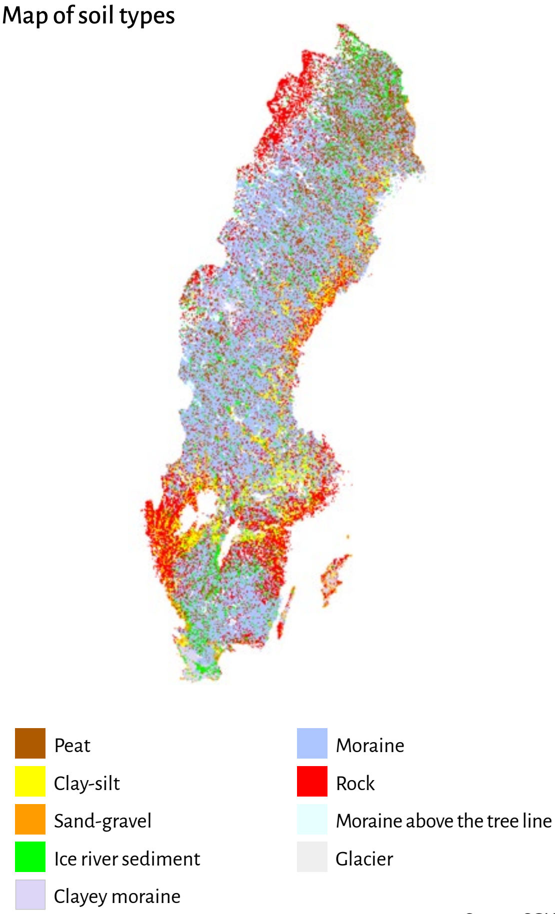
The bedrock in Sweden is covered by soil which is extremely varied in nature. Almost all soil types were formed in the quaternary era. This period began about 2.5 million years ago and extends to the present time. Most Swedish soils were either deposited during or after the last ice age.

The deglaciation

The last Ice Age began 115,000 years ago, and the last ice disappeared from northern Sweden approximately 10,000 years ago. During the peak of this ice age, most of northern Europe was covered by an ice sheet that slowly moved across the landscape. Inland ice, and other glaciers, were formed from the accumulation of snow over many years and transformed into ice. In the central parts, the inland ice mass had a thickness of kilometers. The thick ice eventually became plastic and highly viscous from the pressure of its self-weight. This caused transportation from the central parts of the ice sheet towards the edges, where the ice melted or broke off as icebergs. During this process, the ice carried material from the bedrock and older soils to the edges of the ice sheet, where the material was disposed. Soils formed during the ice age are commonly referred to as glacial, while those formed later are commonly referred to as postglacial.

It took almost 12,000 years from the time the ice began to retreat from northern Germany until the deglaciation was complete and the last ice residue disappeared from the most northern part of Sweden. The deglaciation processes have shaped Sweden's landscape and soil compound.

Map of soil types



Source: SGU

Moraine - traces of the inland ice

The ice edge retreated primarily in the south to north direction. However, the inland ice moved constantly from north to south during the retreat. The material transported by the ice was disposed as moraine at the melting edge. The Swedish moraine soils consist of material containing a mixture of all grain sizes, from clay particles up to giant blocks. However, moraine, dominated by sand and silt, is by far Sweden's most common soil type. In most parts of Sweden, this moraine is also the oldest soil type and is located directly on the bedrock.

The melting ice caused large amounts of water to form rivers in the ice, eroding and transporting material. Near the edge of the ice, the transported material sank to the bottom, forming ice river sediments. The most well-known ice river deposits are the eskers, i.e. ridges of stone and gravel. The ice river deposits are mostly built up of sand and gravel. Large amounts of fine-grained material (clay and silt) was transported further out from the edge of the ice and settled at the bottom of the lakes and the sea.

Plants and animals quickly established themselves in ice-free areas. The temperature increased until about 6,000–7,000 years ago, when the summer temperature was a couple of degrees higher than today's. The southern half of the country was, at this time, largely covered by deciduous forest. This period is sometimes referred to as the Holocene Climate Optimat, during this time large parts of the world experienced a warmer climate. After that, the temperature gradually dropped to stabilize at a lower level about 2,000 years ago. The colder temperatures in Sweden led to the coniferous forests expanding at the expense of the deciduous forests.

Thanks to Sweden's climate and geology, especially the many sand and gravel deposits in the form of, for example, pebble ridges, there is good access to good and easily abstractable groundwater. Almost half of Sweden's drinking water consists of groundwater or so-called artificial groundwater, i.e. water from lakes, rivers and rivers filtered through gravel deposits.

Moraine

The moraine has been formed by direct material deposition from the ice sheet. This means that the material has not been subjected to any actual grain size sorting, thus moraine is an unsorted soil with rock and blocks scattered in a fine-grained ground mass. Moraine soils usually consist of angular material containing a mixture of all grain sizes, from clay particles up to giant blocks. In large parts of Sweden, moraine is dominated by sand and silt. This moraine is by far Sweden's most common soil type, and the area is often used for forestry.

The mineralogy and grain size composition of the moraine are influenced by the local bedrock. In areas with hard and hard-to-crush rocks, the moraine is often blocky and coarse-grained. In some parts of Sweden there are relatively young, easily eroded, sedimentary rocks that have been effectively crushed down by the ice sheets. In such areas, often used as arable land, fine-grained, block-poor moraine clay is often found.

Coarse-grained moraines – sand moraine and gravel moraine – behave mainly like friction soils, while fine-grained moraines – clay moraine and silt moraine – have more cohesion soil character. To be suitable for use as impervious core in embankment dams, and meet requirements of water tightness and processability the moraine should be of silty to sandy type and be free of stones when laid out.

Moraine pit. Photo: Hans Rönnqvist.

Construction of new till core at Burvattnet dam. Photo: Tina Påhlstorp.

The highest coastline

The highest level, which was covered by water during the deglaciation, is usually called "the highest coastline". The level of this coastline varies and is higher above today's sea level in northern Sweden compared to southern Sweden. This is because the ice sheet was thicker in northern Sweden and thus could push the earth's crust down to lower levels. Areas that were covered by (sea) water after the last ice age, but are on dry land today, are shown in darker blue on the map. The figures indicate the height of the highest coastline above today's sea level in meters.

Land uplift

The kilometer-thick ice caused a heavy load on the earth's crust. The ice melt removed this pressure, and as a result, the land started to rise to find a new state of equilibrium. 10.000 years ago, after the melting of the ice, most of Sweden was covered with water. Therefore, relatively large parts of Sweden are made up of land that was previously under water. Through land uplift, many of the former seabeds and lake bottoms have been drained and in many areas form flat clay plains, often used as agricultural land. So far, the land has risen several hundred meters.

Since the ice sheet was greatest in the central parts of Scandinavia, also the land uplift is greatest there. At the highest point, the old seabed can today be found at 286 meters above sea level. The land uplift is still ongoing in Sweden at varying speed. The fastest uplift occurs in the north along the coast of the Baltic Bay (around 10 mm/year) and the slowest in the very south where there is no uplift.

As the land rises, previously formed soils are exposed to waves and currents. This is evident especially at slopes and altitudes where exposure to waves has been high. Therefore, moraine at and below the highest coastline is often completely or partially re-layered by the waves, and sand and gravel that were washed out from the moraine by wave action are today often found on the slopes below the highest coastline.

Photo: Uno Kuoljok.

Rock carvings from the Stone Age at Nämforsen

About 6 000 years ago, during the Stone Age, when it became possible to make the rock carvings, Nämforsen was the first rapids in the Ångermanälven river at the end of an approximately 60 km long sea bay. At Nämforsen, fresh and salty water, inland and coast, met. On the rocks in and by the rapids, the hunting and trapping people of the Stone Age carved their pictures. Here you find one of the largest collections of rock carvings in Europe, with about 2 600 different figures and lines. Since then, land uplift and erosion have changed the landscape. Today, the river's water level downstream of Nämforsen hydropower dam is about 70 meters above sea level. On both sides of the rapids there are remains of settlements from the Stone and Bronze Ages.

Source SGU.

Smooth rock in the Stockholm archipelago. Photos: Maria Bartsch.

Dalkarlsdammen in Garpenberg. Photo: Svenska kraftnät.

The right of public access – “Allemansrätten”

Sweden is filled with forests and open landscapes and one of the unique joys of living in or visiting Sweden is *allemansrätten*, or the right of public access. It allows anyone to roam freely in the countryside, swim and travel by boat in someone else’s waters and pick mushrooms and berries in the forest.

Although landowners can put up signs to exclude visitors from certain private lands, and areas that are particularly vulnerable to damage are always off-limits, the general rule is that visitors are allowed to walk across lands at a reasonable distance from houses, yards, gardens and fenced-in areas. With this right comes the responsibility to tread carefully and to show consideration for landowners and others.

As long as the land is not cultivated, and no damage is caused, this means that most of Sweden’s nature is yours to explore. Except for the area nearest a person’s house, you’re even free to camp or park a motor home on another person’s land for up to 24 hours. After this, you’ll need the landowner’s permission to stay.

Because it has existed for generations, *allemansrätten* is a part of the national identity of Sweden. School groups explore the forests from an early age and families often fish, pick berries or go for walks in the woods together. And nearly everyone knows where to find their secret patch of favorite mushroomes.

Lakes and rivers

More than 100 000 lakes and an abundance of rivers and streams give the Swedish landscape its unique character and beauty. A large river has typically a length of 300–500 km, an annual mean flow of 200-400 m^3/s and a head drop exceeding 500 m along the whole river. Almost all large rivers are in the northern half of Sweden with a flow direction from western mountains to the east in the Baltic Sea.

Already in the mountains there are often lakes which in some cases have considerable size. Downstream of the mountain area the character of the rivers often changes between lakes and stream stretches. Vertically dropping waterfalls are rare. Thus, the typical Swedish river has a mean slope around 1 m/km, which is much less than rivers in mountainous areas in Norway and in the Alps. But it is also a higher slope than many of the large flatland rivers in Europe like e.g. lower Rhine and lower Donau.

All but four of the large Swedish rivers have been exploited for hydropower purposes ; the rivers that have been spared are River Torneälv, River Kalix älv, River Pite älv and River Vindelälv (a major tributary to River Ume älv).

Sweden’s great lakes have developed in different ways over the millennia and are still affected by land uplift. The north shore of lake Vänern is rising in relation to its outlet, so that the lake is losing water and becoming smaller and shallower. The difference amounts to some 5-10 cm over a period of 100 years. Lake Vättern is deep with steep shorelines. Its outlet is in the north, which means that the lake is tilting towards the south with about 14 cm over a period of 100 years, causing more frequent problems with flooding of roads etc in the south end of the lake. Lake Mälaren was a sea bay for a very long time, but as a result of land uplift it gradually turned into a fresh-water lake around the 10th to the 13th century. Today the mean water level is only about 0,7 m above the mean level of the Baltic Sea and eventually the sea level rise will turn Mälaren into a sea bay again.

Largest lakes

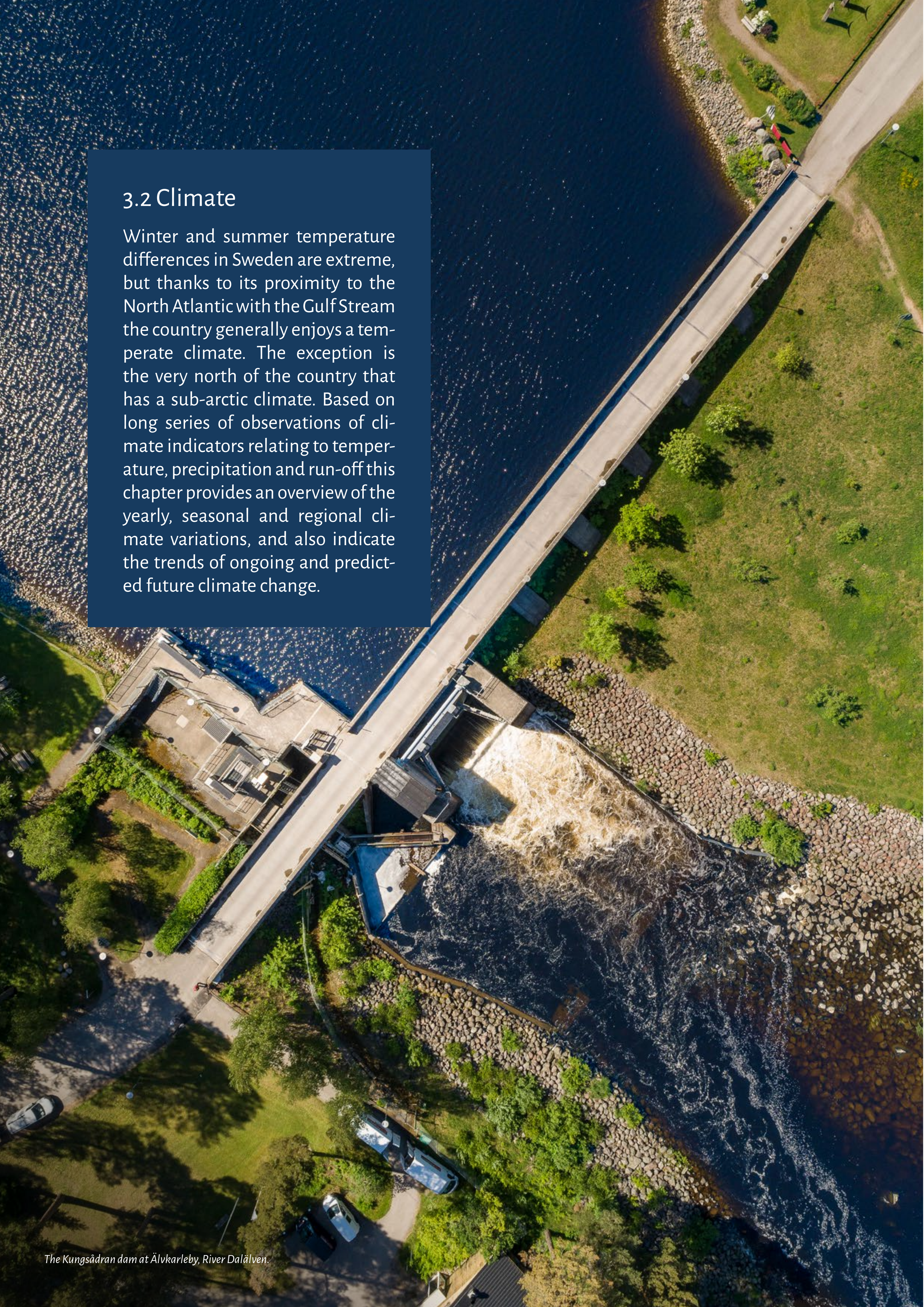
LAKE (NAME)	AREA (m²)	DEPTH (m)	VOLUME (km³)
Vänern	**5 648**	106	**153 000**
Vättern	**1 899**	120	**77 640**
Mälaren	**1 122**	66	14 300
Hjälmaren	484	18	3 000
Storsjön	464	74	8 018
Torneträsk	330	**168**	**17 100**
Siljan	290	134	8 089
Hornavan	250	**222**	11 915
Akkajaure	242	67	6 000
Storuman	171	135	4 185
Virihaure	112	**138**	4 467
Vastenjaure	90	134	2 965
Vojmsjön	83	145	3 114

Largest rivers

RIVER (NAME)	CATCHMENT AREA (km²)	MEAN FLOW (m³/s)	DEGREE OF REGULATION (%)
Torneälv	**35 300**	360	0
Kalix älv	22 900	290	0
Lule älv	25 200	**515**	**70**
Pite älv	11 200	170	0
Skellefte älv	11 600	165	**52**
Ume älv	26 700	450	28
Ångermanälven	**31 900**	**500**	42
Indalsälven	26 700	460	40
Ljungan	12 800	140	27
Ljusnan	19 800	235	20
Dalälven	29 000	370	22
Klarälven	11 800	165	20
Göta älv	**50 200**	**575**	**72**

3.2 Climate

Winter and summer temperature differences in Sweden are extreme, but thanks to its proximity to the North Atlantic with the Gulf Stream the country generally enjoys a temperate climate. The exception is the very north of the country that has a sub-arctic climate. Based on long series of observations of climate indicators relating to temperature, precipitation and run-off this chapter provides an overview of the yearly, seasonal and regional climate variations, and also indicate the trends of ongoing and predicted future climate change.



The Kungsådran dam at Älvkarleby, River Dalälven.

Introduction

Overall, Sweden has a very temperate climate given its northerly location. The North Atlantic Current warms air which is brought up from the southwest by low pressure winds in the Atlantic. From the east, high pressure zones bring bright, warm summer days and clear, crisp and cold winters, while the high mountains of Norway and the plateaux along the western edge of Sweden provide shelter from the mild, wet winds blowing in from the west. Still, the low pressures provide a fairly precipitation-rich climate where precipitation falls all year round. The wettest period is in late summer and early autumn, while across large parts of the country much of the winter precipitation falls as snow.

In Sweden information about the weather as well as how and why the climate is changing is primarily made available by The Swedish Meteorological and Hydrological Institute, SMHI, in its role as an expert authority for knowledge, research and services in climatology and climate adaption.

Being a very long country from north to south the seasons are quite different in the different regions. In the following pages SMHIs results from measurements since more than 100 years are presented in time series and maps, with special focus on changes between the reference period 1961–1990 and the period 1991–2020. You will see that since around 1980 there is a clear trend towards warmer and wetter climate.

Northern lights. Photo: Svenska kraftnät.

Characteristic for the Nordic countries, is the very large differences in the length of the day during the year. In northernmost Norrland there is a polar night for a number of weeks around the winter solstice and midnight sun around the summer solstice, thus the length of the day varies between 0 and 24 h. During the spring and autumn, the change in the length of the day is rapid, which is especially noticeable in the far north where the days go from being almost completely dark in winter to being light around the clock in summer. In southernmost Sweden, the length of the day varies between 7 and 17 hours.

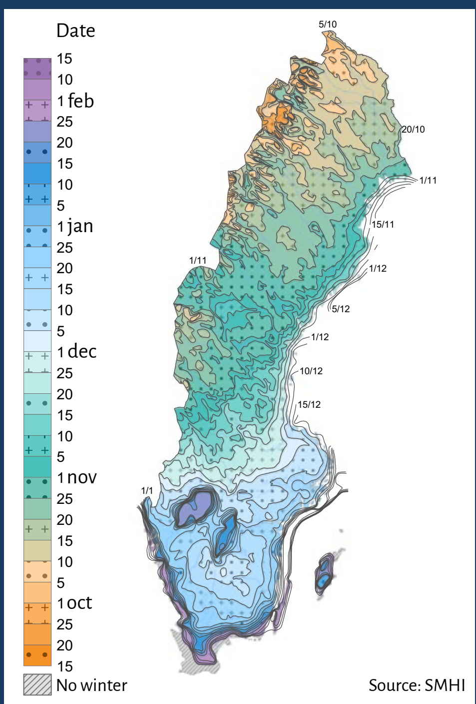
Late evening at the shore of River Lule älv. Photo: Uno Kuoljok.

Seasons

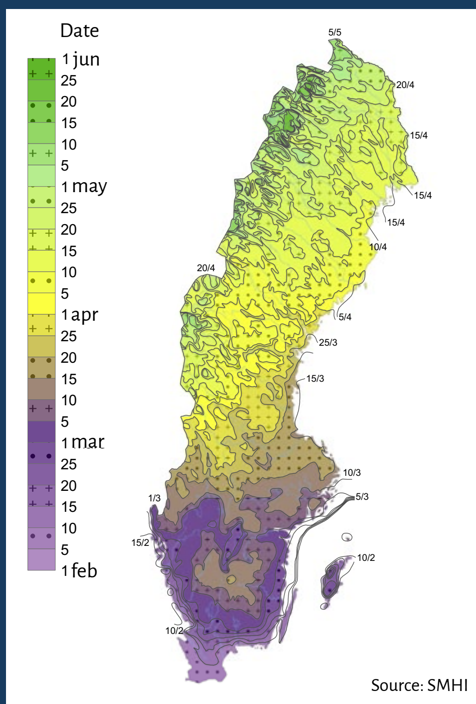
The definition of the seasons varies between countries and regions, and there is no universal standard. In Sweden, the most common approach is to divide the year into four seasons of three months each. However, in northern Sweden, a more nuanced approach is taken, and eight seasons are recognized to highlight subtle changes in the transitioning periods. You can see the divisions in the timeline below.

Winter
Winter in Sweden is characterized by darkness and cold temperatures, with short days throughout most of the country. North of the Arctic Circle, there are periods of no daylight, but the sky is occasionally illuminated by the northern lights.

Spring
Spring in Sweden is a beautiful season marked by the gradual emergence of color and life as the winter snows melts and the days become longer and warmer.



The climatological winter will arrive after 5 consecutive days with daily mean temperature 0.0°C or below.



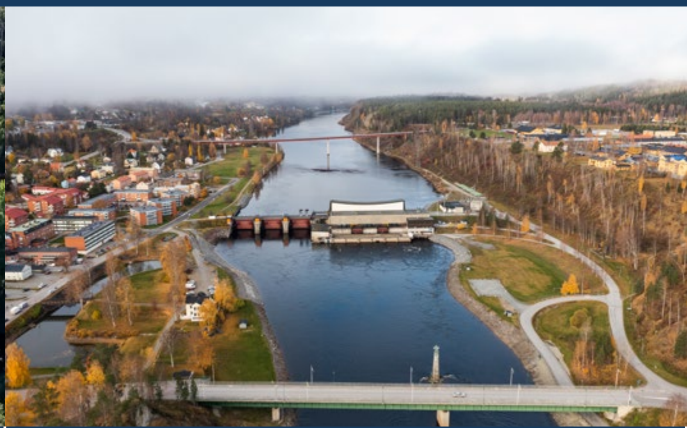
The climatological spring will arrive after 7 consecutive days with daily mean temperature above 0.0°C.

DECEMBER	JANUARY	FEBRUARY	MARCH	APRIL	MAY
Winter (*Dálvve*)			Spring-winter (*Gidádálvve*)		Spring (*Gidá*)

The bottom of the timeline shows the approximate calendar division of the eight seasons used in northern Sweden.

Climatological definition

According to the calendar definition, the seasons are said to occur simultaneously in northern and southern Sweden. However, this definition does not match the actual seasonal changes that occur in Sweden. Therefore, a climatological definition based on temperature patterns is also used. Below, you can see maps displaying the average arrival time of winter, spring, summer, and autumn in Sweden based on temperature data from 1991 to 2020.

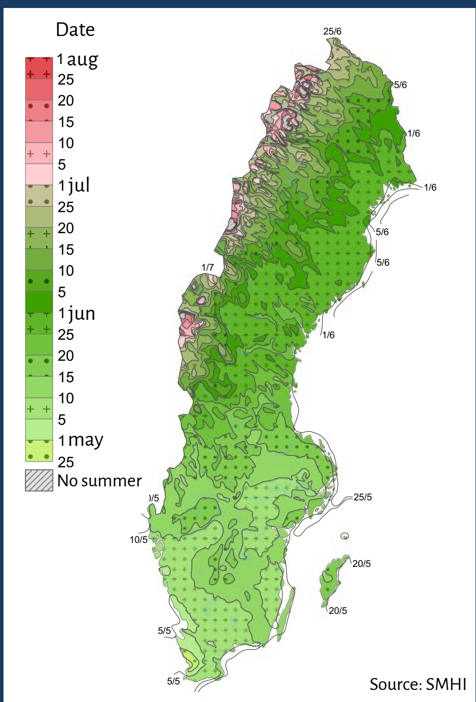


Summer

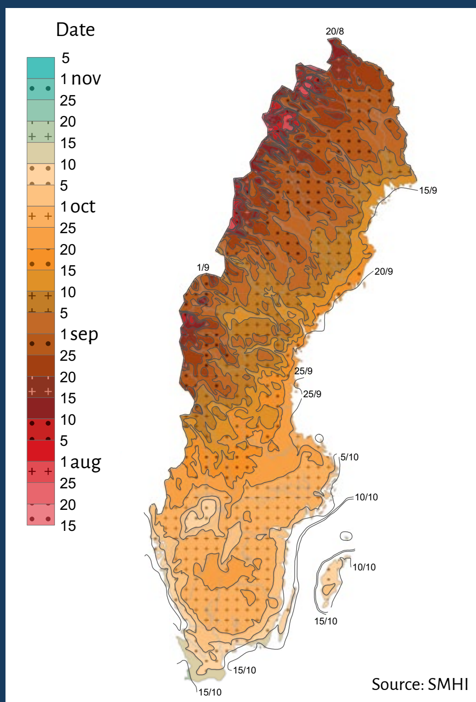
Summer days in Sweden are long, with daylight outlasting the average person's waking hours in the south and the sun never setting for weeks in the far north.

Autumn

Autumn in Sweden is another beautiful season marked by the transformation of the country's landscapes into a stunning display of reds, oranges, and yellows as the leaves on the trees change color and fall to the ground.



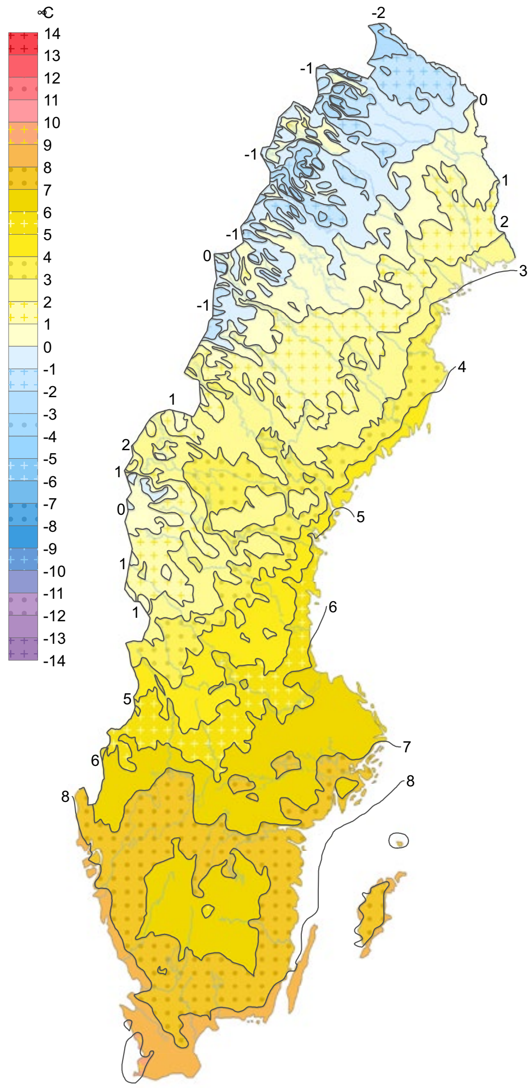
The climatological summer will arrive after 5 consecutive days with daily mean temperature 10.0°C or above.



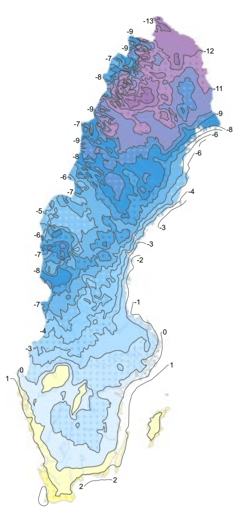
The climatological autumn will arrive after 5 consecutive days with daily mean temperature below 10.0°C.

JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER	NOVEMBER
Spring-summer *(Gidágiesse)*	Summer *(Giesse)*	Summer-autumn *(Tjaktjagiesse)*	Autumn *(Tjaktja)*		Autumn/winter *(Tjaktjadálvve)*

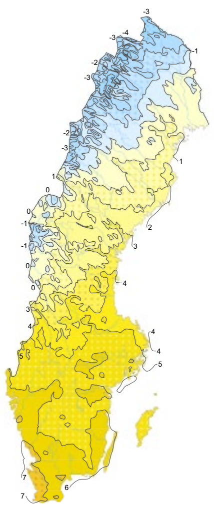
Normal average temperature for the period 1991–2020.



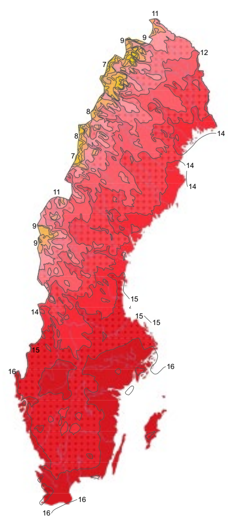
Winter



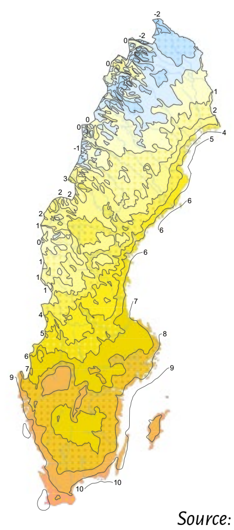
Spring



Summer



Autumn



Source: SMHI.

Temperature

According to Köppen's climate system, Götaland and southernmost Svealand belong to the warm-temperate zone with deciduous forest as a natural dominant habitat type. However, most of the country has a cold-temperate climate with proper snow winters and coniferous forest (taiga) as the dominant vegetation type. Locally in the mountains, tundra climates also occur with only minor plants in the form of dwarf trees and herbs. The border of the tundra largely coincides with the tree line, which is located at an altitude of almost 900 m in the southern mountains and at about 600 m in the northwestern parts of the mountain range.

The annual mean temperature for Sweden is about 9°C in the very south and slightly below 0°C in the very north. The temperature fluctuates heavily depending, among other things, on the position of the polar front.

- During the winter, the coldest air is often found in the valleys. The average temperature in January is 1-2°C in many places on the coasts of Götaland, while the coldest valleys in inner Lapland have -15°C. At its lowest, the temperature sometimes reaches below -40°C in such valleys. The very coldest winter temperature measured was -52°C in Norrland not far from the border to Norway.
- In summer, on the contrary, it is coolest at the top of the mountain peaks. During July, the average temperature is around 18° in many places in Götaland and southern Svealand. The very highest temperatures of 38°C have been observed in southeastern Sweden. The lowest July average temperatures are found on the mountain peaks in the north.

The increase in Sweden's average temperature is now approaching two degrees compared to the late 1800s. The corresponding value of the global average is approximately one degree. Concerning the temperature development in the different seasons, there has been a rising temperature trend for all seasons. However, it is most evident for the spring. When it comes to winter, over time there has been a variation between both warm and cold winters. However, the number of really cold winters has decreased since around 1990.

Future temperature

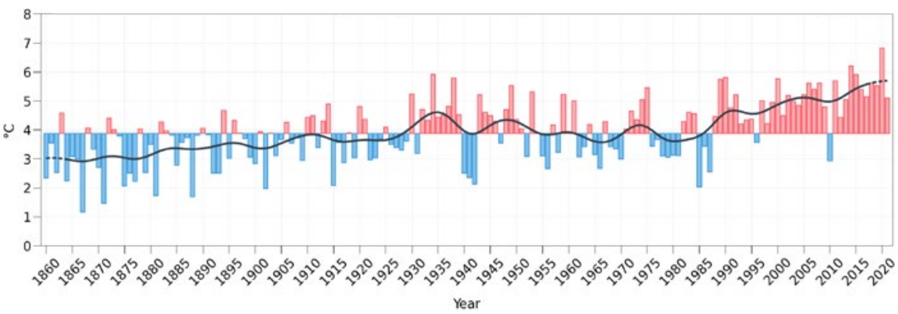
In Sweden, the annual average temperature is increasing about twice as fast as the global average. By the end of the century, the annual average temperature is expected to be 2–6 °C higher than in the period 1961–1990, depending on how much greenhouse gas emissions continue. The temperature is expected to increase in all seasons, but mostly in northern Sweden in winter. Winter is also the season when the variation between individual years is greatest. This means that we will continue to experience winters that are both significantly warmer and colder than the average climate. In the future, we can also expect an increased risk of a variety of extreme weather-related events, such as heat waves, torrential rain and drought.

One effect of today´s warmer climate is the positive effect on the length of the "vegetation period", that is the time during the year that is warm enough for various plants to grow. The trend is that the growing season starts earlier in the year and ends later, which affect agriculture in a positive way.

The vegetation period in Sweden as a whole is today about three weeks longer than it was in the early 1900s. In the south, the extension is about five weeks and in northern Norrland about two weeks.

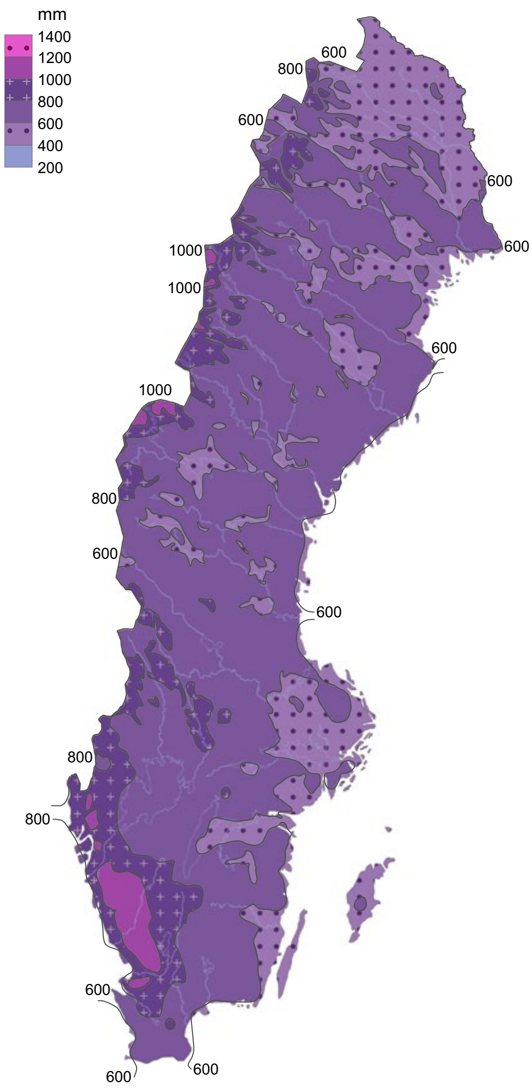
Other indications of the temperature rise include that the tree line is moving higher up in the mountains, that glaciers are generally shrinking, that several heat-loving animal species are spreading northwards and that the snow season has become shorter in southern and central Sweden.

Avarage temperature of the year in Sweden

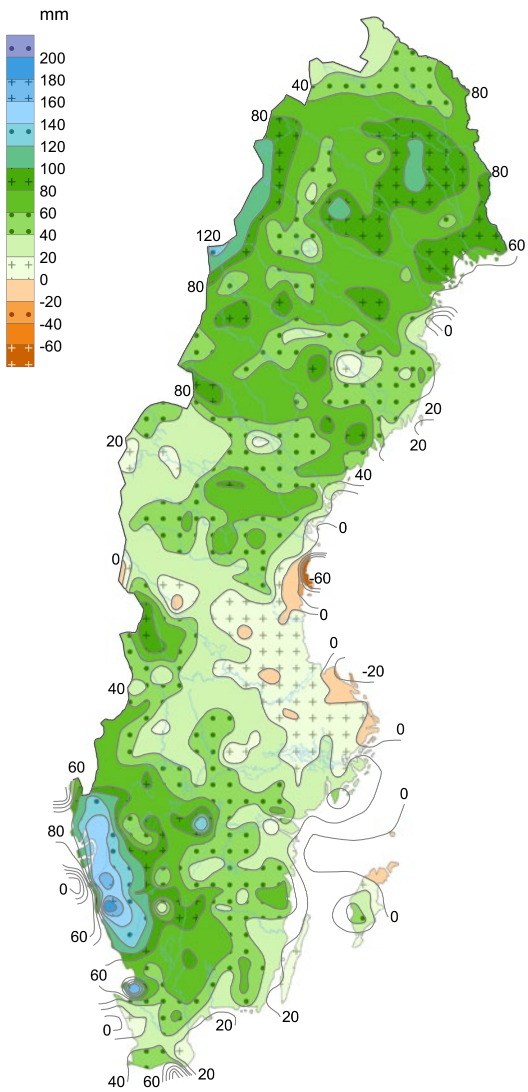


The bars in the chart show the average temperature per year. Red bars show higher and blue shows lower temperatures than the average for the normal period 1961-1990. The gray line shows a running mean calculated over about ten years. Source: SMHI.

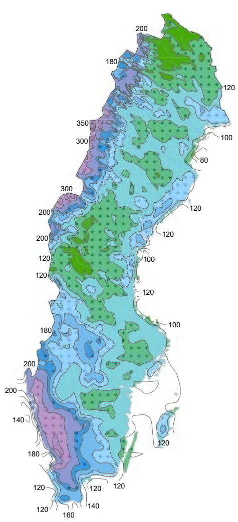
Normal annual rainfall for the period 1991-2020.



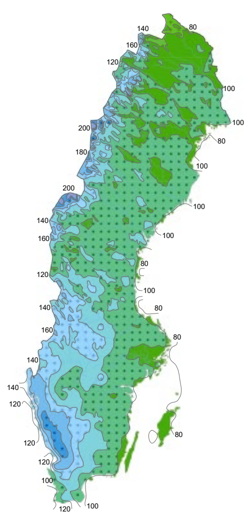
The difference in normal annual rainfall between the periods 1961-1990 and 1991-2020.



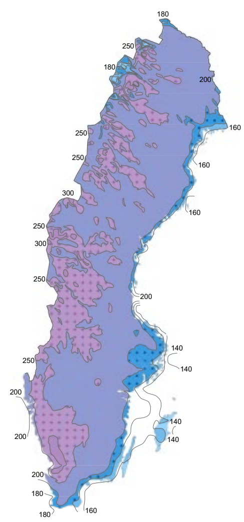
Winter



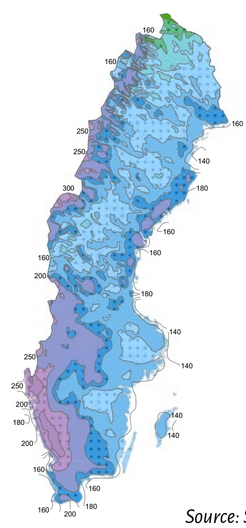
Spring



Summer



Autumn



Source: SMHI.

Precipitation

The annual average rainfall for Sweden was around 600 millimeters until the mid-1970s. Since then, annual rainfall has increased and is now closer to 700 millimeters.

- Winter average rainfall has slowly increased from about 100 mm around 1890 to around 150 mm in the present. (There are many indications that early precipitation observations underestimated precipitation amounts, especially during snowfall.)
- Average rainfall in spring and summer does not show as clear a trend, but a slight increase in spring rainfall since the 1960s can be discerned.
- Since the turn of the last century, the average rainfall during the autumn has increased from about 150 mm to almost 200 mm in the present.

In general, the average amount of precipitation will increase with increasing height above sea level. Roughly speaking, annual precipitation increases by 30-40 mm per 100 m in the interior of northern Sweden. The areas with the greatest precipitation in Sweden are in the high mountains, particularly close to the Norwegian border, and on the west side of the Southern Swedish Highlands. In the latter area the average annual precipitation amounts to between 1,100 and 1,200 mm at 20-30 km from the coast. Some areas in the western mountain range in northern Sweden receive even larger amounts and may be seen as offshoots of the extremely wet steep slopes of western Norway. The highest average annual figures on the Swedish side amount to 1,500-2,000 mm. The driest hollows of all are surrounded by high mountains in most directions and are found in the central mountain regions. Low annual precipitation also characterizes the great lakes in the south.

When it comes to maximum daily rainfall in Sweden, you can see fluctuations between periods of a number of years with large daily amounts interspersed with periods when large daily amounts have been rarer. There is a trend that maximum daily rainfall in winter is increasing in all parts of the country. This is most evident for northern Norrland. Otherwise, it is difficult to see any distinct trends and the variations from year to year are large.

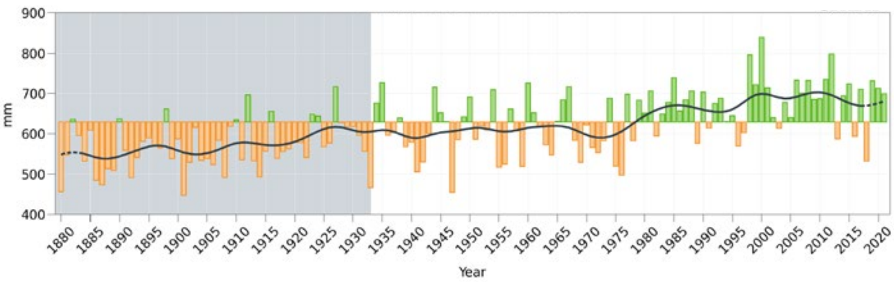
In the summer, precipitation often comes as thunderstorms. Then large amounts of precipitation in the form of rain or hail can fall in a short time. The largest official daily rainfall is about 200 mm, but private measurements of over 200 mm have occurred on several occasions. During a violent thunderstorm, about 300 mm is estimated to have fallen on the east side of Fulufjället in Dalarna on August 30-31, 1997, a rain that produced extreme erosion in streams in the area.

Precipitation in the future

Precipitation greatly varies from year to year and season to season. In a warmer climate, precipitation is expected to increase during all seasons, but mostly in winter with the biggest increase in northern Sweden. In parts of southern Sweden however, the increase is not as clear during summer and autumn. In addition, a warmer climate will mean increased evaporation which can affect available water.

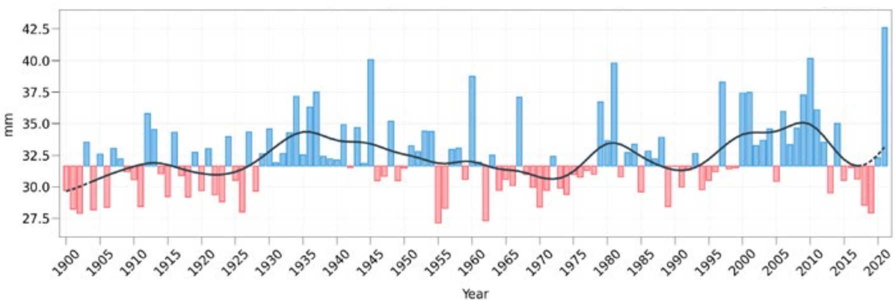
Today, research can clearly link extreme weather to climate change. The probability of heavy precipitation has already increased. In a future warmer climate, the number of days with extreme precipitation is expected to increase.

Yearly precipitation in Sweden



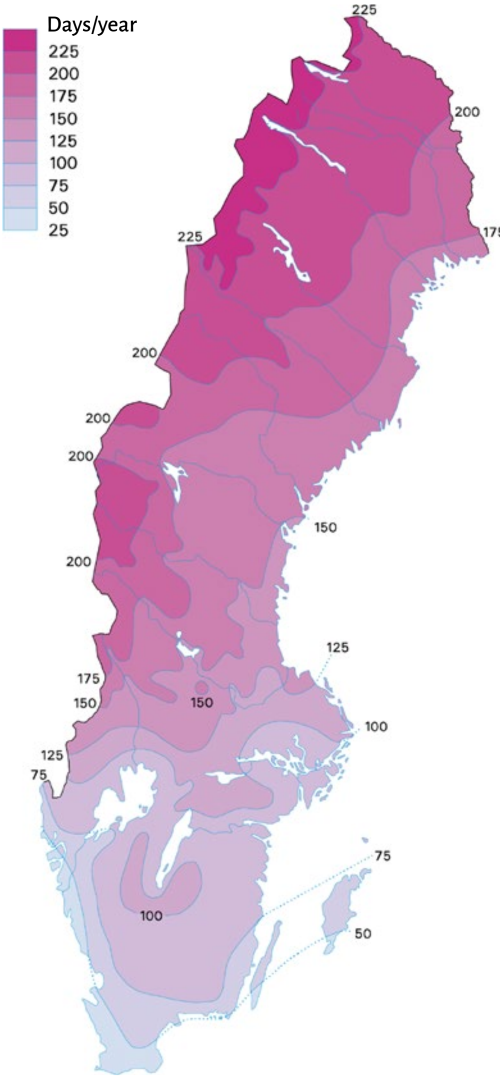
The bars in the chart show total precipitation per year. Green bars show higher and orange ones show lower rainfall than the average for the normal period 1961-1990. The gray line shows a moving average calculated over about ten years. Source: SMHI.

Largest daily precipitation in Sweden

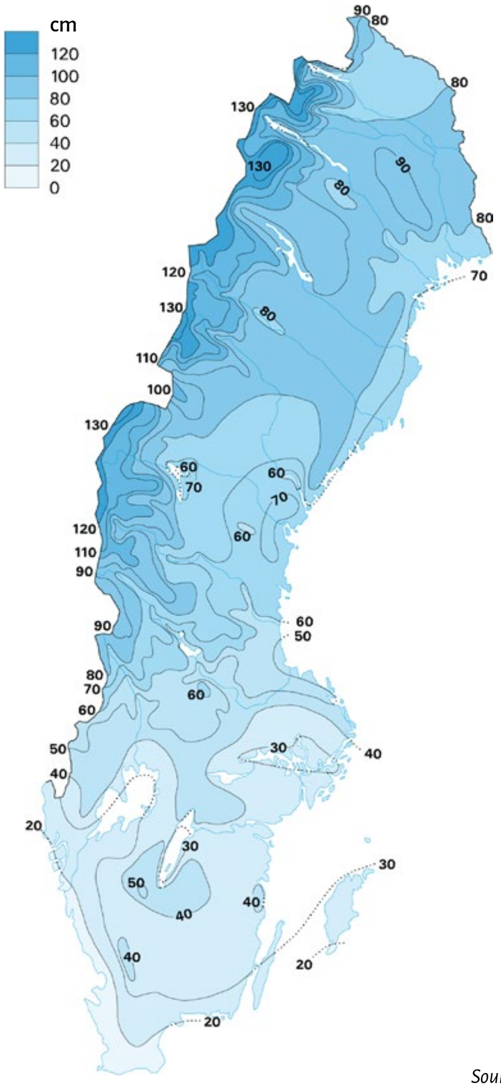


The bars in the graph show the maximum daily rainfall on average per station in Sweden per year. Blue bars show higher and red shows lower amounts than the mean for the normal period 1961-1990. The gray line shows a moving average calculated over about ten years. Source: SMHI.

Average number of days of snow cover per year 1961–1990.



The average of the greatest snow depth during the winter for the period 1961–1990.



Source: SMHI.

Hällforsen dam. Photo: Uno Kuoljok.

Snow Cover

Every winter much of Sweden is covered with snow and ice. This white winter dress greatly affects animal and plant life as well as our human living conditions. Snow creates opportunities for exciting outdoor activities and facilitates transport in the forests and fields, but it also creates needs for heating indoors and problems for example for traffic.

The first lasting cover of snow falls as early as the beginning of October in valleys in the most northwesterly mountain districts and does not disappear until May or early June. On the high mountains, the snow season is even longer. High-lying areas usually receive large amounts of precipitation as a result of orographic factors. These areas are also comparatively cold when precipitation falls since temperature decreases with altitude. Thus, high land often gets deep snow. In the southernmost part of Sweden, on the other hand, the snow does not last long; the likelihood of snow covering the ground at any point in time is less than 50 percent throughout the winter.

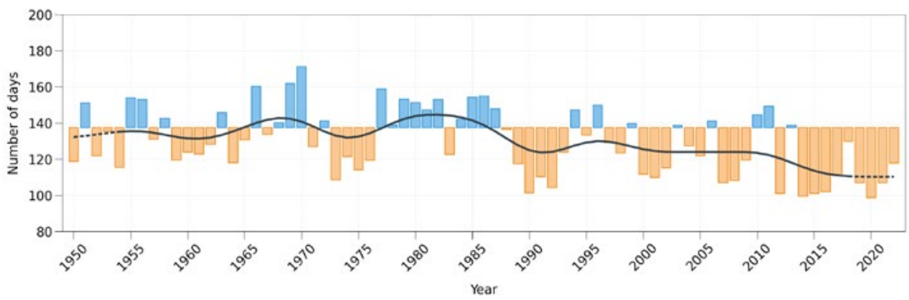
For Sweden as a whole, since about 1990, a decreasing trend has been noticed in terms of the number of days with snow cover. It is possible to observe changes in the snow cover in different ways, for example the greatest snow depth in winter and the duration of the snow cover. Regarding the winter's greatest snow depth, it is difficult to see a clear change over time. For northern Norrland, this also applies to the number of days with snow cover. In southern Sweden, however, the number of days with snow cover has decreased.

Future snow conditions

In a warmer climate, precipitation is expected to increase on average. At the same time, higher temperatures lead to a larger proportion of precipitation falling as rain, and snow on the ground will melt. Therefore, both the number of days with snow and maximum snow depth are generally expected to decrease.

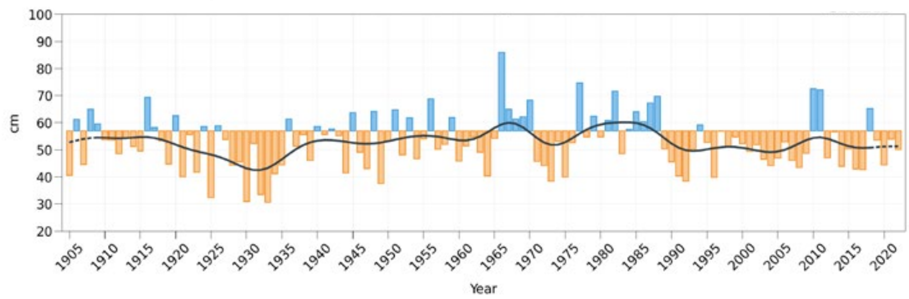
However, higher temperatures over the North Atlantic and a shorter season with sea ice over, for example, the Baltic Sea can contribute to more moisture over Sweden in winter. Therefore, there will also be heavy snowfalls in warmer climates and occasionally great snow depths.

Number of days with snow cover in Sweden



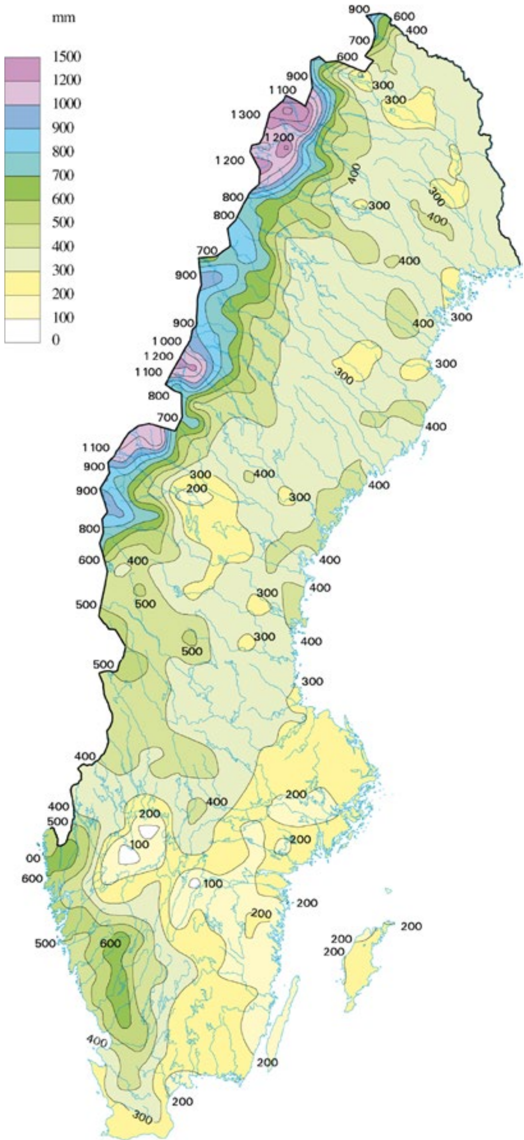
The bars in the chart show the number of days with snow cover in Sweden. Blue bars show more and orange shows fewer days than the average for the normal period 1961–1990. The gray line shows a moving average calculated over about ten years. Source: SMHI.

Maximum snow depth in Sweden

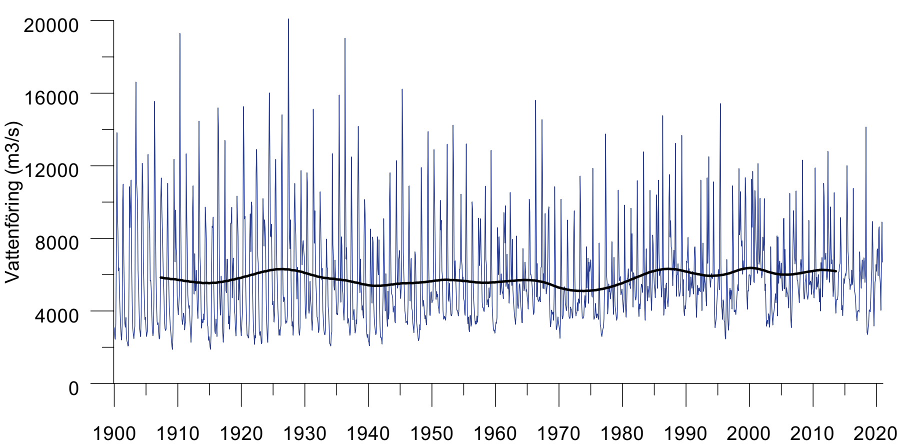


The bars in the chart show the maximum snow depth in Sweden. Blue bars show higher and orange bars show lower snow depths than the average for the normal period 1961–1990. The gray line shows a moving average calculated over about ten years. Source: SMHI.

Normal annual runoff for the period 1961-1990



Monthly values of the total the river flow from the whole of Sweden to the sea.



The graph shows monthly values of the total water flow from the whole of Sweden to the sea since the year 1900, you can see how the water supply has fluctuated over time, but also that the variation within the years has gradually decreased. The reason for the reduced intra-year variation is mainly increased regulation for hydropower purposes, which aims to even out the water supply by saving water from spring and summer to winter when electricity demand is greatest and natural water supply is lowest. Source: Klimat, vattentillgång och höga flöden i Sverige 1860-2020, Energiforsk report 2022:902.

Run-off and river flow

The variation of run-off in the country is mainly determined by the geographical variation of precipitation. Evaporation has less impact on spatial variation, as it primarily depends on the temperature and varies significantly less between different parts of Sweden than the precipitation.

Run-off

The run-off varies between different seasons and parts of the country. The largest amounts of precipitation and thus also the highest run-off values can be found in the mountainous areas, while the lowest run-off occurs in the south-east of the country. The seasonality of run-off is due to a greater extent of the evaporation variation. Evaporation largely follows the temperature and thus reaches its highest value in summer but is low in late autumn and winter. Due to the high evaporation, the run-off in southern Sweden is therefore at its lowest during the summer. In northernmost Sweden, the annual run-off is dominated by water from snowmelt.

The accumulation and melting of snow control the runoff in watercourses during a great part of the year. When precipitation is in the form of snow, which remains on the ground for some time, the supply of water diminishes. In northern Sweden as much as 50 percent of the annual precipitation can fall as snow, while the corresponding figure for southern Sweden is 10-20 percent. In southern Sweden repeated falls of snow followed by thaws result in very uneven flows of water in rivers during the winter.

The time when the snow begins to melt is of importance, not least for the hydropower industry. The culmination of the spring flood and its volume are affected by the intensity of the thaw and the water content of the snow. The speed at which snow melts varies at different altitudes, between north and south slopes, and between forests and open land.

River Flow

In both small streams and large rivers discharge will vary greatly throughout the year. In northern and central Sweden there is a high spring flood when the snow melts. This usually occurs in May-June in the northern provinces and in April-May further south. Autumn rains may lead to another peak, but from then on, the discharge diminishes until the following spring. In southern Sweden the discharge is usually at its lowest in the vegetation period of the summer. During the autumn and winter brooks and streams are filled by rain and melting snow after repeated thaws. On the next page you can read more about the seasonal and regional variations in river flow, and the observed effects of climate change.

There are also great differences between the total water flow in different years.

- Mean water flow is increasing in the north according to observations but is unchanged or decreasing in the south. The mean annual run-off to the Gulf of Bothnia has increased about +10% in recent decades.
- The mean water flow is generally expected to keep increasing in northern Sweden in both a short and long time perspective. For the south unchanged conditions or decreasing mean water flow are indicated.
- For high flows, analyses on an annual basis do not indicate increasing size or occurrence to date. However, analyses of seasonal changes show that the magnitude of the highest autumn flow (created by rain) has increased and that the spring flood (created primarily by snowmelt) in much of the country over time can occur 1 month earlier than historically.
- In the future, high flows are expected to increase in large parts of the country, especially in the south.

Floods

In an international comparison, Sweden has not experienced major disasters linked to large river flows and droughts. Moderate intensity of precipitation and many lakes help to reduce the risk of flooding. Nevertheless, events sometimes take place that create major problems.

High river flow occur less frequently in regulated rivers, but may therefore be more surprising when they occur than is the case of a system without developed hydropower.

Vuojaädno, Padjelanta national park, River Lule älv. Photo: Tony Wallin.

River flow and long-term regulation

Climate indicator - Spring flood

In spring, when the snow melts, the flow in the waterways increases and becomes a spring flood. The flow goes from being very low to being high and the areas along the shores are flooded. When the timing of this event changes, animals and nature in and around the waterways are affected. The fact that the spring flood occurs earlier also affects, among other things, winter tourism and the hydropower companies.

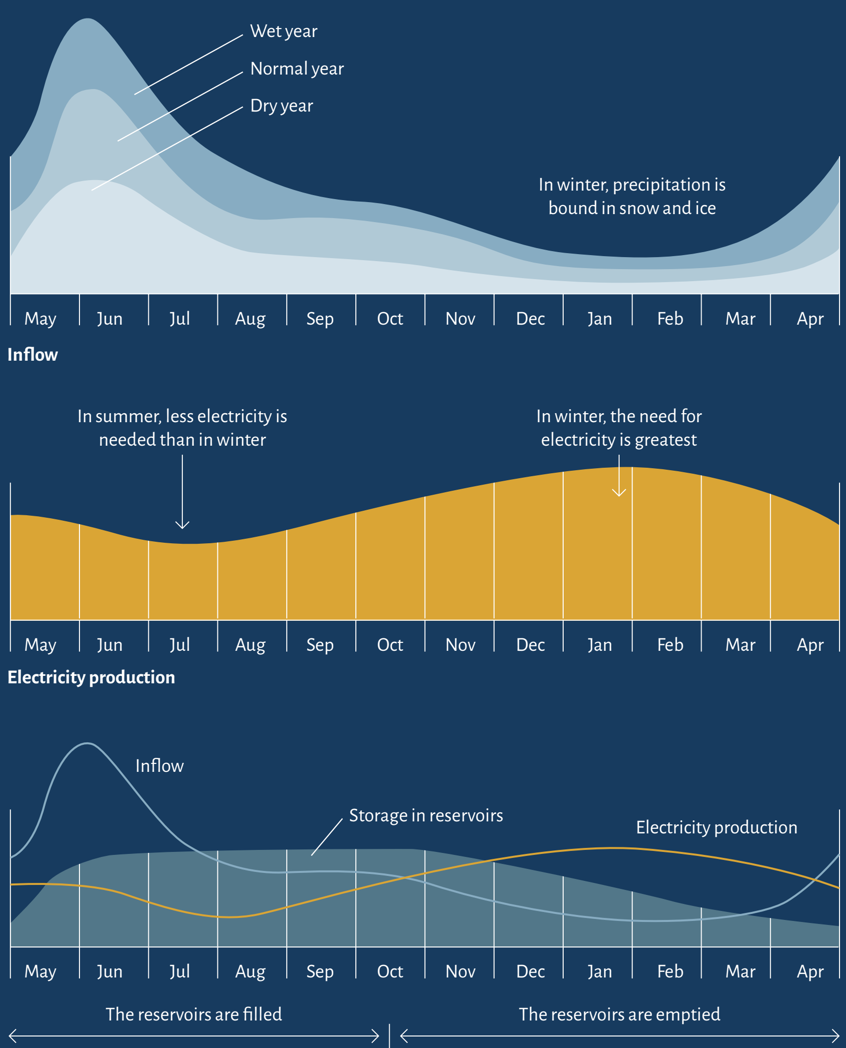
In central and northern Sweden there is clear spring flood, but south of River Dalälven also winter flows occur because there are no sustained freezing temperatures in the winter. Therefore, this indicator only exists for rivers in the northern half of Sweden, from River Dalälven to River Torneälv at the border to Finland.

There is a large variation for when the spring flood starts between years. But, based on the stations examined, a clear change is seen in that it comes earlier in the year. Since the beginning of the 20th century, the spring flood generally start 5 to 15 days earlier.

In a warmer climate, snow will melt earlier in the year. However, the variations between years will still be large. It will also become more common that there will not be a clear spring flood start. There will be higher winter flows and a lower or non-existent spring flood for southern Sweden and that the border for such conditions is moving north.

In the figure to the right you can see how the flow has been distributed over the year, over the past 30 years, compared to before 1990. During the recent mild period, winter runoff mainly in the southern areas has been higher than before. The snowmelt also occurs slightly earlier in accordance with the higher temperature in recent years.

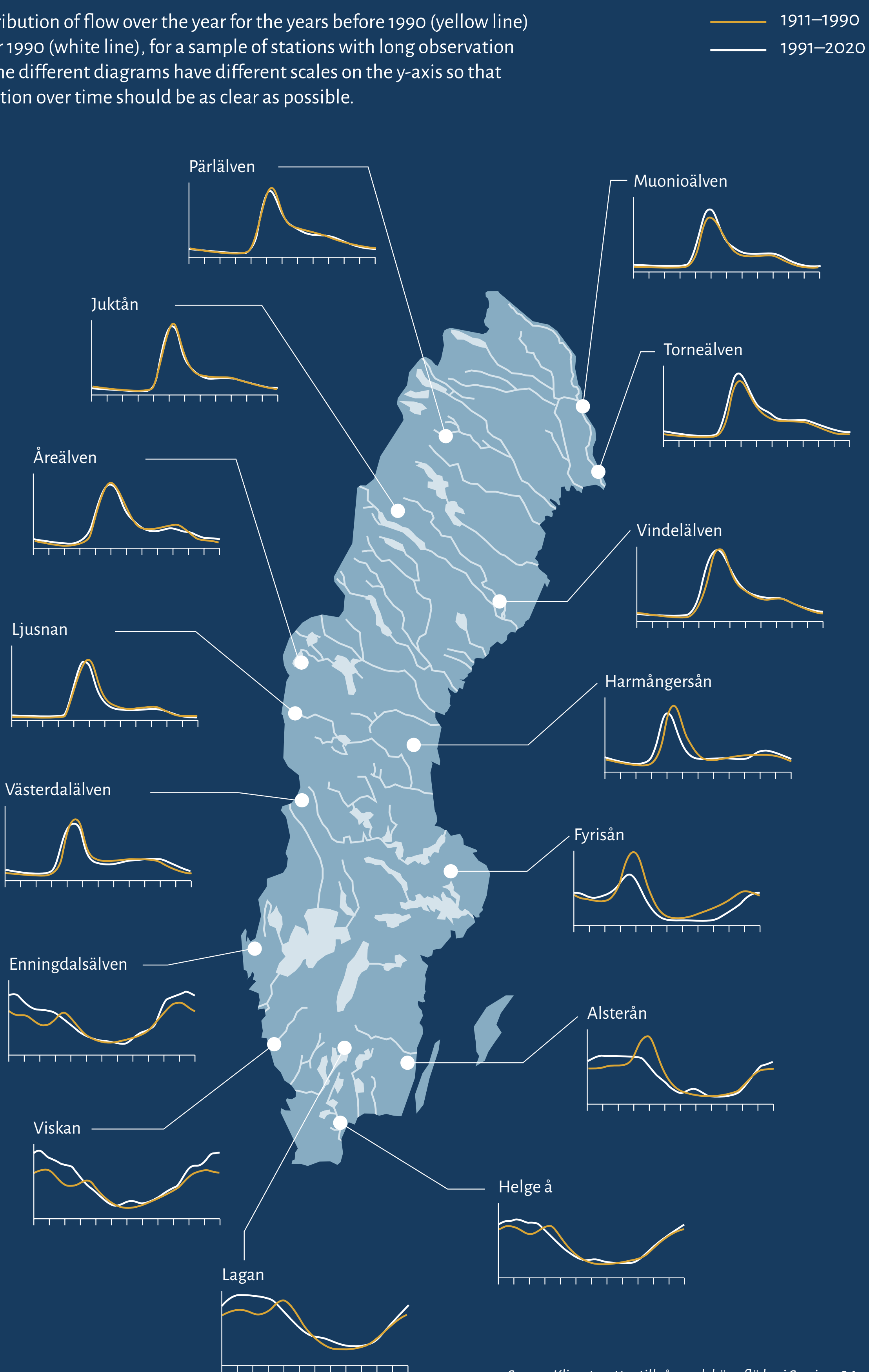
Long-term regulation



Source: Vattenregleringsföretagen.

River flow

The distribution of flow over the year for the years before 1990 (yellow line) and after 1990 (white line), for a sample of stations with long observation series. The different diagrams have different scales on the y-axis so that the variation over time should be as clear as possible.



Source: Klimat, vattentillgång och höga flöden i Sverige 1860–2020, Energiforsk report 2022:902

4. Swedish dams

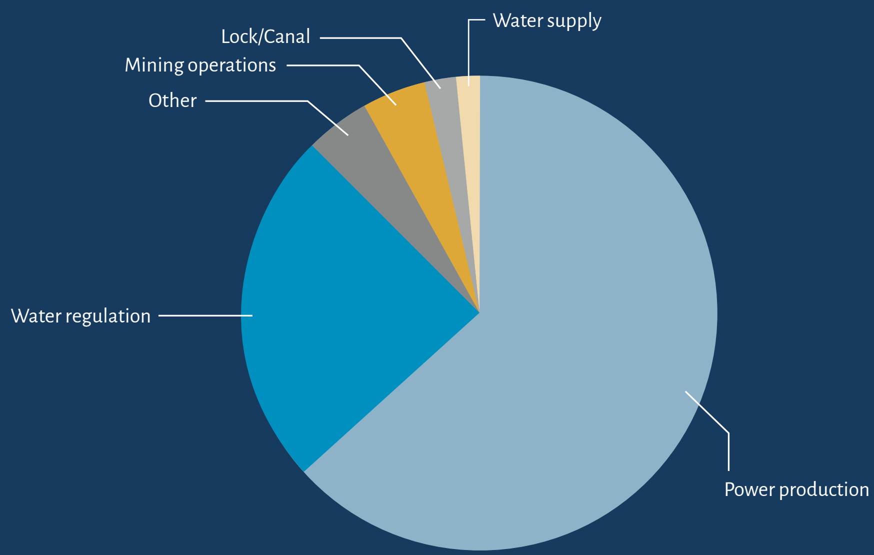
4. Swedish dams

This chapter provides a overview of dams in Sweden, categorized by their primary use in hydropower, mining, and for other purposes.

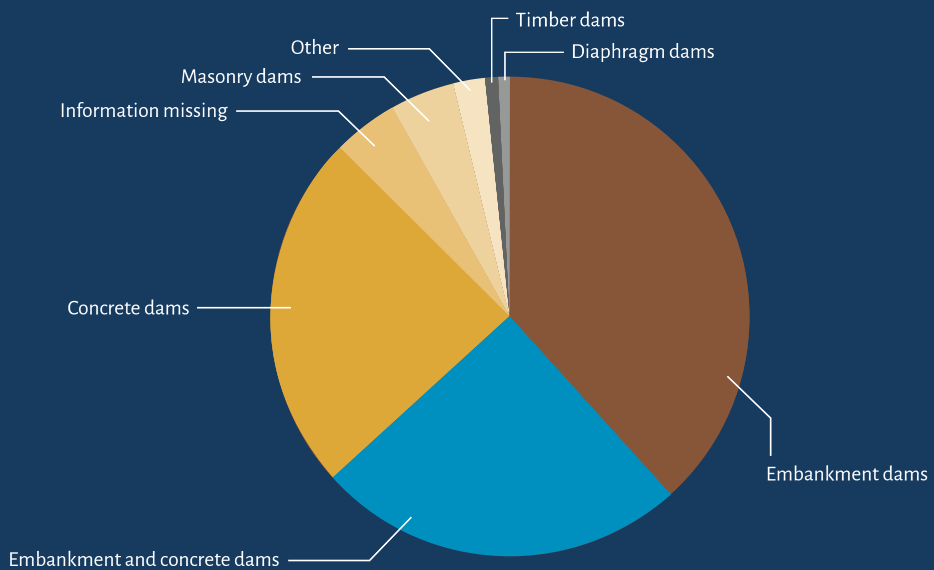
For each category, it present the development of dams in relation to industrial and technical advancements, along with a concise summary of the typical Swedish dam design.

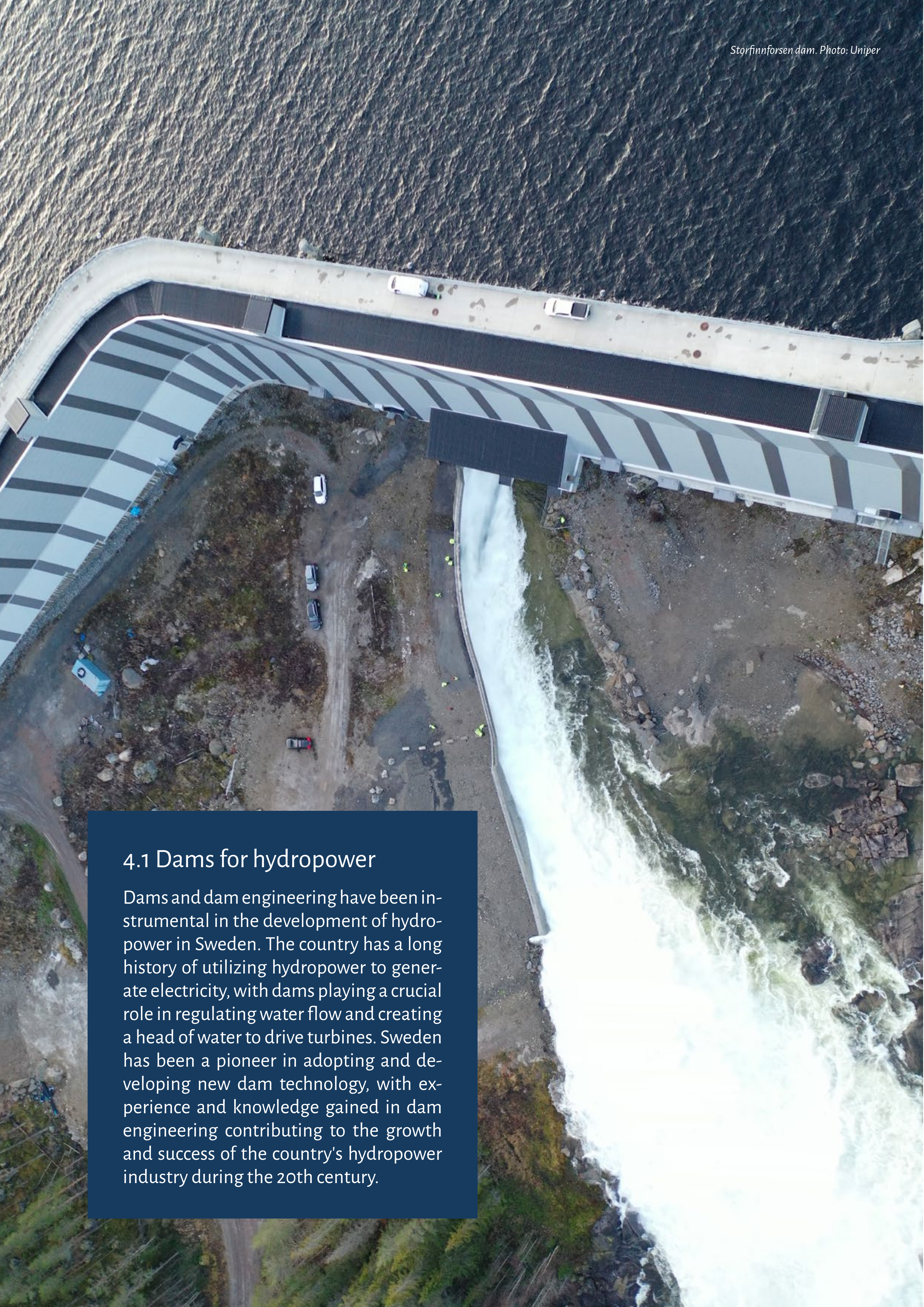
There are approximately 10,000 dams in Sweden, of which around 1,000 facilities include one or more dams that are 5 meters or higher or have a reservoir volume larger than 100,000 m³. The majority of these dams, about 90%, are used for hydropower, with embankment dams being the most common dam type.

Distribution of dams in Sweden based on purpose



Distribution of dam types in Sweden





Storfinnforsen dam. Photo: Uniper

4.1 Dams for hydropower

Dams and dam engineering have been instrumental in the development of hydropower in Sweden. The country has a long history of utilizing hydropower to generate electricity, with dams playing a crucial role in regulating water flow and creating a head of water to drive turbines. Sweden has been a pioneer in adopting and developing new dam technology, with experience and knowledge gained in dam engineering contributing to the growth and success of the country's hydropower industry during the 20th century.

Introduction

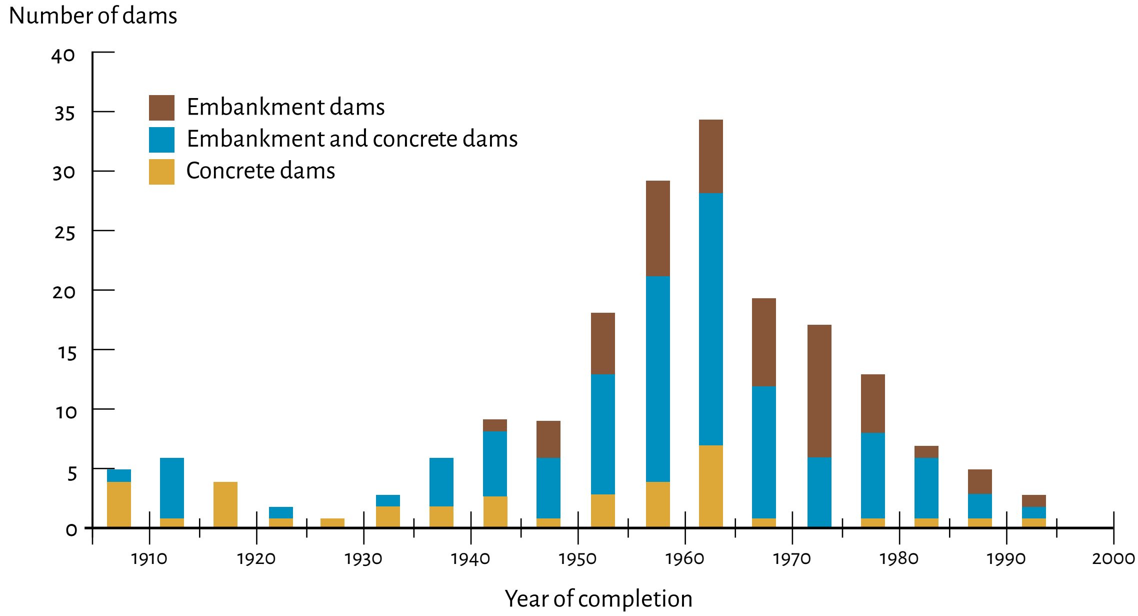
The use of dams in Sweden dates back to medieval times when small dams were used for regulating water flow and powering machinery in watermills. The mining and hydropower industries were closely intertwined, and early mines often utilized hydropower. Before the 20th century, Swedish dams were built using traditional materials like wood, steel, brick, and natural stone. Alternatively, they were constructed as embankment dams with a cross-section of available materials at the construction site, such as moraine, gravel, clay, and topsoil.

The rapid expansion of hydropower stations throughout the country required the construction of large dams. Sweden has been a pioneer in adopting and developing new dam technology, with experience and knowledge gained in dam engineering playing a crucial role in developing the country's hydropower industry during the 20th century. The selection of large dam types in Sweden has primarily been based on safety and cost considerations.

The construction and operation of large dams in Sweden can be broadly categorized into three different time periods:

- **The early large dams – 1890-1950s**
  When large dams were needed, Sweden quickly adopted concrete as the new building material for hydropower facilities. Until the 1950s, large dams were constructed as concrete dams of various types or diaphragm embankments, with a central impermeable diaphragm of either concrete or wood.
- **The fast hydropower expansion – 1950s to 1980**
  The construction of the first large embankment dams in Sweden without a central diaphragm began in the early 1950s. By the 1960s, the design and safety for earth and rock fill dams had developed to such an extent that their cost was considerably lower than for a corresponding concrete dam; see the table. As a result, embankment dams were almost exclusively preferred when constructing new dams from that point forward.
- **From construction to operation, maintenance, and dam safety measures – 1980s to today**
  In the 1980s, the hydropower industry in Sweden entered a period of dam operation and maintenance that continues to this day. During this period, some deficiencies in construction and design were discovered, necessitating the reinforcement, modernization, or reconstruction of many dams.

The upcoming section presents this development for concrete dams, embankment dams, and spillways.



According to ICOLD's classification, 190 hydropower dams are large, with 80% being embankment dams. Additionally, there are nine active tailing management facilities in Sweden. These large dams are primarily located in northern Sweden, where the major rivers and the largest mines are situated.

Storfinnforsen concrete buttress dam before the installation of an insulation wall on the downstream surface. Completed in 1951, this dam illustrates the type of thin buttress dams that were constructed at this time.

Klinte dam, which was completed in 1909, is an example of an early, relatively thick concrete arch dam.

Kattstrupeforsen dam, which was completed in 1942, is an example of a massive concrete dam with a front plate of reinforced cement-rich concrete made with LH cement.

Concrete dams

Concrete emerged as a revolutionary material in the second half of the 19th century, offering features such as easy formability, strength, durability, and impermeability, making it ideal for use in the hydropower industry. The first modern concrete dams worldwide were constructed in the early 1870s. Sweden was one of the countries that quickly adopted concrete as a building material for hydropower facilities, initially using it for foundations and substructures. In 1897, Sweden's first concrete dam, the Avesta Lillfors power plant in Dalälven, was completed and operated for nearly 90 years before decommissioning and demolishing in 1980.

Early concrete dams in Sweden were primarily of the gravity dam type. As the 20th century progressed, the use of reinforced concrete became more widespread. In the early 1900s, the Ambursen Dam was developed in the United States. This type of dam utilized reinforced concrete to create an obliquely inclined slab that rested on vertically standing support columns, using the weight of the water to increase stability and reduce the amount of concrete needed. In 1910, Sweden completed its first reinforced concrete dam of this type at Bullerforsen, located in the upper part of the Dalälven. The design principle of utilizing the water's weight later became dominant in the design of concrete dams in Sweden.

In the early 1920s, extensive damage and leakage were discovered on many concrete dams in Sweden. This caused serious concerns about the suitability to use concrete for dams and prompted extensive investigations into the design and composition of concrete structures that could withstand high water pressure and Sweden's climate. The research efforts resulted in the development of new cement types and more appropriate methods for concrete composition and proportioning. These efforts laid the groundwork for international cooperation on concrete research and were a strong contributing factor to Sweden becoming a member of ICOLD as early as 1931 and hosting the first-ever ICOLD Congress in 1933.

During the early 20th century, a handful of arch dams of modest height and width were built in areas with favorable topography, but these structures were more similar to massive dams due to their thickness. The wide Norrland rivers where large-scale hydroelectric plants were built unsuitable for arch dams. Today, only two major concrete dams in Sweden are arch dams; see the fact box.

Instead of arch dams, massive dams became the most common concrete dams in Sweden up to and including the 1940s. The reason was the experience from previously constructed dams combined with the relatively simple design calculations. The introduction of vibration technology in the 1930s made constructing thin and heavily reinforced structures with high-quality concrete possible. Additionally, the replacement of round steel with comb iron during the 1940s, which has better adhesion to concrete, reduced the amount of reinforcement needed.

The use of reinforced concrete led to a gradual transition from the massive dam to the buttress dam. The early Swedish buttress dams resembled massive dams, while later ones more closely resembled the Ambursen dam.

The 1960s marked the end of the construction of large concrete dams in Sweden, as earth and rock fill dams were now cheaper and more commonly used. However, spillway structures, intakes, waterways, and power station are still built using concrete.

During the 1960s and 1970s, the development of additives and new technologies improved the quality and longevity of concrete, making it an even more reliable building material for hydropower facilities.

During the operation of Swedish dams, stability and durability challenges related to the cold climate have been significant issues. Concrete dams in cold regions are subject to specific external factors, for example, frost and ice. Another challenge is the significant temperature variations between summer and winter. These seasonal fluctuations, combined with the relatively thin concrete dams in Sweden, have resulted in temperature-induced cracks in many dams. To address these issues, common safety measures implemented in Sweden include:

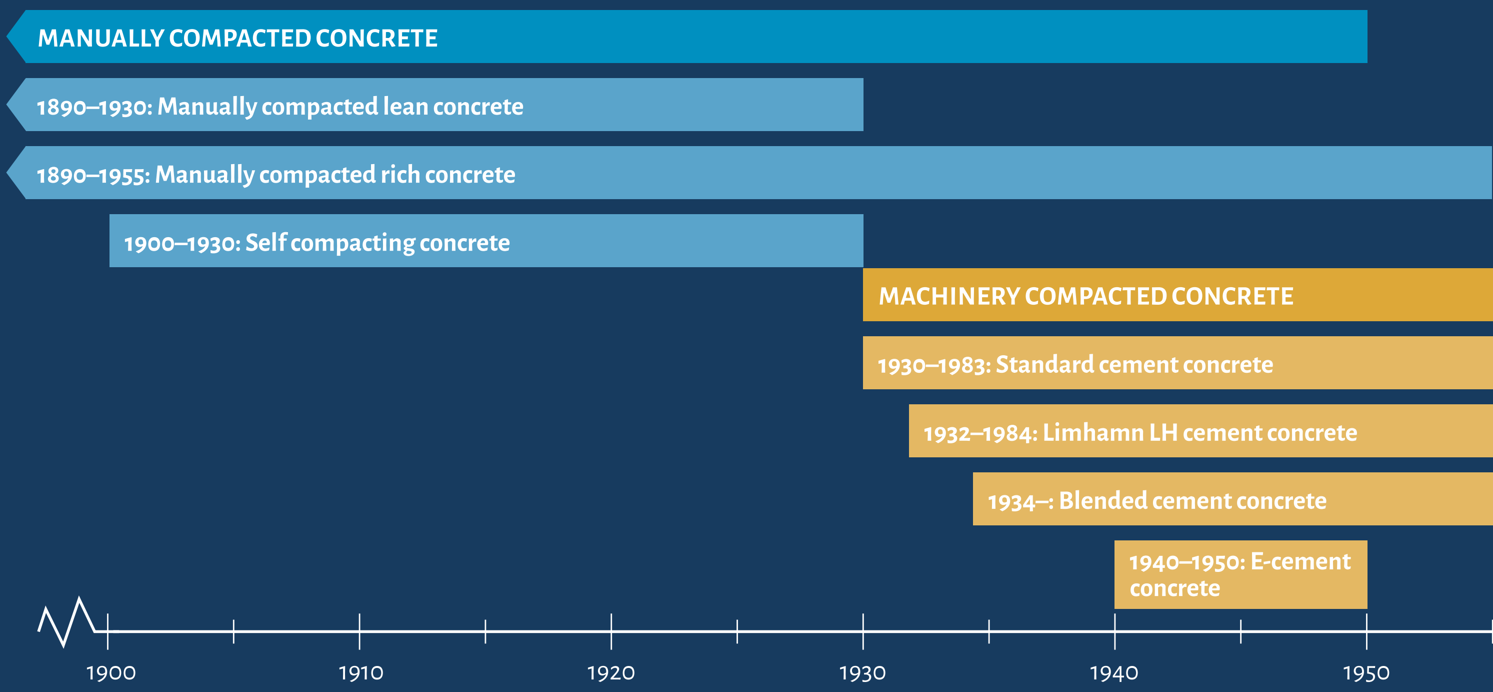
- The installation of an insulation wall on the downstream surface.
- Stabilization control with post-tensioned tendons.
- New proframs for surveillance and condition monitoring.

Today, the Swedish hydropower industry is striving to reduce the climate impact of their concrete structures. For example, Vattenfall has developed a climate-smart concrete for hydraulic construction with a lower cement content that can reduce carbon dioxide emissions by about a quarter. This concrete is being used for the reconstruction of dams in Lilla Edet, in Annex 1.

The two Swedish arch dams

Krokströmmen and Vargfors Dams are the two major arch dams in Sweden, standing at a height of approximately 45 meters each. Built around 1950 and 1960, respectively, these dams are similar in design and construction, and both have notable features that deviate from the standard arch dam design.

- One of the abutments for each dam is a spillway dam with an adjacent earth-fill dam.
- Both dams have an insulation wall covering the downstream face to limit temperature variations.
- The dams were constructed using reinforced concrete, and horizontal rebars cross the expansion joints between monoliths.



MANUALLY COMPACTED CONCRETE

1890–1955: Manually compacted rich concrete

Rich concrete, with a high cement content, was initially used when constructing slender structures with high strength demands and for the exterior waterproof layers on massive structures made of lean concrete. From the late 1920s, cement-rich concrete was used for structures exposed to one-sided water pressure. The use of manually compacted rich concrete in concrete dams and hydropower plants ended in the mid-1950s.

Example from this era in the annex:

- Storfinnforsen (Constructed 1949–1954).

1890–1930: Manually compacted lean concrete

Lean concrete, with a low cement content, was commonly utilized in constructing mass structures where low concrete strength was acceptable. In the early 20th century, cement-poor concrete was primarily used to construct solid dams. Typically, the upstream face of these dams was covered with a layer of cement-rich concrete and, in some cases, an outer stone cladding. The use of cement-poor concrete for hydraulic structures declined in the late 1920s and was discontinued in the early 1930s.

Example from this era in the annex:

- Älvkarleby (Constructed 1911–1915).

1900–1930: Self compacting concrete

Manually compacting wet concrete requires significant space to properly process the concrete mass. As the number of reinforced concrete structures increased, manually compacting the concrete became too labor-intensive and time-consuming. Additionally, it was challenging to ensure that the rich concrete completely surrounded the reinforcing bars. As an alternative to rich concrete, easy-to-work concrete was developed with a higher proportion of water. The use of this water-rich and soft concrete grew in popularity during the early 20th century but ceased in the late -1920s.

Example from this era in the annex:

- Älvkarleby (Constructed 1911–1915).
- Lilla Edet (Constructed 1918–1926).

MACHINERY COMPACTED CONCRETE

In the 1930s, machine-induced vibration replaced manual compaction. However, for hydropower structures, the transition from manual compaction to vibration was not fully completed until the 1950s.

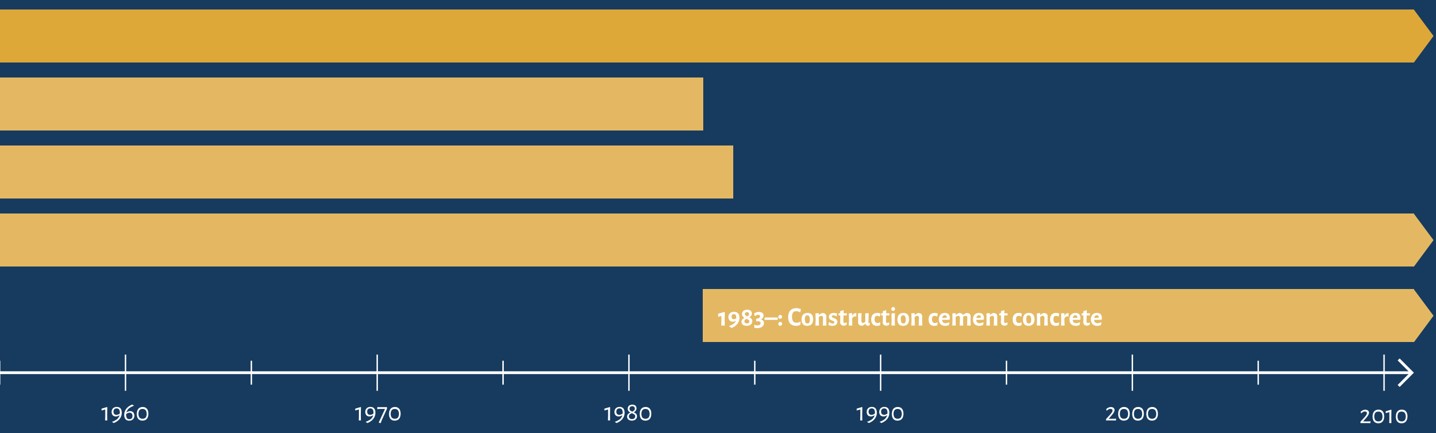
1930–1983: Standard cement concrete

Following investigations into the durability of concrete in hydropower environments during the 1920s, cement-rich concrete became the most commonly used type of concrete in the early 1930s. This type of concrete possesses both high load-bearing capacity and low permeability. The concrete type is known as standard cement concrete since standard Portland cement was used in the concrete mix. Standard cement concrete was used to varying degrees in power plant construction until the 1980s.

Example from this era in the annex:

- Storfinnforsen (built 1949–1954).

Source: Rosenqvist, M. (2018). The development of concrete technology and its significance for the expansion of Swedish hydropower [In Swedish: Betongteknikens utveckling och betydelse för svensk vattenkraftsutbyggnad]. Energiforsk, Stockholm Sweden.



1932–1984: Limhamn LH cement concrete

The increased heat generated by cement-rich concrete caused cracking issues in mass structures. To mitigate this problem, Limhamn LH cement, a slow-hardening cement with low heat development, was developed. From the 1950s and during the rapid expansion of Swedish hydropower, LH cement concrete was the primary type of concrete used for structures exposed to one-sided water pressure. Due to the decline in the construction of concrete dams, the reduced need for LH cement occurred at the same time as energy prices increased following the 1970s oil crises. These unfavorable market conditions ultimately led to the cessation of cement production in Limhamn by the end of the 1970s.

Example from this era in the annex:

- Kattstrupeforsen power plant (built 1939–1942).

1934–: Blended cement concrete

To decrease the amount of cement required for concrete, a strategy is to substitute a portion of the ordinary cement with other supplementary cementitious materials, such as silica fumes, fly ash, limestone, and slag, to create blended cement. Blended cement has been used in various forms since the 1930s and is still being used today. Its use is now primarily motivated by its ability to reduce emissions.

Examples from this era in the annex:

- Lilla Edet (Reconstructed 1980s).
- Skallböle (Reconstructed 1980s).

1940–1950: E-cement concrete

During 1941-1952, there was a rationing of standard cement and silicate cement (LH-cement), with only the highest quality cement being delivered to important and prioritized construction projects. Lower-quality replacement cement (E-cement) was used for other construction activities. Large power plants were considered a priority, as they were critical in securing the country's power supply. As a result, E-cement concrete was only used for minor structures in hydropower facilities.

1983–: Construction cement concrete

The cessation of LH cement production in the late 1970s was a significant setback for the hydropower industry, which still had a need for cement with low heat development for maintenance, repair, and reconstruction of existing dams. To address this need, Cementa developed a construction cement with a chemical composition similar to the Limhamn standard cement. Since the mid-1980s, construction cement has been the primary type of cement used in concrete for Swedish hydropower structures.

Embankment dams

Before the 20th century, Swedish embankment dams were often constructed with a more or less homogeneous cross-section made of materials available at the construction site, such as moraine, gravel, clay, and topsoil. In locations where clay was readily available, it was used to create an impermeable clay core.

Diaphragm embankments

The Porjus hydropower dam was taken into operation in 1914 as the first large embankment dam in Sweden. This dam was built according to a "belt-and-braces approach" with double watertight zones/layers; both a dense core of puddled clay and a downstream placed 25 cm thick wall of reinforced concrete. The dam functioned without problems until 1970, when it was heightened and partly replaced by a higher dam built downstream to allow the raising of the reservoir level, see further description of Porjus in Annex 1.

This approach with double impermeable layers, was seen as a model for future dams in Sweden. Consequently, until the 1950s, large embankment dams in Sweden were generally constructed as diaphragm embankments, with a central impermeable diaphragm of either concrete or wood. The thin diaphragm core was often placed in or adjacent to an impermeable core of clay or till.

Low embankment dams with wooden diaphragms are common in Sweden. Wooden diaphragms have been built with horizontal planks, vertical planks, or a combination of vertical and horizontal planks. There are also examples of dams with two sheet pile rows with compacted clay or till in between. Steel sheet piles in embankment dams are also common for water-tightness purposes for part of a dam but not as the primary diaphragm along the entire dam length. Steel sheet piles have primarily been used at connections between embankments and concrete structures, in the foundation, or as an extension of the core into connecting shores.

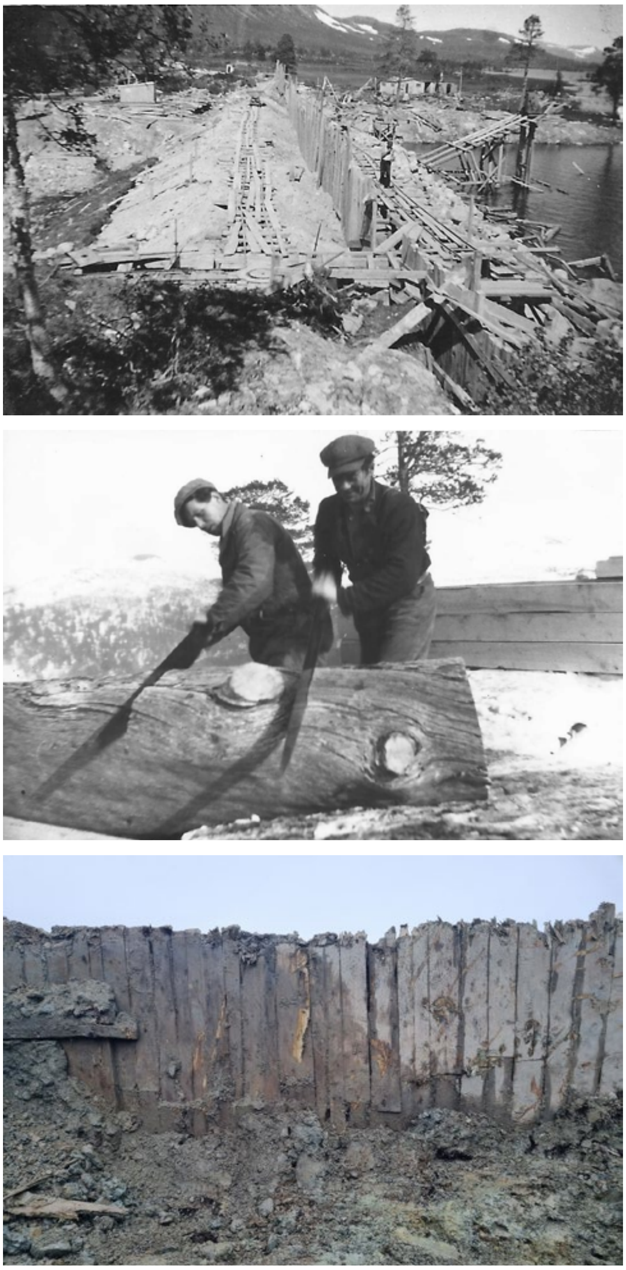
The last and largest dam built during this era is the 50 m high Harsprånget dam. At 50 meters in height, it was twice as high as the previous largest Swedish embankment dam and raised concerns about the structural capacity of the concrete wall. To address these concerns, several innovative modifications were made to the design, resulting in a very impermeable and very expensive dam.

After Harsprånget, the concrete diaphragm disappeared from Swedish embankment dams. It was instead time to build large zoned earth and rock fill dams. By the early 1950s, engineers had developed new techniques for building embankment dams using modern principles, and there were plenty of international examples of successful zoned earth and rock fill dams. This was a pivotal moment for the Swedish hydropower industry, as it was preparing for an immense expansion in dam construction. The relatively low cost of embankment dams made them an attractive option for this expansion.

Estimates from 1959 of the relative cost of constructing concrete dams compared to an earth fill dam.

	DAM HEIGHT		
DAM TYPE	**15 m**	**25 m**	**70 m**
Embankment dam	1,0	1,0	1,0
Concrete dam – Thin butress	1,6	1,4	1,3
Concrete dam – Massive	1,9	1,8	1,5

Based on data reported by Rosenqvist, M (2018), see the previous page.



Wooden diaphragm wall at Burvatten dam, during original construction and excavation in 2022. Photo: Tina Påhlstorp.

The Burvattnet dam, completed in 1943, is an embankment dam with a wooden diaphragm. The dam is situated in located in roadless land and was recently refurbished. Photo: Vattenregleringsföretagen.

The Malfors dam, an early successful example of a high Swedish embankment diaphragm dam, was built in 1934 and is 15 meters high. The dam features a inclined concrete diaphragm with surrounding clay mixed with sand. Photo: Svenska kraftnät.

Embankment dams with till core

In 1951, the construction of the first large embankment dams without a central watertight diaphragm began in Sweden, starting with the Ligga dam located downstream of Harsprånget in the Lule älv river, the Borga dam in Fjällsjöälven river and the dam at Kilforsen in the Ångermansälven river. From then on, large dams in Sweden were primarily built as embankment dams. A problem arose during the first summer of the construction of these dams, which would later recur often during construction of embankment dams. In northern Sweden, construction of till cores were only possible during the short summer season. However, wet weather conditions often cause compaction problems. Prolonged periods of rain made it difficult to dry the core material to a suitable water content for dry compaction. Placing alternating wet and dry layers may result in differential settlements, arching and crack formation, which can be especially detrimental.

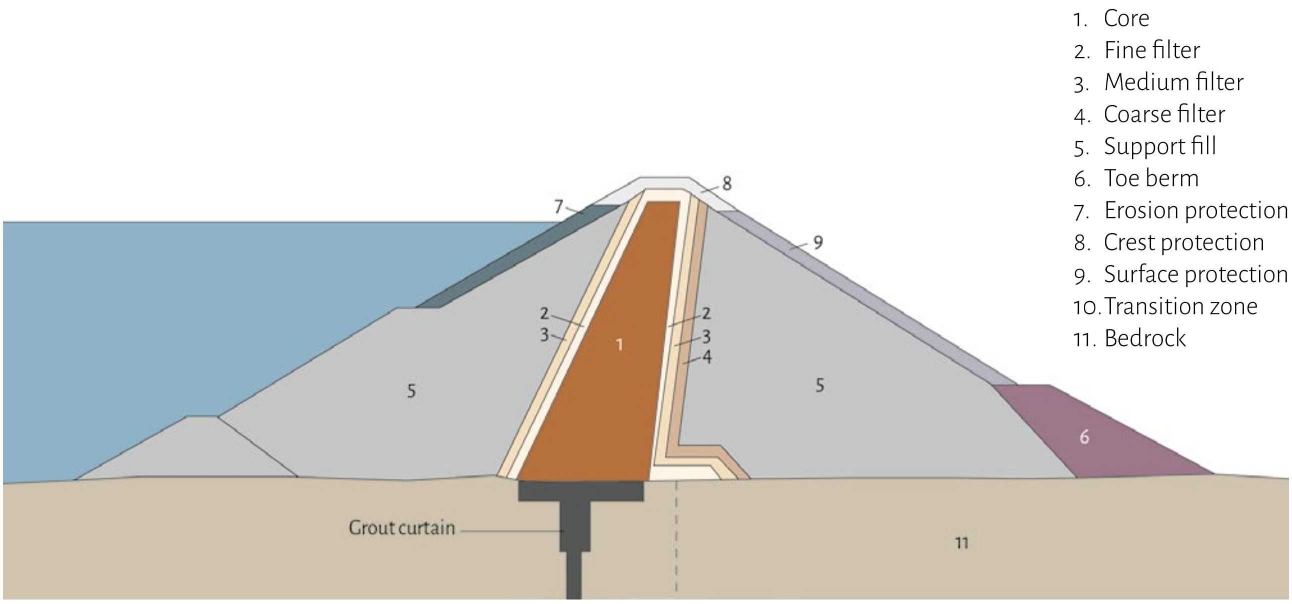
As a result, significant resources were invested in research and development to improve the speed of construction also in wet weather conditions. In particular, a wet compaction method was developed, which allowed a significantly higher water content in the till. This method was popular in Sweden and Norway during the 1950s and 1960s but disappeared in the 1970s and is no longer mentioned in the Swedish dam safety guidelines. The efforts in research and development in soil-compaction technology made Sweden an international leader in this field, with companies such as Dynapac leading the way.

The cross-section of a typical modern Swedish embankment dam, as shown in the figure to the right, consists of several zones with different functions. At the center is a core of compacted moraine with low water permeability. On both sides of the core, filters made of sand and gravel prevent the core material from eroding. The support fill creates the dam's stability and is the main load-bearing zone. The dam is protected from waves, surface water, and ice by riprap and rock fill placed at the crest and slopes.

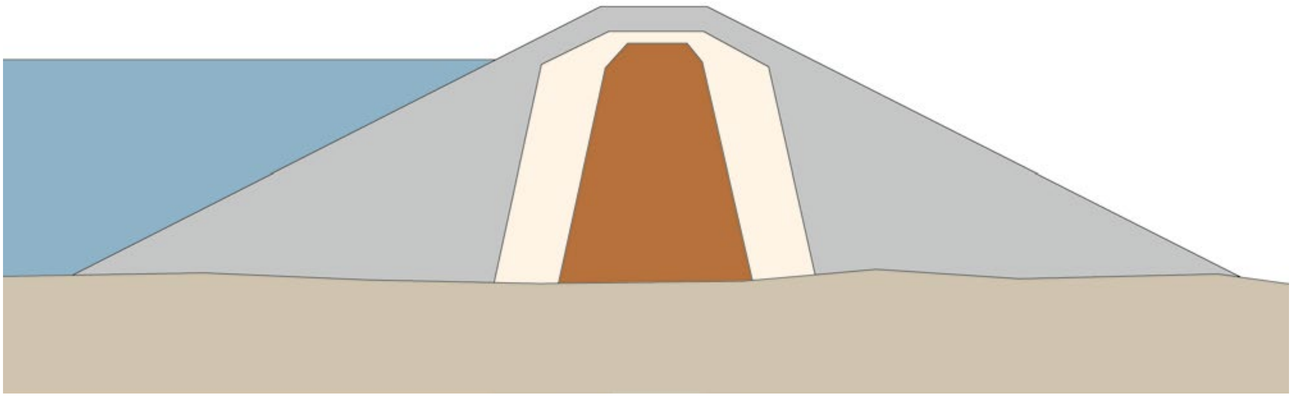
During this period, the rapid pace of expansion meant that speed and economy sometimes had priority over best practices. As a result, many dams were constructed using faster, simpler, and cheaper methods and design solutions. It was not uncommon during the 1970s to build embankment dams with only one broadly graded filter between the till core and the shoulders, to allow also larger grain sizes in the filters, to increase the layer thickness during compaction, and to reduce quality control during construction.

In the 1980s, the combined effect of such shortcuts proved to entail problems such as sinkholes and leakage incidents. This led to the need for both remedial measures, such as grouting after incidents, and preventive reinforcements. From the 1980s onwards, large investments have been made to increase the safety of embankment dams. The dominant method has been strengthening of the dam by adding a rock fill toe berm along the downstream dam toe and part of the downstream slope. This improves the dam's stability and ability to withstand large leakage and would thus provide some time for emergency actions such as drawing down the reservoir in the case of a serious leakage incident. Almost all large embankment dams have been strengthened in this way, see Annex 1 for multiple examples.

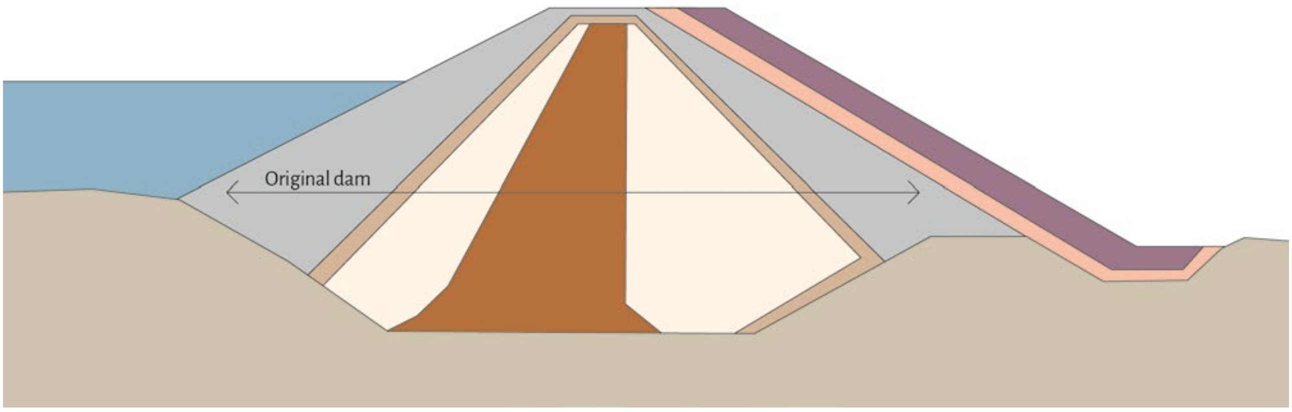
Grundsjön. Photo: Vattenregleringsföretagen.



Zoned embankment dam based on illustration in Vattenfall's Handbook on earth and rock fill dams, 1988.



Typical section of rock fill dams from the 1970s.



Example of downstream rock fill berm extended up to the crest to improve the dams stability and ability to withstand large leakage.

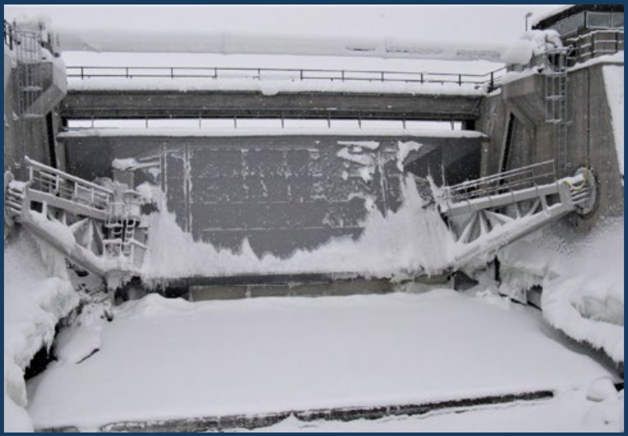
Winter discharge at Moforsen, Betsele and Bålforsen dam. Photo: Uno Kuoljok.

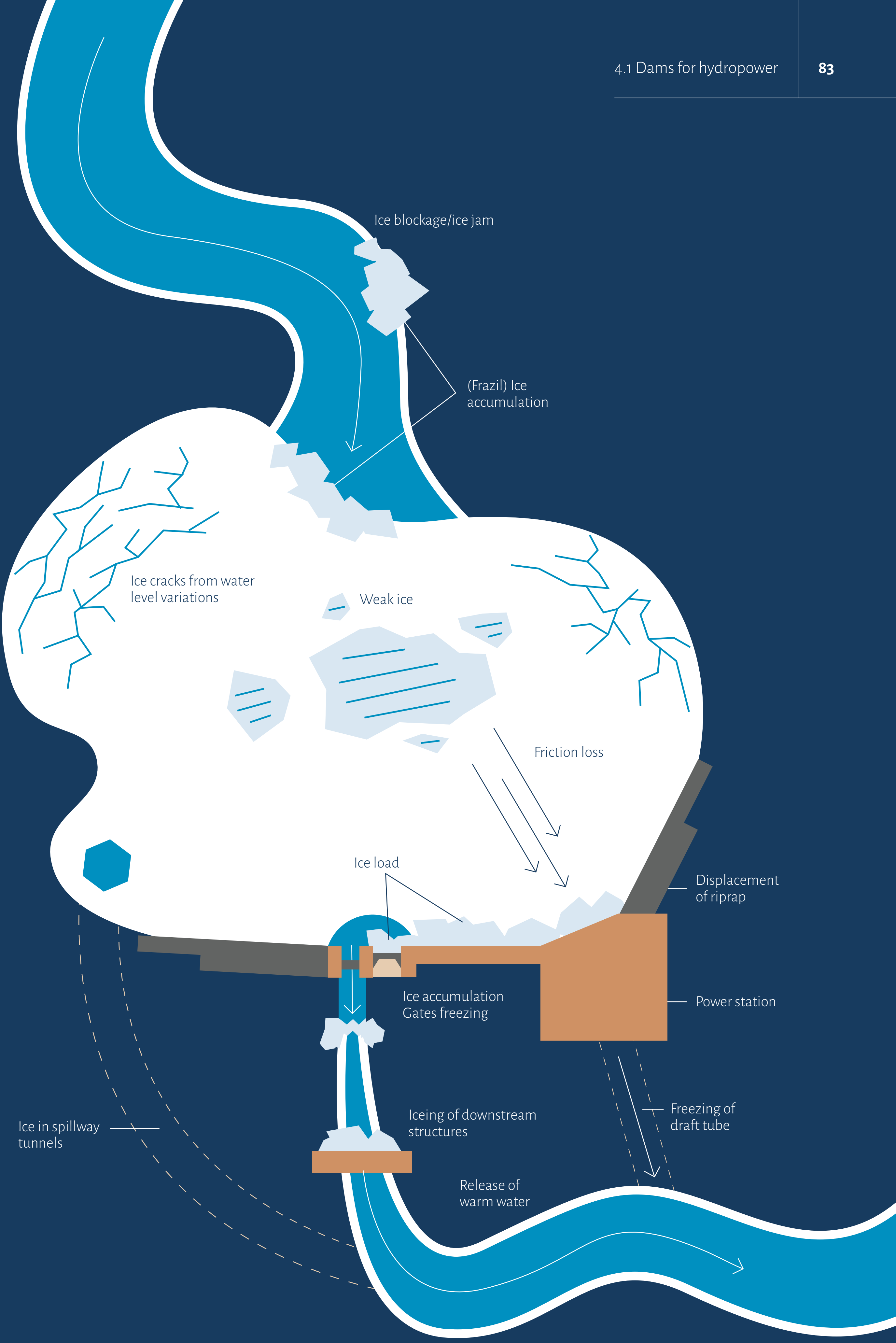
Dam safety in cold climate

In cold regions, dams typically experience severe temperature differences between summer and winter, ice-related issues during winter and significant floods during snow melt in spring. Ice has a considerable impact on the hydraulics in a river, and regulating the river can have a significant effect on the ice cover. The illustration on the right shows a schematic representation of some of the dam safety and public safety problems associated with ice, including:

- Accumulation of ice and ice floes at the intake to the power station, spillways, or various locations in the waterways.
- Gates freezing to adjacent structures or getting stuck in the ice.
- Static and dynamic ice loads on dams and reservoir slopes causing stability and erosion issues.
- Harsh environment for structures and components with repeated freeze-thaw cycles and frost.
- Weakened ice caused by fluctuations in water levels, strong currents, and the discharge of warm water.

Addressing these ice-related issues is typically a challenging task that requires costly measures.




Ice blockage/ice jam
(Frazil) Ice accumulation
Ice cracks from water level variations
Weak ice
Friction loss
Ice load
Displacement of riprap
Ice accumulation Gates freezing
Power station
Iceing of downstream structures
Freezing of draft tube
Ice in spillway tunnels
Release of warm water

Spillways

Spillways regulate water levels in the reservoirs within the permitted levels and discharge water, ice, and debris from the reservoir to the river downstream. Reliable spillways with sufficient discharge capacity are vital for the safety of a dams in case of high river flows or unexpected flow fluctuations.

A typical spillway in a Swedish dam is a concrete structure with two or three gate openings equipped with vertical lift gates or radial gates. Compared to many other countries, Sweden has a high degree of spillways that require active operation. Economic and legal considerations have shaped a tradition of wanting to be able to discharge a 100-year flood with the reservoir at the normal retention water level. Consequently, passive discharge solutions such as overflow weirs that require temporarily raising the reservoir level have often not been used. Instead, active gate operation is necessary to maintain proper water levels during periods of high inflow. This reliance on active gate operation presents an operational challenge, as the discharge capacity for some dams must be available 24/7 all year round.

The method of river diversion during the construction of dams varied depending on the type of dam being built. For embankment dams, tunnels were often used to divert the river during construction. For concrete dams, a cofferdam and a diversion channel was the more common approach. This diversion channel was eventually led through a bottom outlet. On larger dams, these bottom outlets were often taken out of operation for the larger dams and closed after construction. For some smaller dam facilities, the bottom outlets have been included in the regular discharge system and several old bottom outlets have been recommissioned for operation, often after extensive reconstruction and renovation of gates and waterways. As a result, most of the bottom outlets currently in operation are in smaller dam facilities or have recently been recommissioned in recent years.

For smaller dams located on rock of good quality, specific control measures downstream of the spillway have often been deemed unnecessary. For larger dams or when there is a risk of significant erosion, additional measures such as stilling pools, baffle blocks, or rock reinforcement with anchor bars and concrete slabs are often in place. In these cases, the spillway is often placed near the river bank to minimize construction and discharges the water back to the river via a chute or plunge pool.

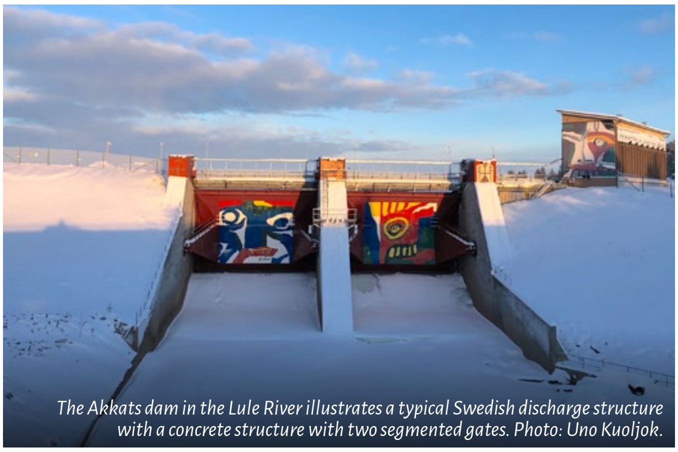
Historically, rivers in central and northern Sweden were used for log floating, and structures to bypass logs were incorporated into the dam facilities, see the next pages. The design of these bypassing structures balanced the need for log transport capacity with a minimal spill of water. Dams with reservoirs for storing excess water during the summer were often constructed with log spillways with submersible sector gates, radial gates, or other specialized overflow gates. Ordinary run-of-river facilities used funnel-shaped shallow intakes with a sector gate and a log flume. Such structures could handle thousands of logs per hour.

The Swedish climate with cold winters poses challenges for reliable and sustainable discharge. Low temperatures can impact electrical, mechanical, and hydraulic systems, causing gates to freeze and get stuck in the ice or against adjacent concrete structures. During winter discharge, ice buildup downstream of the spillway gates can impact structures and waterways. Additionally, the pressure from moving or expanding ice sheets in reservoirs can cause damage to the gates, as they are normally not built to withstand full ice pressure. To address these challenges, spillway gates in Sweden are often equipped with heating elements in the sealing and insulation on the downstream side. Additionally, air-bubble curtains, vortex generators, or utilizing excess heat from power production are employed to prevent ice buildup near the gates.

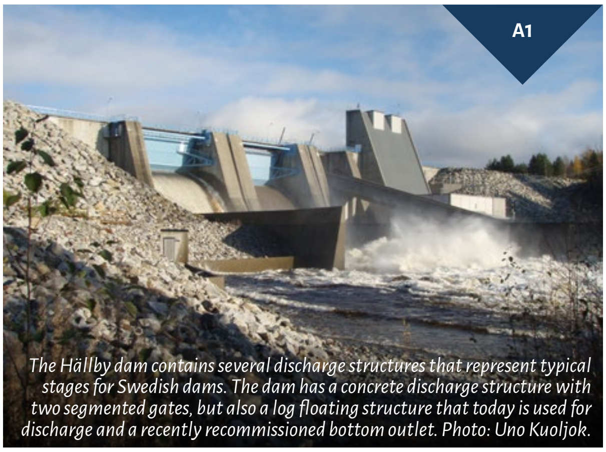
In the early 1980s, it was discovered that the principles used to determine the design flood and thus the spillways' discharge capacity during the hydropower expansion decades in Sweden needed to be revised as they had underestimated the occurrence of extreme floods in regulated rivers. Concerns were raised during high flows in 1983, and investigations had already started when the Noppikoski dam failed in 1985 due to overtopping (for more information, see Chapter 5.1). New guidelines for design flood determination were issued in 1990. Since then, the guidelines have been revised several times, and great efforts have been put into calculating and determining design floods in the hydropower rivers. Numerous projects have been undertaken to increase or secure the discharge capacity of existing dams in Sweden. Some projects involved constructing new spillways adjacent to the existing ones or in a new location, while others involved reconstructing one or more existing spillways or recommissioning inactive spillways. In many cases, the location of the old log chute was utilized for new spillways, or as previously mentioned; bottom outlets were recommissioned.

The effort to secure and increase the discharge capacity in dams in Swedish rivers will persist in the future. With global warming, the magnitude of extreme rainfall is foreseen to increase, resulting in a need for recurring reassessment of the design flood. Many rivers and dam facilities may need operational changes and/or physical measures to allow increased discharge capacity and/or temporary surcharge in the reservoir.

Overview of the discharge structure with three segmented gates at the Krokströmmen dam. Photo: Svenska kraftnät.



The Akkats dam in the Lule River illustrates a typical Swedish discharge structure with a concrete structure with two segmented gates. Photo: Uno Kuoljok.



The Hällby dam contains several discharge structures that represent typical stages for Swedish dams. The dam has a concrete discharge structure with two segmented gates, but also a log floating structure that today is used for discharge and a recently recommissioned bottom outlet. Photo: Uno Kuoljok.

The Höljes dam is an example of a large embankment dam with a discharge structure on one of the shores. The water is discharged via a stilling basin. Photo: Fortum.

A workforce of log drivers from Medelpad. Source: Swedish public domain photo taken sometime between 1910 and 1920.

Log floating

Sweden's northern and middle regions have a rich history of utilizing its main rivers for transporting timber and pulp wood through log floating. This method was favored as the forests in these areas were the source of raw materials for various coastal industries, such as saw and paper mills, which saw an increase in demand with the rise of industrialization. The summer and autumn seasons were ideal for log floating, with the timber being stored along the rivers or on the lake ice in the winter.

To regulate the flow of water and prevent logs from jamming, creating reservoirs by damming lakes in the tributaries was necessary. Cooperative log-floating enterprises were established to manage water regulation, administration and distribute costs among the companies that used the rivers for log floating. At the river mouths, facilities were established for sorting and distributing the logs to their owners.

Water regulation for log floating had a limited impact on water flow as the volume was relatively small, and the lakes were drained during the summer flood season.

At its peak, log floating transported over 200 million logs annually on the rivers during the spring and summer. However, the practise declined in the 1960s and was fully replaced by railway and road transport by the 1990s. The floating channels were gradually closed; today, some hydro-power dams still have log-spillways as a reminder of this era.

The damage caused by the straightening and channelization of tributaties for log floating has significantly impacted the natural life and surrounding areas. Restoration efforts are underway to address this damage by recreating natural habitats, such as fish spawning and river beds, to support a healthy ecosystem.

Log-spillway at the Degerforsen dam. Photo: Uno Kuoljok.

Decline of log floating in the main rivers

Source: SMHI.

Garpenberg tailingsfacility. Photo: Svenska kraftnät.

4.2 Dams for the mining industry

Dams have played a significant role in the Swedish iron industry's development. During the 17th and 18th centuries, hydropower was the primary power source in production, and industrial facilities were often placed near flowing water. Today, dams are essential in the mining industry to store mining residues.

Tailings management facilities

Most of the ore produced in Sweden before the 1950s was for direct use that caused no tailings. Therefore, a majority of the approximately 200 historical mine waste storages in Sweden were slag waste dumps. The first Swedish tailing management facility was constructed in 1930, but it took until the 1950s before this type of facility was used on a larger scale. The design of the tailings dams in the 1960s and 1970s was strongly influenced by techniques used for embankment dams by the Swedish hydropower industry, i.e., zoned earth and rock fill embankments with an impermeable till core, crushed filters, and support fill of waste rock or till. The tailing dams were raised using the downstream or centerline method approximately every fifth year. This design concept resulted in little or no restrictions on the tailings deposition within the impoundment. The factbox on page 91 shows the three main principles for raising a tailings dam: downstream, upstream, or centerline.

The topography of Sweden is conducive to valley or side-hill impoundments, and deposition normally took place from a single/end pipe discharge point from natural ground upslope that drained towards the dam structure, resulting in water along with slimes ponding up against the face of the dam. As the dams were water dams and as Sweden has relatively high precipitation rates, large volumes of water were usually stored within the tailing impoundment. The main design principle shifted in the 2000s from embankment dams designed as impermeable water dams, to drained upstream construction. This resulted in dams with an impermeable starter dam and upstream raises in some cases founded on fine tailing and slimes that had settled under water. The main factors causing this change were an increased rate of rising due to increased production that would have caused escalating dam construction volumes and costs associated with the downstream method. Changed legislation also limited the use of till and environmental constraints to stay within the same footprint.

With the basic principle for the upstream method being drainage and low hydraulic gradients this design change imposed several challenges concerning stability. In Sweden, the general solution to increase stability has been to place waste rock as berms downstream.

The deposition of tailings and water management had to change at the facilities where the change to upstream construction occurred. To be able to build the next raise of the dam, a beach had to be constructed. A beach is an exposed surface of tailings between the current dam and the supernatant pond. For this reason, spigot systems were developed. Initially, these systems were simple: a single discharge point progressively moving along the dam, depositing tailings away from the dam. The new deposit strategy resulted in free water being pushed away from the dam structure reducing the volume of free water in the impoundment to create an adequate beach width along the dams.

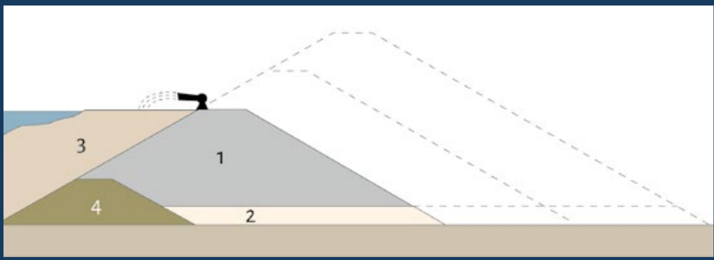
Garpenberg Tailings facility. Photo: Svenska kraftnät.

All Swedish tailing management facilities have clarification ponds separate from the tailings storage impoundment. The purpose of these ponds is to act as a second clarification step and control point before discharging to the recipient, as well as to provide storage of process water. During winter a large part of the process water discharged together with the tailings will freeze within the tailings impoundment and not be accessible until snowmelt in spring time. Water is abundant in Sweden, and saving water has not been a driving force for mining operations. However, the reduced volume of free water in the system caused by the design change has resulted in more water freezing during winter, which can pose challenges due to shortage of free water during cold periods. Water shortage can be avoided either by expanding the storage volume in the clarification ponds or by designing the tailings deposition with minimal distance between the deposition point and the spillway to minimize the time water is at risk of freezing. The latter approach requires that an adequate time for sedimentation of slimes (i.e., fine tailings particles) is maintained. Depending on the fine particle size of the tailings, that is not always possible.

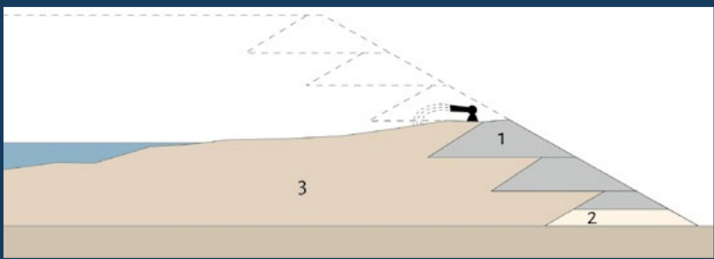
The five tailings management facilities in Norrbotten are all located above the Arctic Circle. The northernmost tailings management facility in Kiruna has an average annual temperature of -1°C and experiences over 200 days of snow cover. Consequently, the facility's design must accommodate the water requirements of process plants during the cold season. Moreover, due to the short summer, the period when dam raises and tailings deposition can occur without the risk of embedding frozen layers in critical zones is limited.

Garpenberg tailings facility. Photo: Svenska kraftnät.

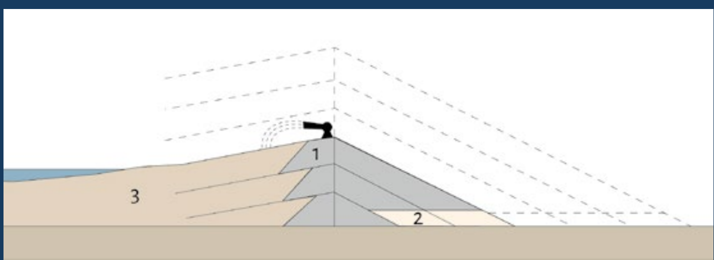
Principles for progressive construction of the main types of tailings dams



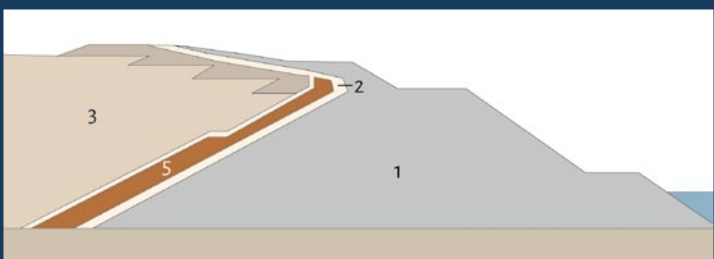
Downstream
This approach involves constructing an impermeable starter dam and depositing tailings into it. The dam crest is raised by building a new embankment on the previous section's downstream slope and moving it downstream with each raise. The height of the dam is typically built up from tailings, side material, or a combination of the two, with a filter layer, sometimes added between the tailings and the side material. The downstream slope of the dam is filled with available waste rock material as support, which is a by-product of mining and processing. Natural materials may also be used if necessary, causing the dam to widen gradually in the downstream direction and requiring increasing amounts of construction material for its height. The stability of the dam is based on natural materials and waste rock.



Upstream
This method starts with a starter dam and forms a tailings beach by depositing tailings. The tailings are compacted to form the foundation for the dam's subsequent levels as it is raised, and the crest moves upstream with each raise. To allow time for the tailings to dry and consolidate, the tailings must be raised slowly. As the raising process continues, the new dam crest rests on the previous tailings, called the beach, which is a sandy zone closest to the dam body. If the water surface is far away, the beach refers to the zone closest to the dam body.



Centreline
This method combines elements of both the upstream and downstream methods. The dam is raised vertically from the starter dam, with the crest remaining fixed in relation to both upstream and downstream directions. The stability of the structure is partially dependent on previously deposited tailings, and internal drainage may be incorporated to improve stability.



Combination
In reality, a combination of dam-raising methods have been used for the same dam over the years. The illustration shows an example of this, a dam constructed in 1974 as a dam with a core of moraine. The dam was initially raised using the downstream method and later with the upstream method, featuring a compact core. Subsequently, the centerline method with a draining section was utilized

1. Support fill 2. Filter 3. Tailings 4. Start dike 5. Till core

Ortophoto of Sweden nine active tailings management facilities.

Current tailings management

There are nine tailing management facilities currently operating in Sweden. The figures above shows aerial photos on them in same scale Aitik is by far the largest mine in Sweden (and one of the largest in Europe), with the largest footprint area, highest dam embankment, and highest rising rate. Kiruna is the second largest, and the other seven sites are more or less the same size. Most facilities are located in the northern region of Sweden (Norrbotten and Skelleftefältet), with just two mines in the historical central mining region Bergslagen. Annex 2 presents most of these dams in more detail.

An individual tailing management facility normally has more than one dam, and depending on topography, operation strategy, deposition of tailings, etc., the individual dams can serve different purposes and have different designs. Hence, a single tailing management facility may have a combination of upstream, centerline, and downstream dams as well as impermeable and drained dams.

Six of the active facilities have been in operation for more than 40 years, and their mines have a remaining life of mine well over ten years. For dam structures at the tailing management facilities with such a long operating life, the purpose, design method, and construction material have all changed during the dam's lifespan, resulting in very complex structures. Furthermore, tailing dams become higher with time and often reaches heights past the original design. The height of the dams that are currently raised is between 20 and 80 m. Understanding the complexity of these structures is critical for dam safety management.

Raising dams upstream on previously deposited tailings is challenging in many regards. It involves building dams on existing tailings that may contain loose slimes previously deposited in the new structural zone. The new design must also incorporate existing dams, such as impermeable starter dams and dams with poor drainage. The ongoing beach development is also problematic. The typically short summer period in the northern part of Sweden limits the annual period of optimal conditions for tailings deposition and active consolidation. During winter deposition, the risk of permafrost layers and drainage barriers must be carefully managed. Dealing with these complex and often conflicting constraints is an ongoing challenge for Swedish tailings management.

Recent tailings dam failures, especially the Brumadiñho disaster in Brazil in 2019, have brought global attention to the risks associated with upstream construction. While many mining companies have long favored upstream construction due to its cost efficiency and reduced need for external materials, the risks of building on and with deposited materials can no longer be ignored. As a response, Swedish mine companies have implemented several new measures to safeguard their dams' stability. Moreover, there has been a shift towards reverting to the original centerline or downstream design in order to reduce the dam's reliance on the material properties of the deposited tailings. Some facilities have already begun implementing this change, while ongoing investigations are being conducted to assess the feasibility of this modification in the remaining facilities.

Zinkgruvan tailings management facility. Photo: Zinkgruvan Mining.

Swedish tailings management facilities (TMF) in operation in 2018.

TMF	COMMISSIONING OF TMF	MINE	TYPE OF ORE	START OF MINING OPERATION (EARLIER MINING)
Garpenberg	1963	Garpenberg	Sulphide (Cu, Zn, Au, Pb)	14th cent.
Enemossen	1977	Zinkgruvan	Sulphide (Zn, Pb, Cu, Ag, Co, Ni)	mid-18th cent.
Malmberget	1980	Malmberget	Iron	1820
Kiruna	1977	Kiirunavaara	Iron	1860
Svappavaara	1963	Gruvberget *, Leväniemi	Iron	2010-2018, 2014 (1964–1983)
Hötjärnsmagasinet	2010	Kristineberg, Renströmgruvan, Maurliden, Kankberg	Sulphide (Cu, Zn, Pb, Ag, Au, Te)	1940, 1952, 2000, 2012 (reopened)
Aitik	1968	Aitik	Sulphide (Cu, Ag, Au)	1968
Björkdalsgruvan	1988	Björkdalsgruvan	Gold	2001 (1988–1999)
Kaunisvaara	2012	Tapuli	Iron	2018 (2012–2014)
–	–	Lovisagruvan**	Sulphide (Zn, Pb)	1993 (not contin.)

** Production ceased during 2018, currently on hold.*
*** The ore is sold and processed at other sites.*

Borenshults locks in Göta canal. Photo: Svenska kraftnät.

4.3 Dams and levees for other purposes

In addition to hydroelectric power and mining, dams, dikes and levees in Sweden also serve other purposes. They are used to create watercourses for inland transportation, protect cities and agriculture land from flooding, provide drinking water, process water, and even for artificial snow production. This section describe these dams.

Other dams and levees

Canals

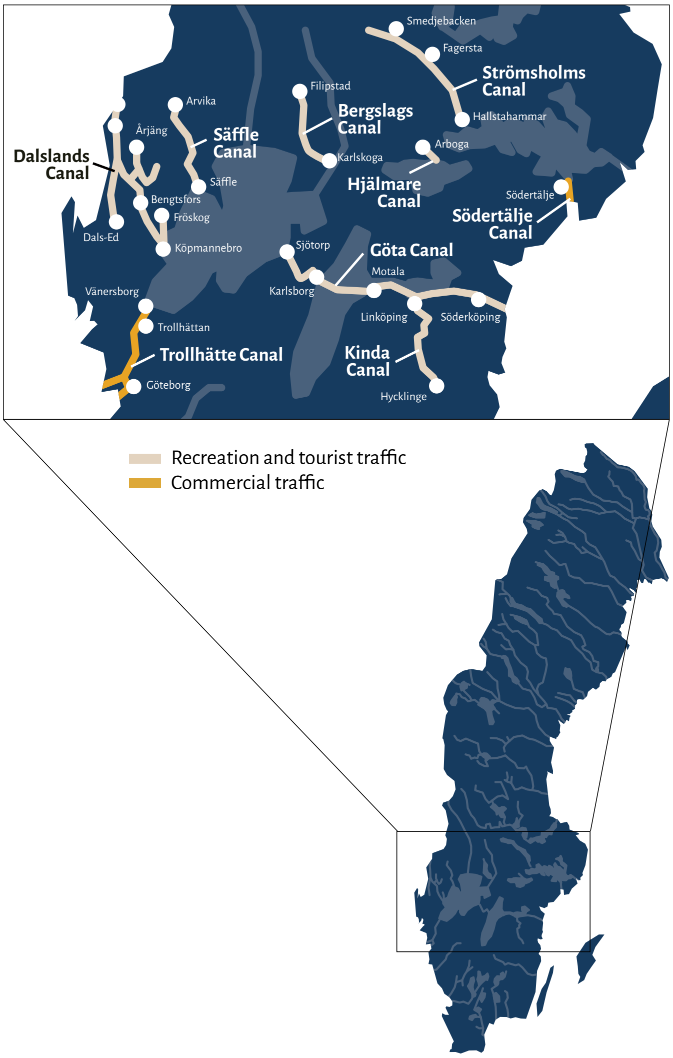
Swedish lakes and watercourses have been used for transportation ever since humans first re-inhabited the country after the last ice age. Transportation occurred on natural watercourses, and people walked or pulled boats overland between lakes or past rapids and other natural obstacles. The first canal built in Sweden is the 180-meter-long Drags canal in Kalmar in the southeast part of the country, completed in 1558. The canal was built through a peninsula on the coast and did not require any dams. The canal enabled ships to approach the Kalmar Castle without crossing the difficult-to-sail Kalmar strait.

Canal traffic developed strongly in the central Swedish forest and iron districts, and this is where one finds the once economically important canals, mainly in central Sweden. The first long canal with locks was the Hjälmare Canal connecting the two lakes, Mälaren and Hjälmaren. The canal was completed in 1639 and then rebuilt in 1701 and 1830.

The most well-known canals, are Göta canal, together with the Trollhätte canal, which links a number of lakes and rivers to provide a route from Gothenburg on the west coast to Söderköping on the Baltic Sea. Nowadays, the Göta canal is, like most of the canals in Sweden, operated only by tourist traffic. The two exceptions are the Trollhätte Canal and the Södertälje Canal, which still fulfill an important role in providing commercial traffic access to lake Vänern and lake Mälaren, respectively.

Canals have also been used for hydropower in Sweden, primarily through the use of inlet canals that lead water to the power station's intake. Such structures are used for intakes away from the main river or to transport the water past several natural falls to increase the head at the power station. In addition, canals can redirect water from the power plant back into the natural waterway. However, dams are usually not needed in this case.

Inland waterways with canals



Sweden's most important canals and inner waterways

NAME	COMMENCED	TOTAL LENGTH (km)	MAN MADE LENGTH (km)	HEIGHT DIFFERENCE (m)	NO OF LOCKS
Bergslags Canal	1850	64	4	16	6
Dalslands Canal	1864	250	10	66	31
Göta Canal	1810	190,5	87	92	58
Hjälmare Canal	1629	13,7	8,5	22	9
Kinda Canal	1871	80	6	50	15
Strömsholms Canal	1777	110	10	100	26
Säffle Canal	1837	80	0,5	1	1
Södertälje Canal	1806	6	4	0,6	1
Trollhätte Canal	1800	82	10	44	6

Wetlands

During the 19th century, it became essential to make agriculture more effective to support Sweden's rapidly growing population. To create more arable land, the water level of many lakes and wetlands was lowered. This intensive drainage era lasted from 1880 to 1950, affecting some 2,000 lakes. Removing wetlands negatively impacted plants, birds, and other animals that thrive in such an environment.

However, today, efforts are made to create new wetlands and recreate lost ones. In many parts of Sweden, wetlands have recently been recreated by building small dams to flood meadows along watercourses and by re-raising the water level in previously drained lakes.

The drainage of the lakes Tåkern and Hornborgasjön exemplify both the often radical drainages projects and the subsequent restoration. You can read more about them in Annex 3.

Flood control

Rising sea levels and storm surges pose a threat to coastal areas around the world. Compared to many other countries, the Swedish coastline is relatively spared from problems related to rising sea levels thanks to its topology and the ongoing land uplift. In large parts of the country, land uplift still occurs faster than the expected sea level increase. However, rising sea levels are not an insignificant problem in Sweden. Especially for the flat and well-populated southern parts of the country. For example, due to its low elevation and vicinity to the sea and a major river, the city of Kristianstad, see Annex 3, is protected by a levee system and has to address the effect of sea level rise and more extreme river flow.

Many of the large and medium-sized cities in Sweden are located near the water, which means that they may be vulnerable to flooding when the water level in the sea, lakes, or watercourses rises above normal. Sweden has so far been relatively spared from major flood disasters, and deaths associated with floods are rare. However, material damage and costs for society due to floods are significant. The major

Tåkern. Photo: Svenska kraftnät.

floods that occurred at several locations in the catchment area of Lake Vänern year 2000/2001 have triggered investigations, cooperation, changes in water regulation, and investments in extensive flood defense. Read more about such an example in Annex 3 about Arvika.

Water Supply

Until the mid-19th century, groundwater was used as the main water supply for both rural areas and cities. When cities grew with increasing population and density, the natural groundwater could no longer supply the water demand. This increased demand was met by using water from lakes and rivers as drinking water. Today, 50 % of Sweden's water supplies are surface water from lakes and watercourses, and the other 50 % is from groundwater. Some examples of important water reservoirs for water supply are lakes Bolmen and Vombsjön.

Dams and the water in reservoirs primarily used for hydropower may also constitute important water supplies to nearby communities.

Irrigation

There are few dams constructed for irrigation purposes due to dry periods. You can find examples of smaller dams and reservoirs for irrigation, such as crops and golf courses.

Snow production

This chapter started with dams used in the early creation of modern societies. Therefore, concluding the chapter with examples of how dams are used for new purposes today is appropriate. Tourism has become an ever-growing share of the world's and Sweden's economies. Especially with increased urbanization and the decline in production industries in rural areas, tourism is a significant industry for many communities. Tourism in the Swedish mountains is winter-dominated and driven by downhill skiing. Dams store water to create artificial snow to maximize the length of the skiing seasons. One example of such a dam is the dam at the ski resort Björnrike, see Annex 3.

Göta canal. Photo: Svenska kraftnät.


Former hydropower dams in Norrköping. Photo: Svenska kraftnät

5. Framework for dam safety

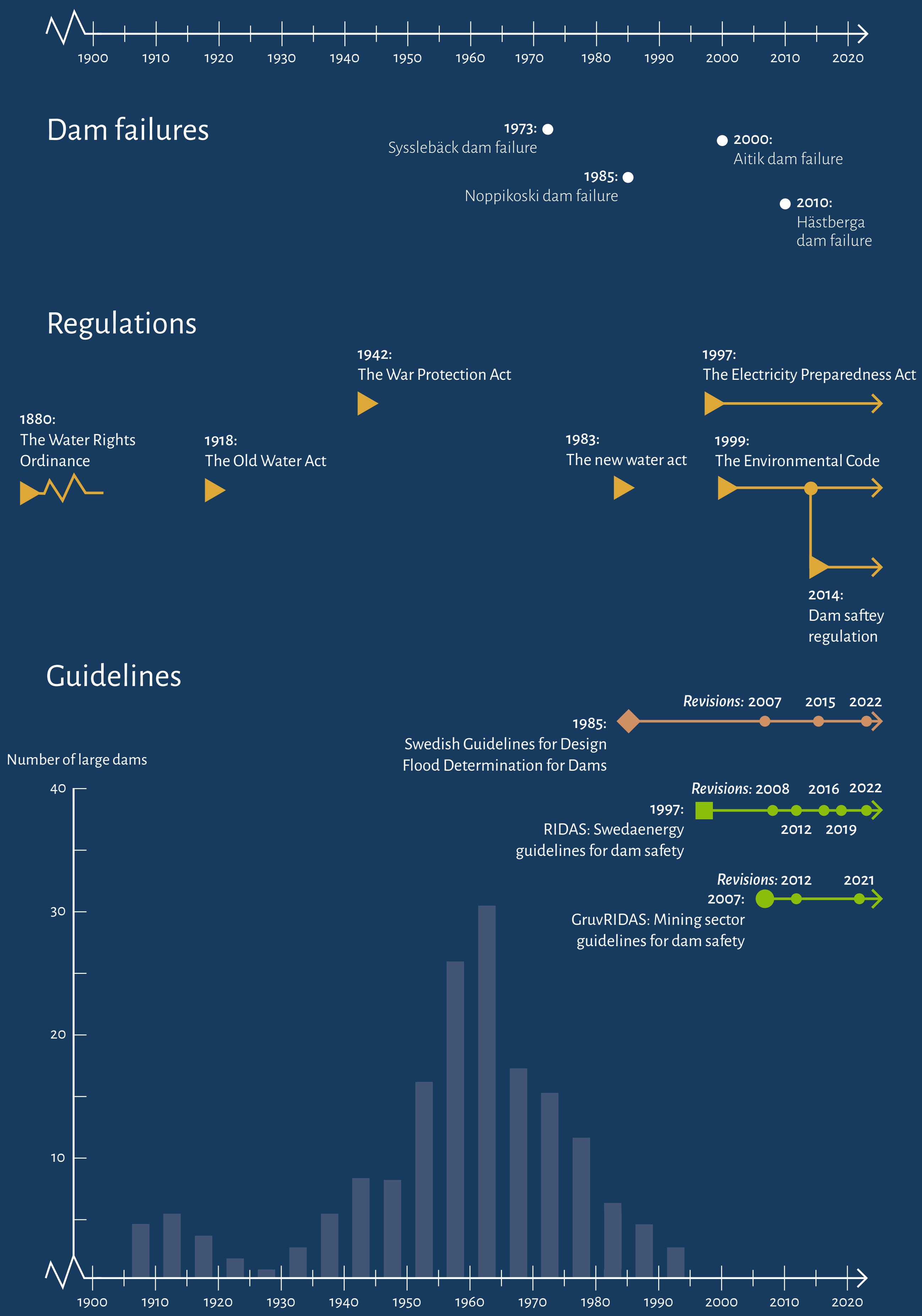
5. Framework for dam safety

This chapter presents the Swedish framework for dam safety and its development over time.

Historically, dam safety issues have not been subject to regulatory supervision to any great extent in Sweden. Dam safety development has not been governed by state standards or regulations for how dams should be built or monitored. Instead, the industry has developed practices and guidance through various initiatives.

During the 20th century, the legal framework was strengthened to facilitate the development of hydropower resources necessary for meeting the increasing demand for electricity. Over the years also the occurrence of floods and dam failures, as well as changes in the expectations and the balance of societal interests have called for actions by the state.

As a conclusion the basics of the current the dam safety regulations and some key statistics are summarized.



The Swedish framework for dam safety has mainly been developed after the construction of the large dams.

5.1 Historical developments

This section presents the emerging legalislation related to dams, driven by the nations aspiration of industrialization as well as accidents and floods.

Tåkern dam. Photo: Svenska kraftnät.

A brief history of older laws

Dam structures used for various purposes have played a central role in Sweden's development over the past centuries, and the first known regulation for watercourses dates back to the early Västgöta Law from the 13th century.

Older laws and rights for water operations

According to the Swedish Building Code of 1734, landowners were entitled to use the water on their own land as long as this was not detrimental to other interests. Permits were not required, but landowners held strict liability for damage caused to another party's land. In order to conduct commercial activities, however, landowners were required to have a letter of privilege issued by the Swedish Crown. A party that undertook activities without the support of a letter of privilege could invoke the right of possession as the legal basis for the activities, provided that the water activities had been conducted for an extended period of time (around 90 years).

As from 1846, the freedom to run any type of business was gradually introduced. The 1880 Water Rights Ordinance made it possible for landowners to apply for a permit from the court to build or renew a dam. The permit process included a socioeconomic assessment and notification of the applicable terms to ensure that the activity would not cause harm to other parties. However, damage to another party's land caused by a dam could be permitted if it was minor compared to the benefit of the dam, and compensation was paid for the damage.

Water Act of 1918 and technical expertise during the hydroelectric power expansion era

During the 19th century, dams were an important part of the transition to industrialism. In 1918, the Water Rights Ordinance was replaced by the Water Act (1918:523). Combined with technological development, the Act enabled major exploitation of the country's hydroelectric power assets. Permits were granted by special water courts with specialised members who focused their review on socioeconomically balancing the benefits and the costs and damage that a dam facility would entail. There were no specific regulations about dam safety in the Act. The main structure and layout of the facility was normally described in the application to the court, but it was up to the dam owner to decide the detailed aspects of design, construction and surveillance of their dams. Consequently, most dams were designed and constructed without intervention by the authorities on technical aspects, with the exception of requirements regarding protective measures for dams and power plants in the event of war.

In general, the Swedish dam owners have been aware of their responsibility and used the knowledge and experience available at each time, and have also supported research and development in the field of dams. At an early state, the State Power Board (Statens Vattenfallsverk, now Vattenfall), developed various instructions for the design and construction of dams, which were also used by other companies. Swedish engineers were engaged in international committee activities, and in 1931 Sweden became one of the first member counties of ICOLD. During the hydropower expansion period there was also technical expertise and a hydraulic laboratory at the Royal Institute of Technology in Stockholm.

Since the 1920s, the state highlighted the need for measures to reduce the vulnerability of electricity supplies. During the Second World War, the Act on Special Protective Measures for Certain Power Plants (1942:335), known as the War Protection Act, was adopted.

Rasmus mill, Röttle. Mill dam from the 1650s. Photo: Lars Bånge.

Fast hydropower expansion – 1950s to 1980

After the war the construction of large hydropower facilities took off and culminated in the 1950s-1970s. Since the late 1970s there has been no major new construction of hydropower facilities, which means that most of large dams have been examined under the old Water Act from 1918.

Industry collaboration on dam safety

Knowledge and experience of dam construction technology was crucial for this development, and dam safety developed into a separate discipline. Through the Power Industry Foundation for Technical Development Work, VAST, the Swedish power industry issued instructions for the safe operation and surveillance of dams in the 1960s, followed by several updates up to 1990.

Introduction of authority supervision and the New Water Act of 1983

For many years, Sweden did not experience any dam failures with serious consequences. In 1973, however, the small Sysslebäck dam failed during a flood in the River Näckån, a tributary to River Klarälven, and caused one fatality. The accident attracted attention in the media, and dam safety caught the attention of the government and the parliament. As a result, the parliament issued a new provision in the Water Act of 1918, empowering the county administrative boards with a legal possibility to intervene against negligent dam owners.

Furthermore, an official commission with the assignment to prepare a bill for a new Water Act was given an additional assignment to propose how to arrange authority supervision of dams. In 1983, the new Water Act (1983:291) containing provisions that designated county administrative boards as the supervisory authority for water companies and water installations, including dam safety supervision.

In parallel, the Swedish Power Association (now Swedenergy) and the State Power Board (now Vattenfall) had set up an advisory dam safety board in 1978 with the task to provide written recommendations for dam supervision and safety issues. The Government found the initiative to be of great importance and appointed its' members in 1982. Until the late 1990s, among other things, the dam safety board issued guidelines for the county administrative boards' supervision of medium-sized and small dams and provided a list of qualified dam safety experts that could be hired for inspection of dams.

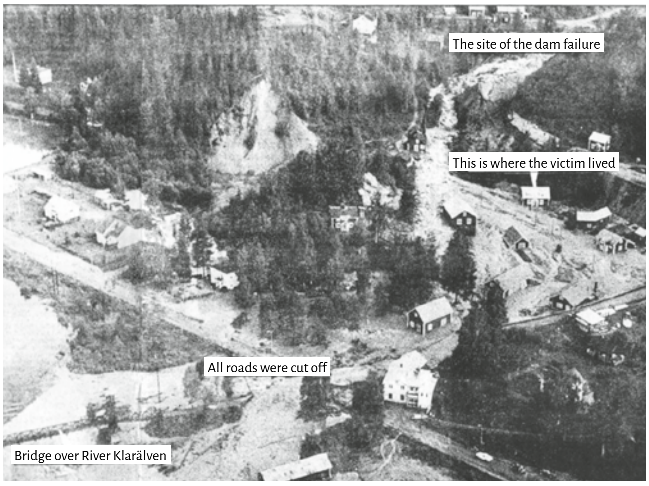


Photo: Unkown.

The Sysslebäck dam failure, 1973

The dam failed through overtopping during a floodevent and the reservoir of about 12 000 m³ was released. Headline from the newspaper Aftonbladet (photo to the left), Sunday July 22, 1973: "*Sysslebäck a few hour after the catastropy. Everything is chaos*."

The dam was located at the top right of the photo, the person who was swept away and killed lived in a small house just downstream. All roads were cut off, as well as the bridge across River Klarälven.

The 1,2 km long and 24 m high Sveg dam in River Ljusnan dam. The hydro power facility was taken into operation in 1975. Photo: Svenska kraftnät.

Floods, dam failures and government enquiries – 1980s and 1990s

Flood, failures and a government enquiry 1980s

In the mid-1980s high river flows and flooding occurred in different parts of the country. In connection with a flood in September 1985, an embankment dam at the Noppikoski power plant in the Ore River in Dalarna was overtopped and breached. The dam failure resulted in damage to forests, roads and a downstream power plant, but no personal injury. As a result of these events, the government ordered an enquiry in December 1985. The enquiry submitted its report “Dam Safety and Protection from Flooding” (SOU 1987:64) in 1987 and the conclusion was that “dam safety in Sweden is generally good and is being further improved”. Nevertheless, proposals were made to amend the Water Act in order to give safety aspects impetus in court during the permitting process and to instruct certain county administrative boards to undertake dam inventories. The enquiry also stated that county administrative boards should make greater use of the dam safety board’s expertise than hitherto.

New stricter design flood guidelines

In 1985, yet before the Noppokoski dam failure, the power industry and the Swedish Hydrological and Meteorological Institute had already formed The Swedish Committee for Design Flood Determination, with the mission to draw up guidelines for design floods for dam facilities. Five years of extensive research and development work demonstrated that the magnitude of extreme river flow had previously been underestimated. In 1990 the new design flood guidelines were published and the government was officially informed. The power industry declared they would take active responsibility for applying the guidelines. As a result, since 1990, the majority of Swedens’ large dams have been upgraded to be able to withstand and pass larger design floods than their original design.

Floods and a government enquiry, 1990s

Also in the 1990s, the occurrence of high river flows was frequent and extensive flooding affected different parts of the country. These events caused the government to appoint a special investigator with the task of investigating issues relating to dam safety and flood protection. The investigation reported its results in 1995 in the report “River safety” (SOU 1995:40). The conclusion was that Sweden lacks cohesive governance and control of dam safety and preventive measures against floods. Among other things, the investigation therefore proposed that a central body for authority tasks should be established. Furthermore, it concluded that long-term research is necessary in order to maintain and develop knowledge and expertise in dam safety, and that the state should make a targeted effort to ensure that such research takes place.

Construction work to provide the Håckren dam with a new surface spillway. Photo: Vattenregleringsföretagen, 2006.

Photo: Lantmäteriet.

The Noppikoski dam failure, 1985

The Noppikoski dam was an 18 m high earth fill dam with central till core from 1967. After a period with more rain that normal and thus high ground water level, heavy rainfalls lead to rapidly increasing river flow in the beginning of September 1985. When the operators attempted to open the spillway, consisting of two openings closed with stoplogs and operated with one joint hoisting machine, a mechanical fault occurred. One stop log got stuck in the guides and at the same time it was not possible to release the hoisting machine from the stop log. Without the machine the stop logs in the other spillway opening could not be lifted either.

The incident occurred during the night, and given the weather conditions, flooding and erosion of access roads it was not possible to get a mobile crane to the site in time and helicopters were unable to fly. Also the power to the facility was cut, the telephone line to the dam went dead and it was difficult to find additional qualified staff.

The water level in the reservoir kept rising and after about 10 hours it reached the dam crest. The crest was overtopped and erosion started in the downstream slope and rapidly resulted in a dam breach. The reservoir of 1 million m^3 was emptied in 45 min. The flow caused damage in a area of 20 km along the river. Due to the fact that the area was "wilderness" the damage was limited to destroyed bridges, roads and forest.

The dam was rebuilt in 1986. The eroded section of the earth fill dam, about 66 m, was replaced by a concrete buttress dam designed as an overflow dam with crest level 0,2 m above the normal retention water level. The old stop logs was replaced by a radial gate in each spillway opening.

5.2 Modern developments

In the 1980s new contruction in hydropower ceased. In recent decades, instead, rebuilding and upgrading of existing dams with regard to aging and new safety guidelines has been – and is – an extensive activity. In parallell modernization of the legislation, roles and reponsibilities have continued.

Forse hydropower facility. Photo: Svenska kraftnät.

A national dam safety authority and industry guidelines, late 1990s

Svenska kraftnät takes on the role to promote dam safety

Based on the enquiry's proposal for a central body for official tasks, as from 1998 the government assigned Svenska kraftnät, the Swedish National Grid Agency, a central role in the area of dam safety. Since then, Svenska kraftnät has the overarching authority task of promoting dam safety in Sweden, including provision of supervisory guidance to the county administrations, promoting the development of coordinated preparedness for dam failures and floods, and supporting research, development and education in cooperation with the industry are important areas for Svenska kraftnät's dam safety activities.

Transfer of the Water Act's provisions to the Environmental Code

In 1999 the provisions of the Water Act were transferred to the Environmental Code. From there on, the Environmental Code's generally applicable general rules of consideration and the self-regulation provisions, together with the provisions of the previous Water Act on e.g. maintenance obligations for water installations, have constituted the main regulatory framework for dam safety.

Power industry develops comprehensive dam safety guidelines, RIDAS

In the 1990s there was an increasing awareness of dam safety issues in the power industry and a request for common, comprehensive dam safety guidelines. After extensive investigative and development work Swedenergy published industry guidelines for dam safety, "RIDAS", in 1997. Since then RIDAS has been complemented by application guides and revised several times, and Swedenergy provides a package of regular training courses on dams, dam safety and RIDAS.

The Swedish industry guidelines, just as the guidelines for the determination of design floods for dams, include requirements that in many cases are stricter than the demands of the time when the majority of the dams where constructed. As a result the guidelines have triggered and still trigger dam safety measures and major upgrading of high consequence dams.

Svenska kraftnät gets the mandate to promote dam safety, 1998

Svenska kraftnät promotes dam safety through activities in the following areas:

Requirements and guidance:
We contribute to national coordination and development through clear requirements, guidance and follow-up. We have the mandate to issue regulation regarding the requirements in the Dam Safety Ordinance (2014:214).

Supervisory guidance:
We guide the county administrative boards in dam safety matters under Chapter 11 in the Environmental Code in order to achieve effective supervision. We provide advice and assistance to the county administrative boards in supervisory matters. We coordinate, follow up and evaluate the supervision on dam safety.

Climate change and design floods for dams:
We follow the impact on dam safety related to climate change. We interact with the hydro power industry, the mining industry and the Swedish Meteorological and Hydrological Institute (SMHI) in the development work. Together we have issued guidelines for determination of design floods for dams.

Emergency preparedness for floods and dam failures:
We work to reduce the risk of serious impact to society caused by flooding or a dam failure in regulated rivers. We participate in the development and practice of coordinated emergency preparedness planning for dam failures in major regulated rivers.

Capacity building and development:
We promote capacity building through research, development, education and information in collaboration with stakeholders. We support development projects in the dam safety program of the Energiforsk (Swedish Energy Research Centre). We also support the competence center Swedish Centre for Sustainable Hydropower.

Information and collaboration:
Together with stakeholders we spread information and experience on dam safety both nationally and internationally. We also participate in various networks and reference groups. In support of our function, we have a consultative body, the Dam Safety Council.

Permit applications and formal consultations:
We participate in consultations and respond to submissions and referrals, inter alia, in permit application cases under Chapter 11 of the Environmental Code.

Overall information on Svenska kraftnäts role as National Transmission Grid Agency in Chapter 2.

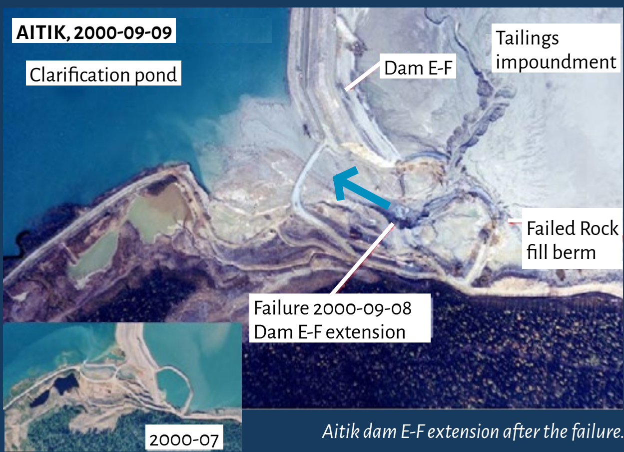
Source: www.svk.se

Tailings dam failures, regulation on extractive waste and development of industry guidelines

Failures in the Aznalcóllar tailings management facility in Spain in 1998 and in Baie Mare in Romania in 2000 had major environmental impacts and led to the EU Directive (2006/21/EC) on the management of waste from extractive industries, which includes tailings dam safety.

In 2000, a tailings dam failure also occurred in northern Sweden in the Aitik tailings management facility. The consequences could have been extensive, but were fortunately relatively limited as the tailings were mainly deposited in the clarification pond. In 2002, the Swedish mining industry organisation Svemin decided to use RIDAS as the starting point for the development of special guidelines for tailings dams, GruvRIDAS. A common dam safety policy was adopted in 2005 and the first issue of GruvRIDAS was completed in 2007. In the same way as Swedenergy, Svemin updates the guidelines as required, and holds recurring courses on dam safety for tailings dams.

In 2008, the EU directive was implemented in Swedish law in 2008 through an ordinance on extractive waste (revised and replaced in 2013 by ordinance 2013:319). The safety requirements on tailings storage facilities include systematic accident prevention work and contingency planning. The Swedish Civil Contingencies Agency (MSB) is the central authority for these issues, and the county administrative boards act as supervisory authorities.



Aitik dam E-F extension after the failure.

The Aitik dam failure, 2000

In year 2000 the Aitik tailings impoundment was limited by the surrounding landscape and four embankments - including the dam E-F extension, a homogenous till embankment. The starter dam had a central impermeable core of till and support fill of till. Filters were used on the downstream side of the core and between the foundation and the support fill. The embankment had been raised four times using the downstream method. Water was decanted by a decant tower and a horizontal culvert through dam E-F extension, for final clarification in the clarification pond downstream.

In the evening on September 8th in 2000, a section, 120 m wide and approximately 17 m in height, of the dam E-F extension failed, which led to the discharge of totally 2.5 million m^3 of water from the tailings impoundment. The subsequent rise of water level in the clarification pond (1.3 meters) caused an uncontrolled discharge of 1.5 million m^3 clarified water into the downstream recipient. 1 million m^3 of water was kept in the clarification pond. No environmental consequences were recorded except for a temporary and limited rise of suspended solids content in the river system.

There are two main theories explaining the course of event of the failure.

- One theory is that seepage led to elevated pore pressures in the downstream part of the dam due to poor draining capacity of the filter layers. This resulted in erosion or sliding failures in the support fill (till) at the toe of the dam. The first slip surface at the toe of the dam then lead to subsequent larger slides, which finally caused a complete failure.
- The other theory is that internal erosion along the discharge culvert (possibly in combination with openings in the joints between the culverts concrete pre-fabricated elements and /or collapse of the culvert) forced the embankment to fail.

After the failure, the production in the mill was suspended. The production could, however, be resumed successively during the coming week. Erosion damages around emergency spillways, caused by the excessive flow, were corrected immediately as they were threatening the safety of the clarification pond dam I-J, which held approximately 15 million m^3. Water was discharged using the two main spillways from the clarification pond dam I-J, until the permitted water level was reached in the beginning of December.

During the autumn the failed dam E-F extension was replaced by a new dam, dam E-F2. Dam E-F2 was built as an upstream dam using tailings, filters and waste rock.

Towards enhanced dam safety regulation, 2006 -

Review and oversight of the state's commitment to dam safety

In 2006-2007, the National Audit Office conducted a review of the state's efforts for dam safety. The finding included a proposal for the government to initiate oversight of state dam safety initiatives. The assignment was given to Svenska kraftnät and in 2010 Svenska kraftnät reported that dam safety needs development and that the current dam safety system does not fulfil the safety requirements of today's society. The recommendation for strengthened government measures were primarily motivated by the fact that there are dams that, in the event of failure, would not only endanger the lives and health of many people, but could also cause serious disruptions to society's essential services. For these facilities, it is particularly important that society has expert insight into and control of safety. Svenska kraftnät considered the authority supervision of dam safety to be weak and that there was a need for governing principles and more detailed dam safety regulations, as well as clarification of what the dam owners' responsibility for self-regulation, as required by the Environmental Code, actually entails.

Dam failures in southern Sweden

In autumn 2010, just after Svenska kraftnät's report to the government, there were two embankment dam failures in southern Sweden. At Granö power plant in Mörrumsån, there was a minor breach of a canal dam at the connection to the intake structure, resulting in damage to the power plant. At Hästberga power plant in Helge Å, there was a full-scale dam failure with local consequences, around one million m^3 of water flowed out of the reservoir flooding nearby properties, a road and causing collaps of a bridge. The Hästberga dam failure was investigated by the Swedish Accident Investigation Authority (RO 2011:01).

Government enquiry on dam safety regulations and enhanced supervision

Based on the recommendations expressed in the recent investigations of the state's effort for dam safety by the National Audit Office and Svenska kraftnät, a governmental investigator was appointed in 2011 with the mission to submit proposals for a clarified set of regulations for dam safety, complementing the general provisions of the Environmental Code. The enquiry reported its results in 2012 in the report "Dam safety – clear rules and effective supervision" (SOU 2012:46).

The Hästberga dam failure, 2010

The Hästberga dam was a 14 m high earth fill dam from 1953 with a central sheet pile of wood and concrete as water stop. The freeboard was a little less than 1 m. The spillway consisted of two openings with radial gates.

The water flow in the river was normal before the accident. The power station stopped in the evening of Nov 5. The remote control system did not work properly and no actions were taken from the owner's organization. This together with lack of power for the alarm system and the gate control system resulted in a slowly rising reservoir water level, that went unnoticed. The automatic gate opening system did not open the spillway gates and at noon on Nov 7 the dam was overtopped. Erosion started in the downstream slope on the embankment dams on both sides of the power station, accelerated very rapidly and resulted in a dam breach.

The storage volume of about 2 million m^3 at crest level was discharged in a couple of hours. The flow caused damage in an area of 5 km along the river to a lake situated downstream where the flow was reduced to the size of a high flood. The damage was limited to a destroyed bridge, roads, agricultural land and forest.

The dam has not been reconstructed.

Dam failure in Hästberga Dam 2010. Photo: Maria Bartsch.

Basic legal framework

Instead of a specific law concerning dam safety, several general statutes are applicable to dams and dam safety issues. The most important regulations are found in the Environmental Code and the Civil Protection Act. The Environmental Code, which includes the former Water Act, applies to all dams irrespective of size, purpose and type of owner. Within this set of rules and regulations there are also government ordinances concerning owners' self-regulation and the role of supervisory authorities.

Supervision and supervisory guidance

The entities concerned with the supervision of dam safety in Sweden:

- Svenska kraftnät (Swedish National Grid Agency) has the function as a national authority for dam safety. The overarching task is to promote dam safety in Sweden, provide regulations and guidance related to the dam safety regulations and to provide supervisory guidance on dam safety to the regional supervisory authorities. In practice supervisory guidance includes development of uniform routines for dam safety supervision, to coordinate, support, follow-up and evaluate the supervision. Svenska kraftnät also sponsors research, development projects, education and capacity building, and acts for development of coordinated emergency preparedness for dam failure and floods in regulated rivers.
- The 21 county administrative boards are the operative supervisory authorities for water operations, according to the Environmental Code, which include all dams and dam safety. The supervision comprises among other things to check that the regulatory framework and the terms of permits allotted by the Environmental Court are adhered to, and that the owner takes action when necessary to improve the safety of a dam.
- The 290 municipalities are responsible for planning for and providing rescue service for example concerning flood situations caused by heavy rainfall and snow melt or dam failure. The municipalities are responsible for supervision of the dam owner´s compliance with the Civil Protection Act for about 200 dam facilities classified as dangerous facilities.

Technical expertise

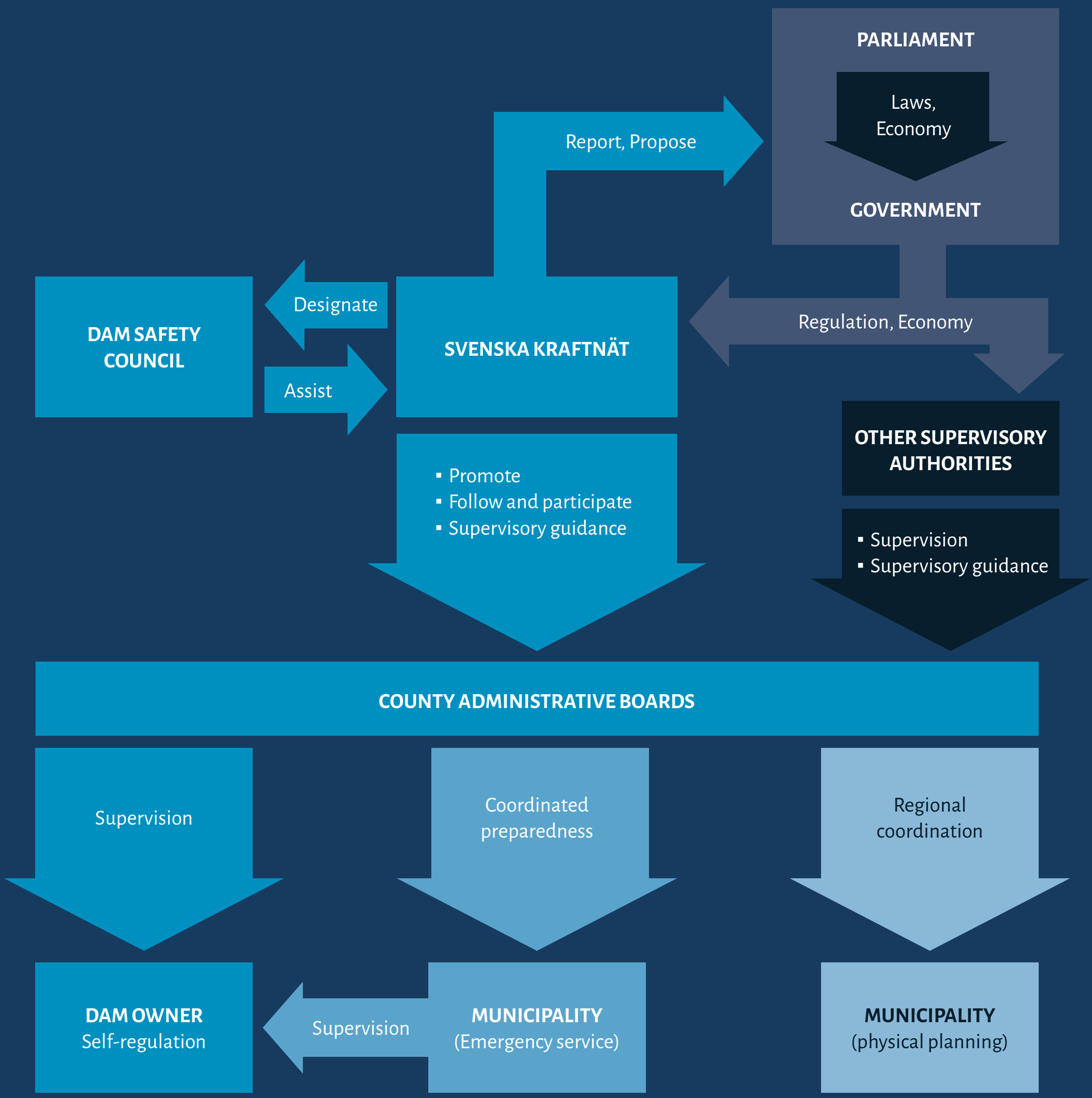
- There is no formal authorization for engineers dealing with dams. According to the industry guidelines for dam safety the dam owner should appoint a dam safety engineer with appropriate theoretical and practical education, as well as experience from working with dams, for each dam. In the guidelines appropriate education and experience is specified for e.g. the dam owner's key personnel and consultants appointed to carry out surveillance activities such as inspections and periodic dam safety reviews.

The responsibilities of the dam owners

The central principle in the Environmental Code is that the owner (operator) of an enterprise shall continuously plan and monitor the operations through self-regulation in order to prevent or counteract harm to human health or the environment.

- The owner is obliged to acquire the required knowledge, investigate and evaluate the risks related to the enterprise, draw up and follow routines for self-regulation, as well as to take the measures required and have preparedness in order to avoid damage. The routines and the findings should be documented.
- The owner is obliged to maintain the dam and in doing this he shall use the best available technology and the precautionary principle.
- A permit by an Environmental Court, which has replaced the former Water Courts, must be obtained for new dams and water operations within the framework of the Environmental Code. The permit should where appropriate include provisions concerning purpose, location, scope, safety and technical design of the activity, as well as supervision, inspections and checks.
- Also when significant alterations or repairs of an existing dam are to be undertaken a permit by an Environmental Court must be obtained within the framework of the Environmental Code. In urgent cases, if necessary due to occurred damage or to prevent damage, work may commence without prior permission. However, the owner shall as soon as possible submit an application to the court for approval of the implemented measures.
- Should a dam failure nevertheless occur, then the owner is strictly liable for damage caused by the dam failure.

Roles and responsibilities related to dam safety



Älvkarleby dam. Photo: Svenska kraftnät.

5.3 Today's regulation of dam safety

This section introduces the main requirements of the 2014 dam safety regulation and an overview of its implementation.

Enhanced regulation on dam safety

With the support of the Dam Safety Bill 2013/14:38, new dam safety regulation came into force in 2014, in the form of amendments to the Environmental Code, the Dam Safety Ordinance (2014:214) and some additions to existing regulations.

The dam safety ordinance

The new regulation concerns dams where failure can have consequences of societal importance and/or present a risk to human life. It aims to prevent dam failures with serious consequences, by supporting development of the dam owners' safety work and strengthening dam safety supervision. The basis for the new requirements is the introduction of a classification system, based on the possible consequences of a dam failure, as the foundation for differentiated requirements of dam safety, owners' self-regulation and authority supervision. The new requirements for classified dams and their owners include:

- to establish and work in accordance with a safety management system,
- to conduct periodic in-depth dam safety reviews,
- to submit annual dam safety reports,
- to pay annual fees to the regional supervisory authority.

Dam safety classification

For dams with a minimum height of five m and/or where a dam failure would result in the release of 100.000 m^3 of water and/or sediments/tailings the owner should analyze the consequences of dam failure and assess if it should have a dam safety class or not. The consequence assessment should describe:

- how a dam failure may occur,
- which areas that would be flooded,
- what damages and disturbances that may result from the flooding and other effects of the failure.

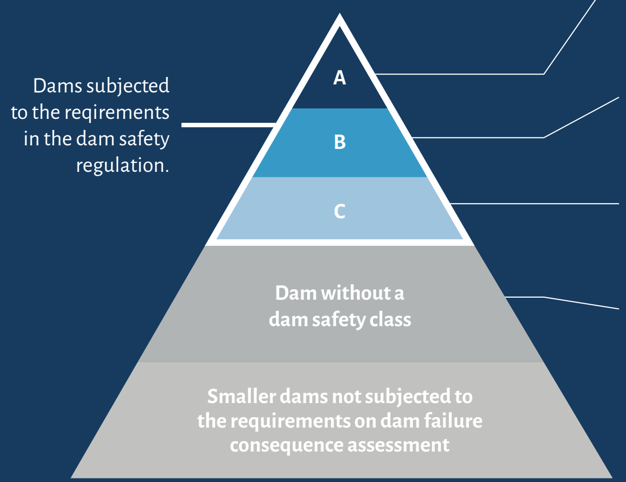
The consequence assessment together with the owner's suggestion on classification should be given to the regional supervisory authority, who should make the official decision on the classification of the dam.

The basis for the dam safety classification system is an assessment of the overall societal consequences of a dam failure. The type of consequences that must be addressed include:

- the risk of loss of human lives,
- destruction of buildings, critical infrastructure and/or disruption of vital public services, such as the electricity supply, transportation, water supply and telecommunications, etc.,
- serious damage to environment, cultural sites and economic values.

The classification system applies to all types of existing and new dams, except temporary coffer dams, independent on their purpose; hydropower, mining, water supply, locks and canals, flood protection, recreation etc.

The system comprise the following three dam safety classes:



Class A: Very large consequences - A crisis affecting many people and large parts of society that threatens fundamental values and functions, national consequences, many lives at risk.

Class B: Large consequences - Long disruptions of critical infrastructure and vital public services, large regional consequences, and/or lives at risk.

Class C: Moderate consequences - Temporary disruptions of critical infrastructure and vital public services, local consequences.

Dams without a dam safety class: Dam facilities where dam failures are estimated to have only minor consequences are "dams without a dam safety class", and are not subjected to the additional requirements in the new regulation.

Co-ordination and guidance on the implementation

Svenska kraftnät, the national dam safety authority, has facilitated and guided the implementation process by regulations on consequence assessment and classification, guidelines on the new requirements for classified dams as well as provision of education and templates supporting a uniform application.

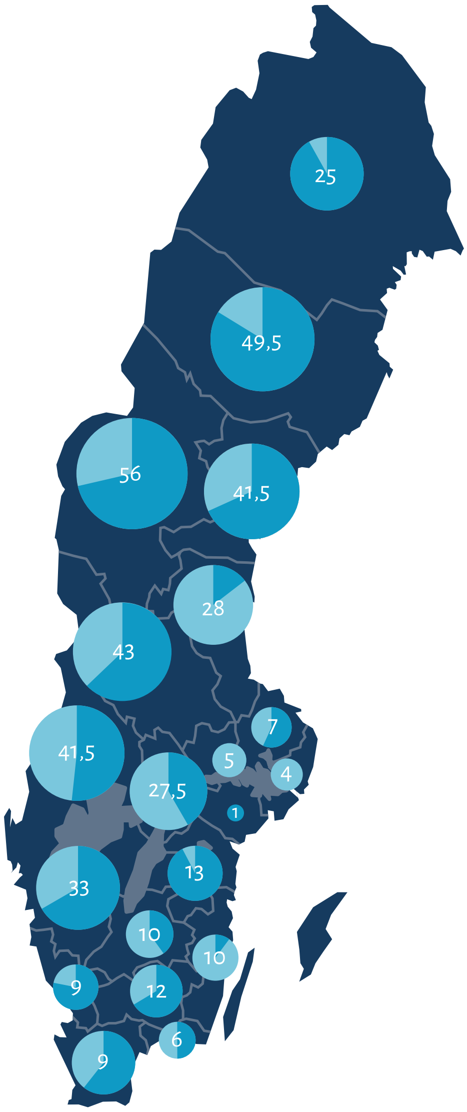
The industry organisations have revised their guidelines several times to be in line with the regulatory changes and support the owners in their implementation process. The guidelines build on and makes reference to Svenska kraftnät's guidelines, standards, results from research and development, ICOLD bulletins and guidance from other internationally renowned organisations for further details.

Follow-up of the implementation

Svenska kraftnät has carried out two "control stations" as assignments from the government, in 2018 and 2021, with the aim to follow up the implementation, analyse to what extent the overall purpose of the new dam safety regulation has been met and when necessary recommend supporting actions.

As per 2023 more than 1 200 consequence assessments have been carried out and about 450 dam facilities, with about 120 different owners, have been classified in dam safety class A, B or C. All owners submit annual dam safety reports and pay annual fees to the regional supervisory authorities. The dam owners have successively commenced implementing the new requirements. The regional authorities are gradually strengthening their supervision, with guidance from Svenska kraftnät.

Facilities with dams in dam safety class A/B and C



450 dam facilities with dams in dam safety class class A/B (clear blue) and class C (light blue) in each county based on the dam owners annual dam safety reports to the regional supervisory authorities from 2021/2022.

Annual follow-up of dam safety reporting shows progress

Svenska kraftnät makes annual compilations of the dam owners' reporting on dam safety. The compilation for the year 2021 includes 440 dam facilities. The majority of the dam facilities, approximately two-thirds, are owned by around ten large owners in the hydropower industry. At the same time, there are over 90 small owners with only one or two dams.

The compliance with the requirement to report annually on dam safety is very good. The owners assess that a large proportion of the facilities have satisfactory dam safety, although deficiencies have been identified for about one-third of the dams. Dam owners who have identified deficiencies should draw up and implement action plans regarding investigations and physical measures as well as improvement of routines and documentation.

However, since the new regulation came into force, periodic in-depth dam safety assessments have only been carried out, and reported to the regional supervisory authority, for a small percentage of the facilities. As a result the owners will have to carry out a large number of such assessments in the next few years.

Ramsele dam. Photo Uniper.

6. Dam safety challenges of today

Garpenberg tailings management facility. Photo Svenska kraftnät.

6. Dam safety challenges of today

The dam safety challenges faced by the hydropower and mining industries today differ.

The hydropower industry is tasked with managing an aging portfolio of dams, while the mining industry is continuously raising their dams at tailing management facilities in active operation. Furthermore, there is a growing expectation from owners, authorities, and investors to enhance dam safety and promote sustainable development while balancing diverse societal interests. This chapter outlines these challenges through the lens of the six themes selected for the SwedCOLD symposium during the ICOLD meeting in Gothenburg.

SwedCOLD symposium: Management for Safe Dams

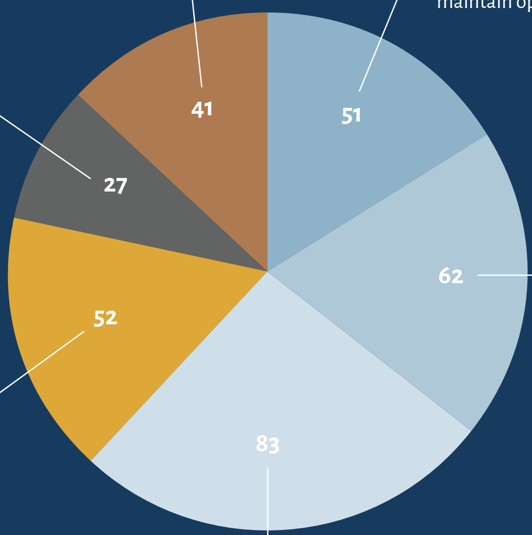
Managing an aging dam portfolio is a complex and challenging task that requires careful consideration of various technical, economic, environmental, and social factors. As dams continue to age, the risks associated with their operation and maintenance increase, requiring more sophisticated management strategies to ensure their safe and sustainable operation. For these reasons, *Management for Safe Dams* was chosen as the heading for the SwedCOLD symposium during the ICOLD annual meeting in Gothenburg. The symposium covers six themes and their application to various dam types and purposes, including hydropower, flood control, irrigation, levees, and mine tailings.

The symposium proceedings includes 316 papers distributed on six selected themes

T6 - Innovation:
This theme focuses on developing innovative solutions for new technologies and methods related to all previous themes, specifically focusing on sustainable hydropower for the regulation of intermittent energy sources and mining activities owners. It also stresses the importance of balancing the power system, preserving biodiversity, and fulfilling dam safety requirements.

T1 - Safety Management of Dams and Levees:
This theme focuses on the systematic and consistent management of dam safety to maintain operational dam safety objectives.

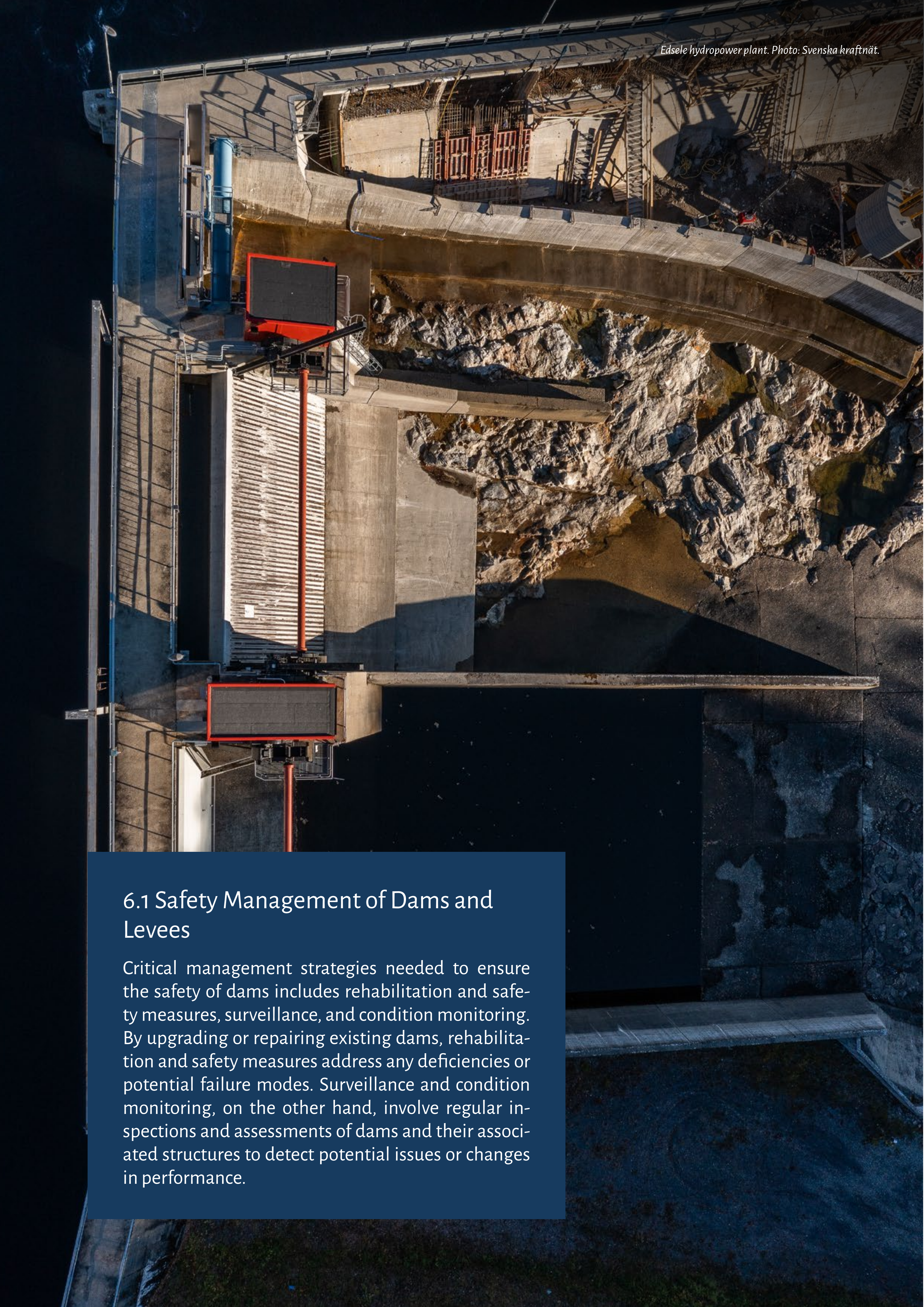
T5 - Climate & Environmental Adaptation:
This theme highlights the challenges that a changing climate and increased societal expectations pose for dam owners and the importance of balancing the power system, preserving biodiversity, and fulfilling dam safety requirements.



T2 - Surveillance and Condition Monitoring:
This theme focuses on gathering high-quality data on the status of dams through efficient monitoring methods and defining relevant alarm and alert levels.

T4 - Rehabilitation and Dam Safety Measures:
This theme focuses on taking measures to reduce load, slow down degradation, or increase/restore performance or capacity when a deviation from set requirements is unacceptable.

T3 - Analysis, Modelling and Decision Making:
This theme emphasizes the importance of models, from simple behavior models to advanced numerical simulations, to determine if dams and spillways fulfill the requirements.



Edsele hydropower plant. Photo: Svenska kraftnät.

6.1 Safety Management of Dams and Levees

Critical management strategies needed to ensure the safety of dams includes rehabilitation and safety measures, surveillance, and condition monitoring. By upgrading or repairing existing dams, rehabilitation and safety measures address any deficiencies or potential failure modes. Surveillance and condition monitoring, on the other hand, involve regular inspections and assessments of dams and their associated structures to detect potential issues or changes in performance.

Rehabilitation and dam safety measures

Performing rehabilitation and dam safety projects in existing dams can be complex and challenging, requiring careful planning and execution. Such projects must be planned concerning the region's seasonal climate conditions and the watercourse's hydrological conditions. Chapter 4 presented the most common dam safety measures per category, such as stability increase with post-tensioned tendons for concrete dams, stabilizing rock-fill toe berms for embankment dams, new or reconstructed discharge structures to increase the total discharge capacity, and periodic increase of the dam height for tailing dams to provide additional storage capacity. While these types of reinforcement measures are still ongoing, the other primary reasons why dams are upgraded today are:

- Ageing and degradation.
- Changes in external conditions or usage.
- Introduction of new, sometimes stricter, requirements.

Dams are built to last for several decades, even centuries, but over time, they can deteriorate due to natural wear and tear and exposure to the elements. This can lead to a range of issues that compromise the safety and effectiveness of the dam. Dam owners need to implement rehabilitation and dam safety measures to address these issues.

One of the critical safety concerns of aging dams is the deterioration of non-inspectable structural parts, which can compromise the dam's stability and integrity. Grout curtains, rock bolts, wooden and concrete diaphragms, and the core and downstream filter of embankment dams are structural components that are difficult to inspect, test the performance of, or monitor, making it challenging to assess their condition accurately. To address this issue, a belt and braces approach is often used, which includes reconstructing the dam components with alternative designs and adding redundant or protective safety measures.

In the mining industry, one of the primary challenges is adapting tailings dams to modern safety requirements and conditions that may go beyond what was considered during the original design and construction. Furthermore, the continuous extraction of minerals and metals results in a constant accumulation of mine tailings that require safe storage. Consequently, there is a need to increase the height of existing dams to accommodate the growing volume of waste material. The heightening process must be done carefully considering the variety of heightening approaches that may have been used during the dam's lifetime to ensure the structure's safety and stability.

Dams are also subject to changing environmental and operational conditions that may require dams to be upgraded or reconstructed to meet these modern requirements and uses. Such conditions can include new environmental requirements, and changes in operational patterns. For example, the ongoing fast-increasing share of wind and solar power in the energy mix impacts the way hydropower is utilized. As a result, today, hydropower is often used as a regulator to balance fluctuations in wind and solar power production. This shift in operational patterns directly impacts the safety of dams and the need for rehabilitation measures. Two key areas of concern are the gates and other parts of the spillways that are used more frequently and therefore experience more wear and tear, as well as the concrete structures in the splash zone that are exposed to water fluctuations.

Also, climate change and changing weather patterns can result in more frequent and severe weather events such as floods, which may require reassessment of the design flood, operational and/or physical measures to ensure dam safety. Read more about climate change and dam safety in in the coming section.

Messaure dam. Photo: Maria Bartsch.

Hällby dam. Photo: Jan Liif.

Surveillance and condition monitoring

Ensuring dam safety is a critical task that requires the expertise and commitment of everyone involved in the operation and maintenance of a dam. To manage the risks associated with dams and ensure the long-term reliability of the dam, various measures need to be taken, such as conducting regular inspections, monitoring dam performance, and carrying out maintenance and repairs when needed.

Internal erosion is a significant factor contributing to the failure of embankment dams. To ensure the safety of embankment dams, it is crucial to have methods for monitoring seepage and detecting internal erosion. However, experiences worldwide suggest that the current surveillance methods are not ideal, and many dams require improved monitoring techniques. In Sweden, one method that has been at the forefront of development for seepage monitoring in embankment dams is using temperature measurements.

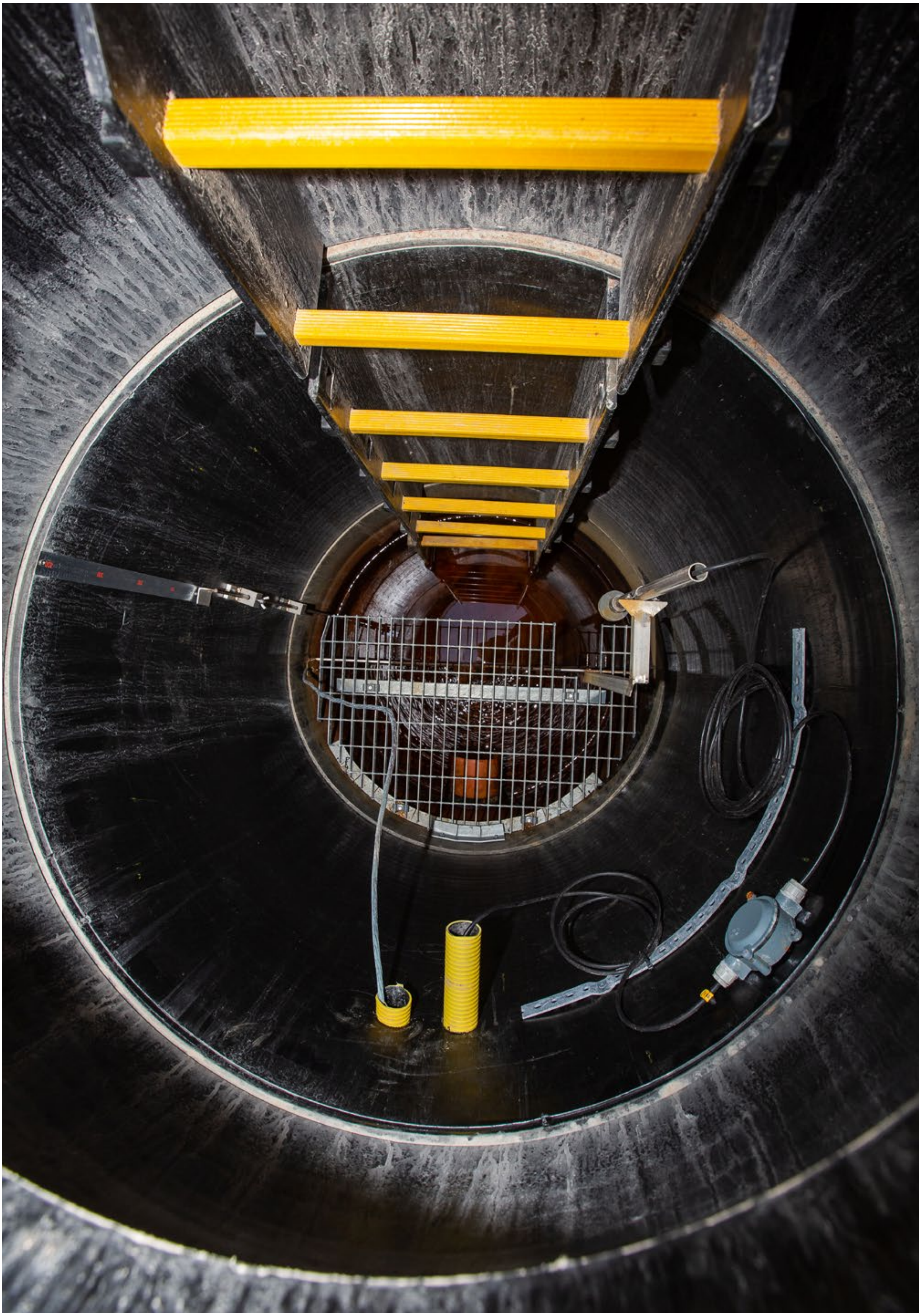
The method began with manual temperature measurements in standpipes for water level measurements 30 years ago but has since evolved to involve the installation of a fiber optic cable along the dam body and using distributed temperature sensing technology to measure temperature changes along the cable. This resulting data can be used to detect seepage anomalies by comparing them with reference data or models. Such fiber optic systems have been installed for seepage monitoring and internal erosion detection in many embankment dams and tailings dams in Sweden.

With the development of new technologies such as drones and scanning equipment, it is now possible to obtain highly accurate and detailed measurements of embankment dam structures. This presents new opportunities for monitoring the condition of dams and detecting changes early on. However, the large amount of data generated by these methods also creates new challenges in making the data accessible, interpreting it, and managing a large amount of information. As a result, it is essential to develop new methods for processing and analyzing this data.

There has been a growing interest in utilizing data-based and artificial intelligence (AI) methods for dam monitoring in recent years. These techniques rely on sensors and data analysis tools to collect and process data on various dam parameters continuously in real time. By leveraging the power of AI, these methods can detect and predict potential issues much faster and with greater accuracy than traditional techniques. The AI-based dam monitoring methods involve machine learning algorithms to analyze significant volumes of data from different sensors and sources. For instance, machine learning models can be trained to identify patterns in data related to dam behavior and predict potential issues. Such methods are gaining popularity worldwide, and several research projects are ongoing.

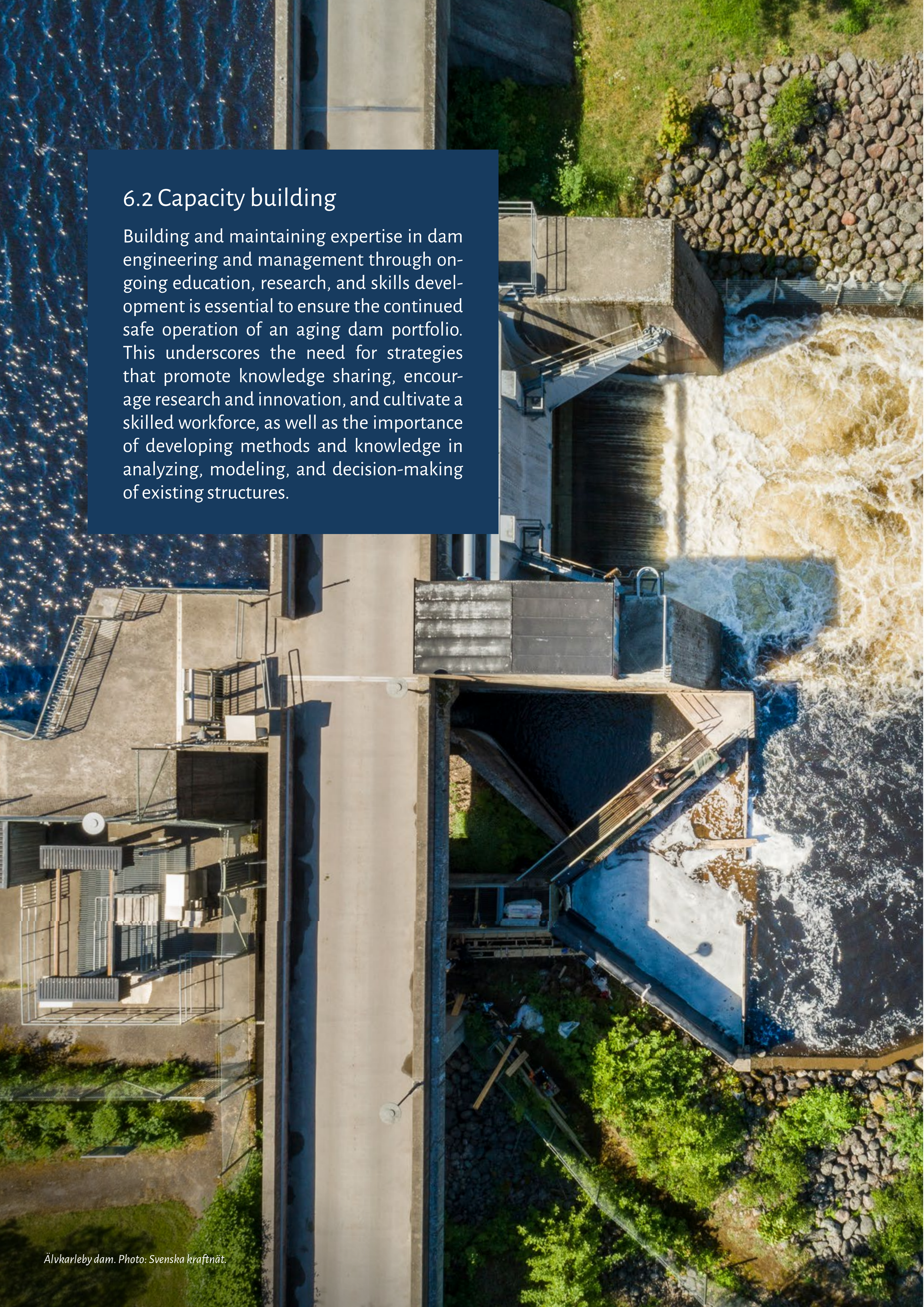
Photo: Svenska kraftnät.

Photo: Svenska kraftnät.



6.2 Capacity building

Building and maintaining expertise in dam engineering and management through ongoing education, research, and skills development is essential to ensure the continued safe operation of an aging dam portfolio. This underscores the need for strategies that promote knowledge sharing, encourage research and innovation, and cultivate a skilled workforce, as well as the importance of developing methods and knowledge in analyzing, modeling, and decision-making of existing structures.



Älvkarleby dam. Photo: Svenska kraftnät.

Research, education and skill supply

Sweden has a long-standing involvement in dam safety and a history of organized research in this field. The country demonstrated its early commitment to research and development in dam safety through it's early and significant involvement in ICOLD. In addition, the research organization, the Swedish Power Industry Foundation for Technical Development (VAST), began developing instructions for dam safety in the late 1960s, with its first set of instructions on surveillance and monitoring being released in 1968. These instructions were periodically updated until 1990, when they were replaced by the industry guidelines RIDAS.

The Swedish State Power Board was the state organization responsible for developing about half of Sweden's hydropower. During the period of rapid hydropower growth, the board issued guidelines for the design, construction, and control of their dams, which were also utilized by private entities in Sweden. The board's knowledge was summarized in the Earthfill and Rockfill Dams handbook in 1988, which has been significant for the Swedish dam industry.

Today, Vattenfall, a successor to the Swedish State Power Board, is a major player in the Swedish energy market Vattenfall R&D (Research and Development) is a robust research organization centered around its hydraulic laboratory in Älvkarleby. Vattenfall and other power companies are also a significant funder of research in hydropower and dam safety in Sweden.

VAST funded and initiated several research and development projects related to discharge safety and other aspects of dam safety. In 1993, VAST was later transformed into Elforsk in 1993 and Energiforsk in 2015. Energiforsk is today owned by Energiföretagen Sverige AB and Svenska kraftnät and several technical universities and is a hub for energy research with more than 50 research programs divided into six subject areas. Together, VAST, Elforsk, and Energiforsk have published hundreds of dam safety-related technical reports.

During the 1990s, the lack of recent new dam construction and the retirement of experienced dam engineers led to a shortage of skilled engineers with expertise in dam safety. To combat this shortage in the hydropower industry, the Swedish Energy Agency and Svenska kraftnät jointly established the Swedish Hydropower Center (SVC) in 2005. Today, the center's name is Swedish Center for Sustainable Hydropower, reflecting an expanded scope. This university education and research center aims to contribute to the long-term competence supply in three areas; civil and hydraulic engineering; hydropower technology; and environment and society. Read more about SVC on the next page.

The experimental embankment dam at Vattenfall's laboratory facilities in Älvkarleby is utilized for research into damage detection methods. The dam was designed and constructed following the Swedish dam safety guidelines but has six built-in defects that could cause a dam failure. Photo: Svenska kraftnät.

Energiforsk

Energiforsk is a Swedish energy research center that is co-owned by industrial actors and Svenska kraftnät with the aim to meet common energy challenges for industries, authorities and society. Energiforsk conducts research and development in six energy areas: hydropower; heating and cooling; nuclear power; reliable electricity supply; energy systems; and solar and wind. Some of Energiforsk's programs that are related to dam safety are:

- **Dam Safety**
  This program provides knowledge for the strategic work with dam safety and is beneficial for the long-term development of the Swedish hydropower production. The program has been running for twenty years. Its purpose is to promote the development of dam safety through relevant and urgent development projects, and through knowledge and competence development within the dam safety area. The goal is to enable the hydropower companies to maintain and further develop a sustainably high level of dam safety. The program should also support the power industry's dam safety policy in the long term and provide support for the continued development of the industry's guidelines, RIDAS
- **Hydropower Rock Engineering Research R&D**
  This program presents tools, guidelines, techniques and descriptions for performing maintenance measures and cost-effective investments for hydropower rock engineering. The program covers topics such as rock mechanics, rock engineering, grouting and sealing of rock fractures.
- **Hydropower Concrete Program**
  This program develops and manages hydropower concrete structures to increase safety and reduce production losses. The program covers topics such as concrete technology, concrete durability, concrete design and concrete repair.
- **Hydrological Development Program**
  This program develops new knowledge and methods to improve forecasting to predict hydropower water inflow. Currently projects are being implemented to improve input data, to develop models and to measure snow more effectively. The Hydrological Development Programme, HUVA, also includes standardisation, external monitoring and educational activities in the field of hydrology in hydropower.
- **Environmental Program for Hydropower**
  This program aims to strengthen knowledge of various measures designed to improve free passage for aquatic animals, plants and improving spawning and nursery grounds by making adaptations to rivers with hydropower.

SVC - Swedish Center for Sustainable Hydropower

Swedish hydropower center, SVC, was established in 2005 and has been a centre of expertise since 2018. Luleå University of Technology is the host university and Energiforsk is responsible for the competence center, whose current period runs until 2027. Through research and development of technology, systems, methods and issues related to hydropower and dams, we contribute to a renewable energy system.

In 2022, the scope of the center's research was broadened to include environmental and societal issues related to hydropower, and its name was changed to Swedish Center for Sustainable Hydropower to reflect this expanded focus. It operates a centre of expertise established by the Swedish Energy Agency, Energiforsk, and Svenska kraftnät together with Luleå University of Technology, KTH Royal Institute of Technology, Chalmers University of Technology, Uppsala University, Umeå University, Lund University and Karlstad University.

The program develops new knowledge for hydropower aimed at meeting society's need for balanced power and renewable electricity production in a safe, efficient and environmentally friendly manner. The initiative means that both society at large, and the hydropower industry will have new technical and academic competence for future maintenance, rebuilding and renewal of hydropower. Issues related to hydroelectric dams and mines are included in the program.

Vattenfall's Research & Development laboratories in Älvkarleby constitute important test environments for SVC.

Read more on the focus areas for SVCs dam safety research in the next section.

Photos from the laboratory facilities in Älvkaleby showing an experimental embankment dam, a scale model in the hydraulic laboratory, and a hydraulic laboratory for investigations on fish. Photos: Svenska kraftnät.

Photo: Svenska kraftnät.

Vattenfall Research & Development Laboratories, Älvkarleby

- 6 000 m² laboratory space
- 120 R&D Engineers
- Active since 1943
- National resource for large scale experiments for hydropower

Areas:

- Fluid mechanics and hydraulic engineering
- Hydropower turbines
- Rotating machines
- Fatigue tests
- ICT-labs
- Concrete technology
- Soil mechanics
- Embankment dams
- Eco-hydraulics
- 3D-engineering
- Digital inspections (land, air, on/in water)
- Batteries (MW/MWh-scale)

Analysis, modelling and decision making

With an aging dam portfolio, the focus has shifted from design to analysis, modeling, and decision-making, particularly for existing dams. Regardless of the type of analysis, a model is essential to interpret the effect on the facility, forming the basis for simplifications and assumptions. The purpose of the analysis is to investigate whether the facility, such as a dam or spillway, meets the necessary requirements, and validation of models or acceptance criteria is essential to ensure reliable results for decision-making.

In Sweden, and SVC, the focus on dam safety is concentrated on four key areas: Structural engineering, Geotechnics, Rock mechanics and Hydraulic engineering.

Structural Engineering is primarily concerned with large concrete structures used for hydropower purposes. One critical aspect of this area of research is the prediction of ice loads on concrete dams, which is essential for ensuring the safety of the structure and its surroundings. Another important area of research is the prediction of dynamic loads on hydropower unit concrete structures, which can cause significant damage and even failure of the structure. In addition, there is a need for realistic failure modes and surveillance of concrete dams to detect any changes in the structure's behavior and prevent a potential failure.

Geotechnics is mainly concerned with embankment dams and their stability. One significant challenge in this area of research is the investigation of seepage and internal erosion in embankment dams. The researchers need to model particle movements and sorting and their effect on global stability, water pressures and flow, clogging, and sinkhole development. Furthermore, there is a need to develop methods for the stability and risk analysis of hydropower and tailings dams, as well as the surrounding slopes. This includes a methodology for modeling deformations as part of condition control of dams, including updating models based on measured parameters like inclinometer and pore water pressures. The researchers also explore methods for reparations of embankment dams, drilling, grouting, and follow-up/monitoring/control. Another area of research in geotechnics is the use of crushed material as construction material in embankment dams, replacing naturally available material. The influence of change in materials on erosion and (long-term) stability is being investigated.

Rock Mechanics is mainly concerned with foundations of concrete and embankment dams, construction of tunnels, and other waterways in rock, including sealing and grouting. The main challenge in this area of research is the development of methods for stability and risk analysis for foundations on rock, mainly linked to the assessment of existing dams. The researchers are exploring maintenance and repair methods for sustainable resource utilization over the life cycle of dams and tunnels. This includes methods for sealing and grouting of the foundation, rock support, and drainage systems.

Hydraulic engineering deals with the interaction between flowing water and structures and rock in waterways. The researchers analyze the hydraulic loads on constructions and rock and develop solutions and tools for energy conversion during discharge. They also explore current issues regarding discharge capacity and various methods for increasing discharge capacity. The researchers are developing flow and water construction engineering measures to facilitate and guide fish migration, known as eco-hydraulics, with limited negative production impact. They are exploring the use of advanced measurement systems such as image analysis, satellite measurements, or geophysical measurements to predict and simulate the behavior of embankment dams.

Björkdalsgruvan tailings management facility. Photo: Maria Bartsch.

Professor Knutsson guides students on the course Tailings dams safety on Björkdalsgruvan tailings management facility. Photo: Maria Bartsch.

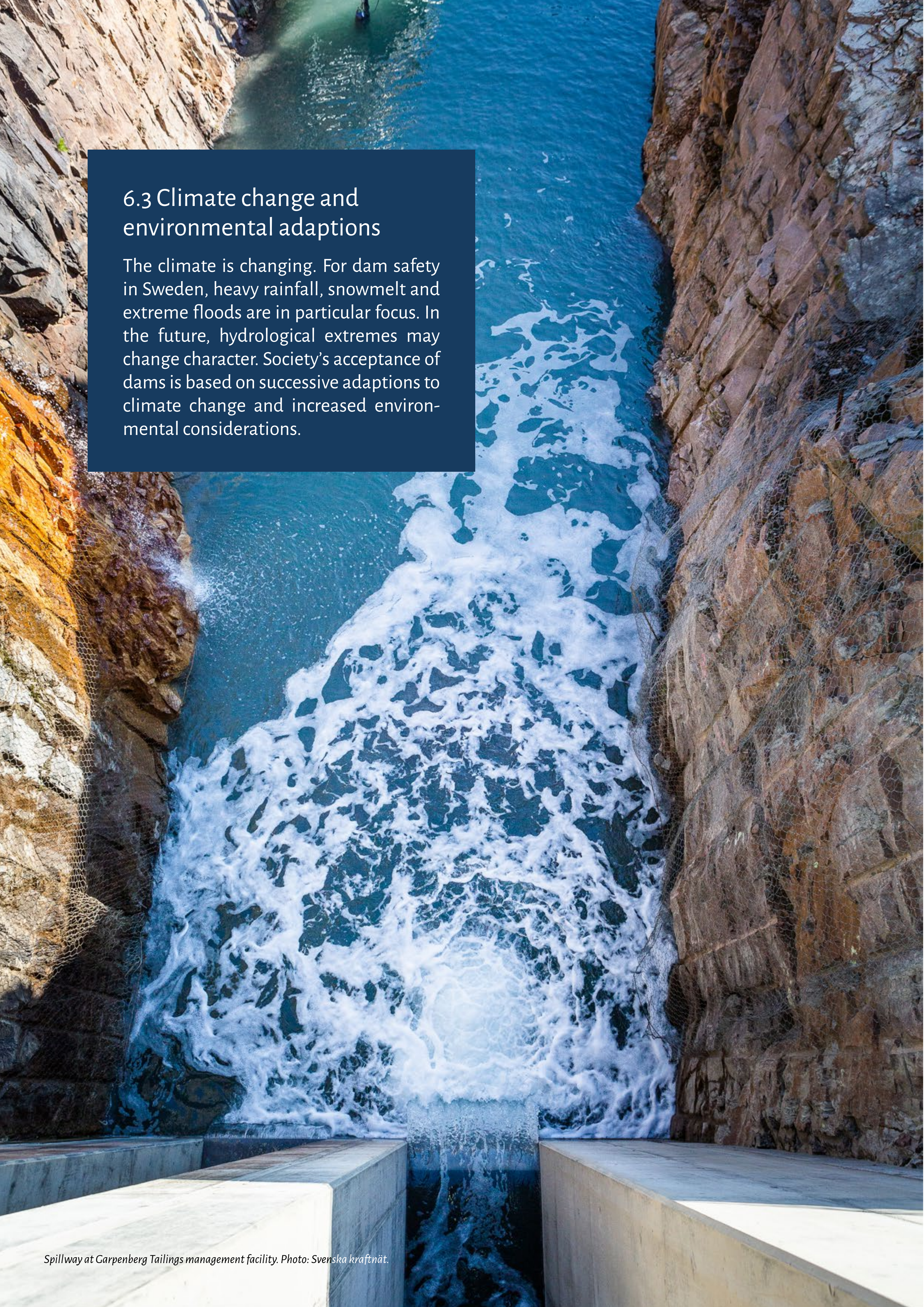
Capacity building initiative in ICOLD and SwedCOLD

The challenge of skill supply is not confined to Sweden but is a global issue affecting the entire dam industry, including water dams, hydropower dams, and tailings dams. The field of dams (including design, construction, and operation) is experiencing a lack of capacity (worldwide) regarding the number of well-experienced engineers and new young engineers. This is relevant to the entire dam industry, including water dams, and tailings dams. ICOLD has taken initiatives through the two Committees; ZX2 – Young Professionals Forum and Z – Capacity Building. With the main objective to create a network to stimulate participation and engagement among young engineers within ICOLD, the vision of a Young Professionals Forum committee vision initiated at the ICOLD Congress in Brasilia in 2009, and the first meeting took place in Lucerne in 2011. Since then, meetings have been held at every ICOLD meeting, ensuring long-term sustainability and knowledge as well as providing a forum for young engineers to make contacts with each other and enable the exchange of experiences.

In Sweden, the Young Professional Forum (YPF) functions as a network for professionals in the industry under the age of 40. YPF organizes two annual activities, including a formal meeting and dinner, where younger employees from SwedCOLD member companies present current projects and discuss the organization's activities. Additionally, YPF maintains a membership list with contact information distributed within the network several times yearly to facilitate easy exchange between members. SwedCOLD also offers cost subsidies to enable young engineers to participate in ICOLD's activities, ensuring they can access the organization's resources and knowledge.

6.3 Climate change and environmental adaptions

The climate is changing. For dam safety in Sweden, heavy rainfall, snowmelt and extreme floods are in particular focus. In the future, hydrological extremes may change character. Society's acceptance of dams is based on successive adaptions to climate change and increased environmental considerations.



Spillway at Garpenberg Tailings management facility. Photo: Svenska kraftnät.

Climate change and dam safety

Society's emissions of greenhouse gases and other human activities have already had a significant impact on the global climate, and further changes are expected in the coming decades. The prevailing trend in northern Europe and Sweden is towards warmer temperatures and increased precipitation. This trend is consistent with broader patterns of climate change observed worldwide, but the temperature increase in Sweden is about twice as large as the global average. Future climate scenarios indicate a continued shift in seasons in Sweden, increasing temperatures, and more precipitation, which to an ever lesser extent, will fall as snow. Climate change will also lead to changes in extreme weather events. Such changes include more intense heat waves, less frequent and severe cold snaps, and both more intense rainfall and increased risk of droughts during precipitation-poor years.

Safe design and operation of dams are often based on experience and assessments of extremes. Since extremes are by definition rare, evidence and the ability to demonstrate robust trends or changes in observational data are limited. Against this background, using several future climate scenarios with combinations of emission scenarios, global climate models and regional climate models, are an important tool for assessing many possible changes before they have manifested themselves. Methods that include the use of climate scenarios have been tested and are generally applicable for calculation of the climate impact on extreme river flow. Therefore, recommendations on the use of climate scenarios have been included in the Swedish guidelines for design flood determination since the 2015 revision. In addition to dam safety applications, the results are also relevant to other fields such as physical planning, flood control and infrastructure design.

The Swedish Meteorological and Hydrological Institute (SMHI) has developed climate indicators for society's general needs, but for dams, changes that affect the amount of water the dam needs to withstand and convey safely - such as heavy rainfall, snowmelt, and extreme floods - are of particular importance. Therefore, further knowledge about runoff, water flow, snow, and information about the expected changes in extremes, variability, and duration is necessary for ensuring dam safety. Additionally, changes that impact the durability and accessibility of the dam's components are also significant factors for dam safety.

To address climate change's impact on dam safety, Svenska kraftnät, the hydropower and mining industry, SMHI, and other relevant authorities have formed a "Climate Committee". The committee aims to make current and relevant information about climate change available to dam owners and concerned authorities, and lay the groundwork for strategic climate adaptation of dams. The committee's significance was reinforced in 2022 when the government assigned Svenska kraftnät to analyze the impact of climate change on dam safety in close collaboration with other committee members. The purpose of the assignment is to investigate the impact of climate change on dams and the related societal transition, enhance the development of discharge safety measures, and facilitate the adaptation of existing dams to a changing climate.

It is not always easy to predict how changes in meteorological inputs will ultimately affect dams. In a complex hydropower system, changes and response to changes may cause non-linear relationships and can lead to unexpected outcomes. For example, changes in electricity consumption and the layout of the energy system affect the role of hydropower and its operating pattern. Such changes may have both positive and negative impacts on today's margins and dam safety, and either amplify or mitigate the effects of climate change. As a result of such change or unexpected tipping points, future hydrological extremes may change character or unfavorable conditions may coincide in a way that does not occur today.

Adapting dams to the effects of climate change requires consideration of uncertainties and a research area that is constantly evolving. However, uncertainties surrounding future climate should not hinder necessary dam safety measures today. Instead, efforts should be made to find solutions that not only increase dam safety today but also enable further upgrades in the future. Introducing safety margins can also be appropriate to avoid the need for additional upgrades and provide safety in the present.

New spillway at Dabbsjö dam. Photo: Peder Lönneborg.

Environmental adoption and climate adaptation

Environmental adoption and climate adaptation are simultaneously ongoing approaches. Environmental adoption involves adopting more sustainable practices and reducing our environmental impact, whereas climate adaptation consists in managing and responding to the effects of climate change.

Environmental adoption

During the rapid expansion of Swedish hydropower, the need for electrical power was prioritized at the expense of environmental considerations, and most permits were issued indefinitely. As a result, hydropower has not kept up with modern societal and environmental standards and currently carries a significant environmental debt. To address this issue, the Swedish government has issued the National Plan for Re-evaluation of Hydropower, which aims to re-evaluate and modernize the sector to align with current environmental and social standards. Most Swedish hydropower facilities must be relicensed during the implementations of this plan to meet modern environmental conditions and the EU Water Framework Directive. Ecological rehabilitation of regulated rivers is needed to achieve good ecological status and gain social acceptance from stakeholders living along and using the rivers. Therefore, one of the major challenges for the Swedish hydropower industry in the coming 20 years is implementing environmental mitigation measures at hydropower facilities and dams and along hydropower rivers while ensuring maintained dam safety.

Typical ecological rehabilitation measures aim to improve connectivity and living conditions for riverine species. Such measures include:

- installing fish passes and grids
- ensuring a minimum flow rate and environmental flows
- removing dams altogether.

Fish passes enable fish migration upstream and downstream past dams, while grids are typically placed to direct fish towards the entrance and away from dangerous areas or dead ends. This helps to preserve fish populations and improve ecological balance. Ensuring a minimum flow rate can also aid in maintaining river or watercourse connectivity.

In addition, both the hydropower and mining industries are working on efforts to reduce greenhouse gas emissions and conserve resources. An example of this is the newly developed concrete described in Chapter 4.1.

Climate adaptation

Climate adaptation involves developing strategies to help communities and ecosystems cope with the changing weather patterns and natural disasters such as floods, landslides, forest fires, and heat waves that are expected to become more frequent and severe due to climate change. As a result, taking preventive measures by identifying risks and vulnerabilities and implementing measures to reduce the risk of accidents and mitigate negative climate effects is becoming increasingly important.

Hydraulic engineering plays a crucial role in reducing the risk of flooding by protecting low-lying areas from flooding and transporting excess water away, using dikes, levees, pumps, retention reservoirs, and storm drains. Flood protection projects are currently underway or planned in several parts of the country, and the number of such projects is expected to increase in the coming years. The Swedish government has recently intensified its efforts in this area. However, for a country like Sweden, where hydropower dams primarily have shaped best practices, guidelines, and regulations associated with dams, new challenges arise when dams and levees of new types, for new purposes and with "new" types of owners are to be constructed and safely operated.

NAP – A national plan for modernizing the permits for hydropower facilities

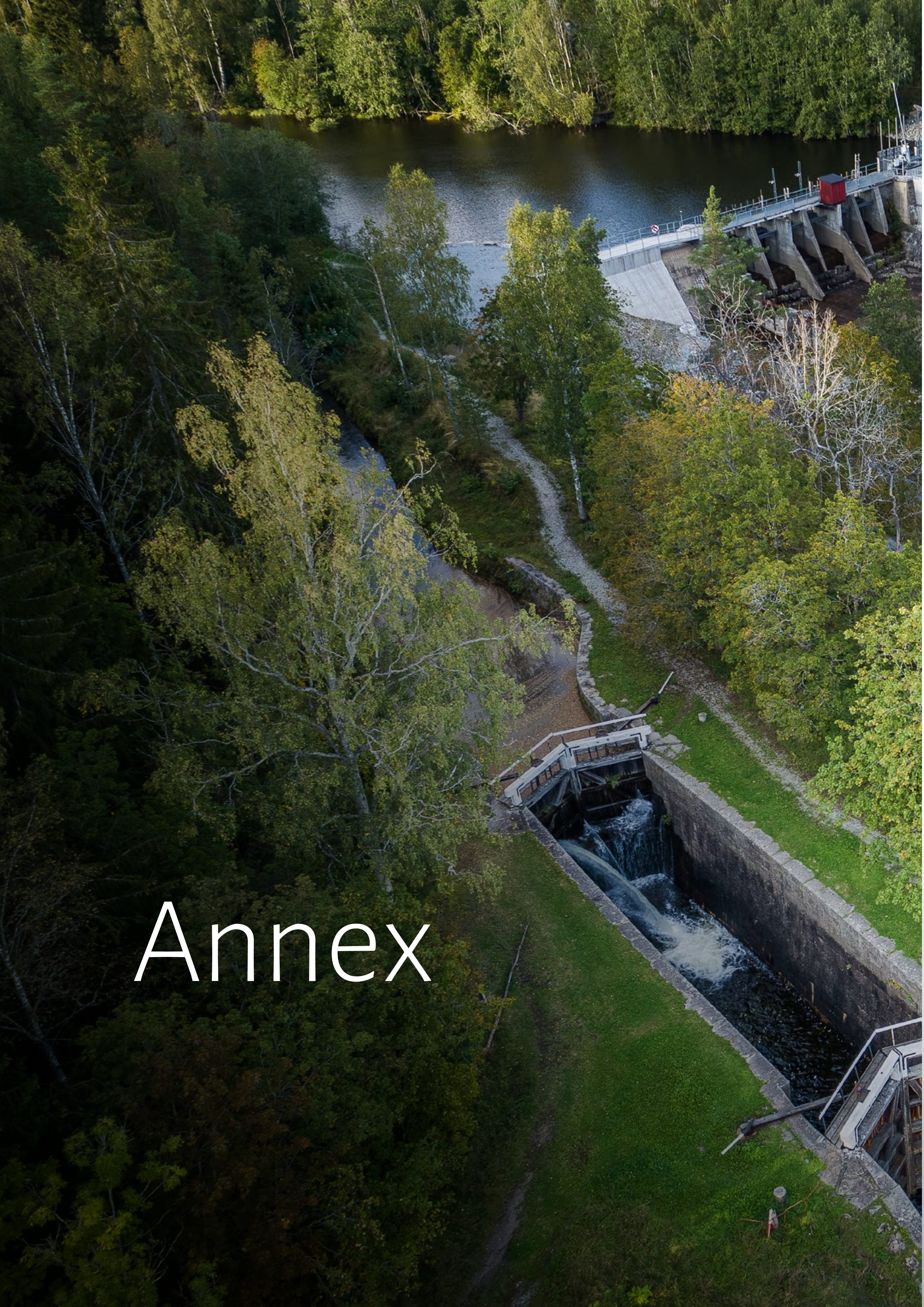
The national plan for re-evaluation of hydropower (NAP) is a plan that aims to modernize the environmental conditions for existing hydropower facilities in Sweden and to meet the EU's Water Framework Directive. The plan contains groups of facilities within the same drainage area and a timetable for relicensing of about 2200 hydropower facilities over 20 years, starting in 2022.

The plan involves a comprehensive review of each facility's environmental impact, including its impact on fish populations, water quality, and biodiversity. The review also considers the facility's impact on local communities, including indigenous populations and other stakeholders.

The plan includes a national annual target loss of 1.5 TWh electricity production. The target loss has been set at a level that can be tolerated without a significant negative impact on electricity production on a national level. In the plan this target loss has been distributed to the main catchment areas to be balanced against environmental objectives.

Stornorrforsen dam.

Upstream exit of a technical fishway passage in Norrköping. Photo: Svenska kraftnät.



Annex

Strömsholms Canal. Photo: Svenska kraftnät.

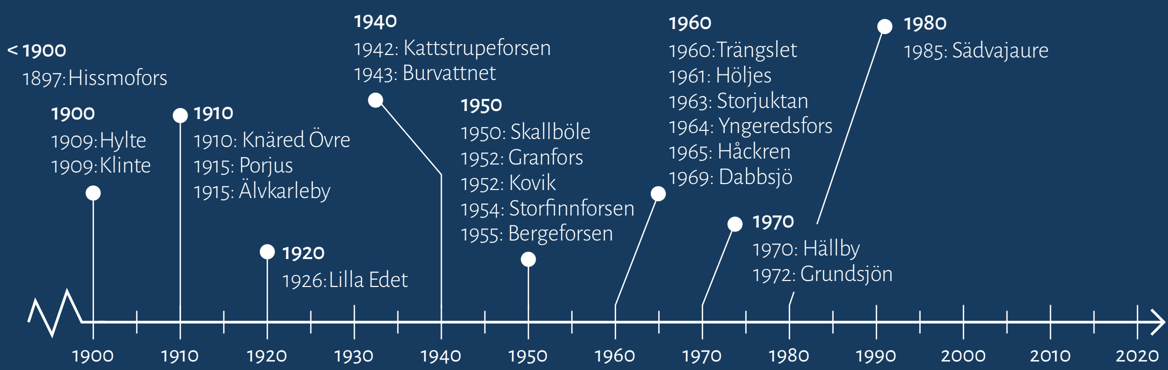
A1. Dams for hydropower

This annex presents a collection of dams used in the hydropower industry, carefully selected by their owners.

As mentioned in Chapter 4, Sweden has over 1 000 dam facilities used by the hydropower industry. To this annex, dam owners have selected a collection of 18 dams to present in more detail. Each dam is presented with informative text, technical data, photos, and, in many cases, drawings, all provided by the dam owners. The dams are presented in chronological order to highlight the development of dam design over time.

Location

Year of construction



Hissmofors

The Hissmofors Dam is situated at the outlet of lake Storsjön.

The reservoir (lake Storsjön) is used both for long-term regulation (annual) and short-term regulation and has a regulation amplitude of 2,75 meters.

Hissmofors dam facility has been expanded in stages. The first dam was built in 1897 and since then the dam has been rebuilt several times. The facility, after the reconstruction in 2011–2013, consists of two stations, six spillways, two concrete dams and fill dams at the left and right abutment. One of the concrete dams is a reconstruction of the old intake to a station which has been removed. Downstream of the concrete dams a backfill of gravel has been placed. Over the years, different types of spillway gates have been in operation. Today the spillway consists of one segment gate and five bulkhead gates.

The left abutment, which is about perpendicular to the main dam, is a zoned earth fill dam with a central core of till, filter, supporting fill and a retaining wall at part of the upstream side closest to the main dam. The right abutment, which also is perpendicular to the main dam, consists of a fill dam with different sealings along its length such as a concrete wall, core of till and wood sheet piling. Rock bolts have been installed downstream of the dam to prevent erosion since the dam is founded on black slate, which has shown tendencies to swell in contact with oxygen.

At low water levels, Storsjön's natural outlet limits the discharge capacity and becomes a bottleneck that affects electricity production in downstream hydropower plants. Therefore the Storsjö tunnel was built in 1987-1990, which is a 3 km long tunnel that connects Storsjön with Hissmofors. The tunnel is most useful during the spring when the water level of Storsjön is low since the bottom of the tunnel is located approximately five meters below the lower limit of the reservoir.

Technical details

GENERAL

Owner	Jämtkraft AB
Purpose	Hydropower
Location	Krokom Municipality, Jämtland County
River	Indalsälven
Drainage basin area	12 120 km²
Mean annual flow	238 m³/s
100-year flow	1 035 m³/s
Year of construction	1897

POWER FACILITIES

Rated head	20,5 m
Maximum discharge capacity	550 m³/s
Installed power	90,9 MW

RESERVOIR

Lake name	Storsjön
Operating range	2,75 m
Surface area	456 km²
Storage capacity	1 254 Mm³

DAM

Type	Concrete dam, earthfill dam
Height	17 m
Crest length	395 m
Foundation type	Bedrock of black slate

SPILLWAY

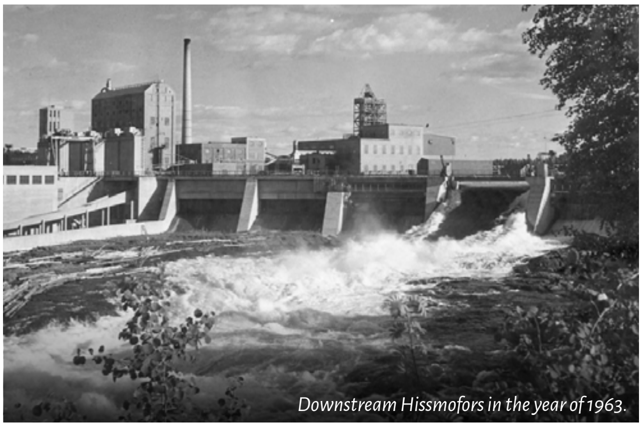
Type	Bulkhead gates and segment gate
Maximum discharge capacity	1 440 m³/s

MAJOR MODIFICATIONS

1918/1941/1993/2013	New hydropower station
1987–1990	Storsjö tunnel

Overview of the facility.

Tunnel construction to the power station. Picture taken around the year 1885.



Downstream Hissmofors in the year of 1963.

Station V, spillway gates and Station VI seen from the left earthfill dam.

Hylte

The Hylte dam facility has a complicated layout with 18 dams.

The upstream dam structures were originally built at the beginning of the 20th century to create land for a new paper mill and a new railway.

There used to be a saw- and flour mill next to Hylte Bygärde (village) that was moved in 1828 to the place where Hylte dam now is situated. The mills were jointly owned by the villagers. In 1907, the construction of a new dam at Hylte began. The dam was then rebuilt on two occasions. On the second occasion in the early 1940s, the dam was raised by just over a metre. In the early 2010s, the decision was made to replace the dam with a new one.

In 1989 a new hydropower station replaced the original one in Hylte and the one downstream, Rydö. The head increased to an impressive 63 meters and a discharge capacity of 50 m^3/s (original 16 m^3/s) through the two turbines. The facility expanded from the upper channel (from which tubes led to the original power station) with an about 1 km long new tunnel that crosses under the community of Hyltebruk. Two new channels and one new small lake, Jakobs sjö, surrounded by 14 new dams, were built in front of the intake to the new power station. The new dams were built as zoned earth-fill dams with a total crest length of about 5,6 km. The original dams were still in use and were upgraded. For example, the concrete in the spillways was grouted.

In 2009, an investigation concluded that the discharge capacity was too low and that the earth-fill dams needed an upgrade, especially the dam to the right of the spillway. A major upgrade of the dam safety was finished in 2020. The main upgrade is the construction of a new earth-fill dam and spillway dam placed 50 meters downstream of the old dam, and an earthfill dam that connects the new spillway with the existing dam.

The new spillway dam consists of four spillways, three 6 meters wide and one 3 meters wide. The new maximum discharge capacity is above 400 m^3/s which is double the capacity of the old spillway. The new dam to the right of the spillway is a zoned earth fill dam.

The existing earth-fill dams were upgraded with new rock-fill toe protection and renewed drain systems. Solar-powered automatic seepage monitoring via radio connection is used, and the new earthfill dam also has a fiber sensor to measure temperature in the downstream filter as well as in the dam toe of the old earthfill dams in the upstream channel.

Technical details

GENERAL

Owner	Statkraft Sverige AB
Purpose	Hydropower
Location	Hylte Municipality, Halland County
River	Nissan
Drainage basin area	1 700 km^2
Mean annual flow	24 m^3/s
100-year flow	170 m^3/s
Year of construction	1909/1989/2020

POWER FACILITIES

Rated head	63 m
Maximum discharge capacity	50 m^3/s
Installed power	27 MW

RESERVOIR

Lake name	Jakobs sjö
Operating range	0,5 m
Surface area	0,7 km^2
Storage capacity	2 Mm^3

DAM

Type	Earthfill dam
Height	Max. 12
Crest length	About 6 500
Foundation type	Mainly on bedrock, till

SPILLWAY

Type	Surface spillway
Maximum discharge capacity	> 400 m^3/s

MAJOR MODIFICATIONS

1989	The new power station and 14 new dams were built
2020	A major dam safety upgrade with a new spillway, one new zoned earthfill dam replacing an old dam and the rest of the earthfill dams had new rockfill toe protection and new automatic measurements of the leakage.

Overview. Photo: Statkraft Sverige AB.

Construction of new dam. Photo: Statkraft Sverige AB.

New construction completed. Photo: Statkraft Sverige AB.

Klinte

Klinte dam is located in the upper part of river Solgenån, which is a tributary of river Emån.

Klinte dam is located in the upper part of river Solgenån, which is a tributary of river Emån. Upstream of Klinte dam is lake Solgen, which is the "large" reservoir to Emån. The level in lake Solgen is regulated at Värne dam, which thus also regulates the amount of water flowing down to Klinte dam.

The dam consists of an arch dam that, on one side, connects to rock and on the other side towards a gravity dam. From the gravity dam, a fill dam extends about 80 m to the gated spillway.

The dam was built in 1909 for hydropower purposes. The electricity was delivered to an industrial plant and later to the municipalities in the area. In 1974, the power station was rebuilt, and a larger turbine of 3.5 MW replaced the previous three smaller turbines. At the same time, the canal intake and the blasted tunnel were made larger.

The arch dam was reinforced with a concrete slab on the upstream side and on the crest in 1962. The construction work was done in dry conditions with a lowered water level. To make dry conditions possible, a tunnel was driven from the downstream side, and a lake tap was arranged since there was no bottom outlet in the dam. Also, an insulation wall was erected on the arch dam downstream side.

In 2018, the fill dam was upgraded with dam safety measures. The crest was widened, the upstream side was strengthened, and also the downstream side was by placing an embankment. At the same time, the old spillway was removed, and a new one was built. The output capacity was increased from about 68 m^3/s to about 100 m^3/s. A new leakage measurement system was also installed at the dam.

Technical details

GENERAL

Owner	Hydro Machines Sweden AB
Purpose	Hydropower
Location	Vetlanda Municipality, Jönköping County
River	Solgenån/Emån
Drainage basin area	642 km^2
Mean annual flow	5 m^3/s
100-year flow	27 m^3/s
Year of construction	1909

POWER FACILITIES

Rated head	27 m
Maximum discharge capacity	15 m^3/s
Installed power	3,5 MW

RESERVOIR

Lake name	Klintedammen
Operating range	1,0 m
Surface area	0,4 km^2
Storage capacity	0,4 Mm^3

DAM

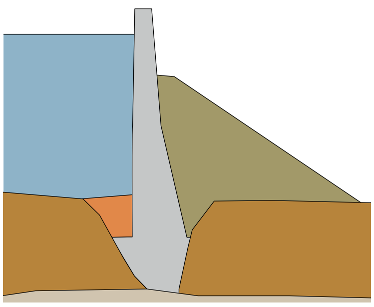
Type	Arch dam, gravity dam, fill dam
Height	25 m
Crest length	60+20+80 m
Foundation type	Bedrock

SPILLWAY

Type	Surface spillway
Maximum discharge capacity	100 m^3/s

MAJOR MODIFICATIONS

1962	Upgrading of the arch dam
1974	Old powerstation replaced by a new
2018	Upgrading of fill dam and a new concrete spillway with gates.



View from upstream.

Arch dam, view from downstream.

Knäred Övre

The Knäred Övre Dam is located downstream of the river Lagan in southwest Sweden.

At the start of the 20th century, the demand for reliable energy in the southwest part of Sweden was great. Municipalities along the southwest coast established a new company, Sydsvenska Kraftaktiebolaget, in 1906. Kraftaktiebolaget built four hydropower stations with dams within 10 km and an extensive transmission system, more or less at the same time. One of these power stations is Knäred Övre, where construction started in May 1907. The four hydropower stations were officially opened on the 17th of September 1910 by the king of Sweden, King Gustav V. Since 2009, Statkraft Sverige AB is the owner of 18 hydropower stations in the river Lagan.

The dams in Knäred Övre are from left to right

- The left earthfill dam.
- Gravity dam.
- The spillways.
- The intake to the hydropower station.
- The right earthfill dam.
- The "Great Dam." This dam is located about 500 m upstream of the hydropower station and the rest of the dams.

The left and right earthfill dams are about 100 m long and about 11 meters and 17 m high, respectively. The "Great Dam" is slightly more than 300 m and about 13 m high. The earthfill dams have an upstream inclined impervious clay core. In 2000, the cores of the dams were raised, and a downstream rockfill toe protection was installed for all earthfill dams. The action was done to be able to raise the upstream surface during extreme floods to increase the discharge capacity. Several standpipes are installed to monitor piezometric water levels, and automatic seepage measurement is performed.

The gravity concrete dam with a triangular cross-section is made of massive concrete with a more impervious upstream layer which was cast with a higher portion of cement. The hydropower station and concrete dam are founded on bedrock. The earthfill dams are mainly founded on natural soils except near the concrete dam and intake structure.

Knäred Övre has eight spillways, each with a fixed-wheel gate with a maximum discharge of about 50 m^3/s at the highest allowed reservoir level.

Technical details

GENERAL

Owner	Statkraft Sverige AB
Purpose	Hydropower
Location	Laholm Municipality, Halland County
River	Lagan
Drainage basin area	5 570 km^2
Mean annual flow	74 m^3/s
100-year flow	293 m^3/s
Year of construction	1907–1910 (3rd turbine 1912)

POWER FACILITIES

Rated head	10 m
Maximum discharge capacity	109 m^3/s
Installed power	7,5 MW

RESERVOIR

Lake name	Knäred reservoir
Operating range	2,0 m
Surface area	0,8 km^2
Storage capacity	3,3 Mm^3

DAM

Type	Earthfill dams, gravity concrete dam
Height	Max. 17 m
Crest length	About 700 m
Foundation type	Bedrock and till

SPILLWAY

Type	Surface spillway
Maximum discharge capacity	About 400 m^3/s at highest allowed reservoir level

MAJOR MODIFICATIONS

2000	The earthfill dams had the core raised and a rockfill toe protection installed.

Overview.

View from downstream, year 1911.

View from downstream, year 2019.

Porjus

The Porjus power plant is situated in the Stora Luleälv river, approximately 210 km from the river's outlet in the Gulf of Bothnia, and about 40 km north of the town Jokkmokk.

Construction of the Porjus power plant began in 1910. Its purpose was to supply electricity to the Malmbanan railway line, which transported iron ore and led to significant growth in Sweden's mining industry. Before the railway's completion in 1911, there was no road or railway access to the location. Materials and supplies had to be transported by hand over a 50-kilometer distance to Porjus from the nearest town, Gällivare.

In 1915, the power station was commissioned and became one of only 20 hydropower plants in Sweden. Porjus drew a lot of attention due to its location and its advanced construction technology for the time. You can read more about the power station in Section 2.3 in the main book.

The Porjus Dam was built in three stages. The first dam was constructed in the 1910s and consisted of both concrete and rock fill dams. The dams' elevation was increased in the 1950s. In the 1970s, new rock fill dams and concrete structures were built directly downstream of the old dam and included two new spillways with segment gates.

The dam facility currently consists, from left to right in the direction of flow, of a left concrete dam, a left rockfill dam, a concrete spillway and intake section, and a right rockfill dam. The main dam is a rock fill dam with a centrally located symmetrical core of moraine. The core is surrounded on the upstream and downstream sides by filters, and the support fill consists of blasted rockfill. The dam facility is mainly built on bedrock, and a toe berm has been constructed on the downstream side of the dam, in accordance with the Swedish industry guidelines for dam safety, RIDAS.

In 2006-2008, dam safety-enhancing measures were carried out in Porjus, including the construction of toe berms on the downstream side, rock fill rip rap on the upstream side, additional instrumentation, construction of a stationary diesel unit, refurbishing of spillway gates, stabilization of concrete structures, and measures in the spillway canal.

Technical details

GENERAL

Owner	Vattenfall Vattenkraft AB
Purpose	Hydropower
Location	Jokkmokk Municipality, Norrbotten County
River	Luleälven
Drainage basin area	– km²
Mean annual flow	268 m³/s
100-year flow	1 043 m³/s
Year of construction	1910–1915 and 1971–1980

POWER FACILITIES

Rated head	59 m
Maximum discharge capacity	1 040 m³/s
Installed power	440 MW

RESERVOIR

Lake name	Porjusselet
Operating range	3,7 m
Surface area	184 km²
Storage capacity	– Mm³

DAM

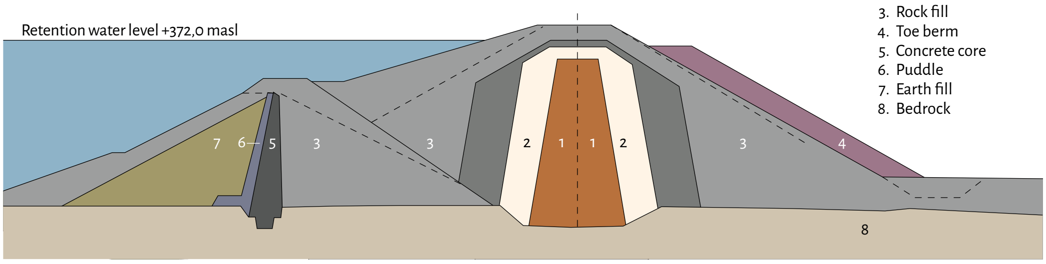
Type	Rockfill dam
Height	25 m
Crest length	2 100 m
Foundation type	Bedrock

SPILLWAY

Type	Surface Spillway
Maximum discharge capacity	– m³/s

MAJOR MODIFICATIONS

2006–2008	Rock fill rip rap on upstream side, toe berm on downstream side, additional instrumentation, improvements concrete structures and spillway canal.



1. Till core
2. Filter
3. Rock fill
4. Toe berm
5. Concrete core
6. Puddle
7. Earth fill
8. Bedrock

Section through dam.

Overview. Photo: Jennie Pettersson, Vattenfall.

Spillway downstream. Photo: Hans Blomberg, Vattenfall.

Älvkarleby

Sweden's oldest hydro power plants – Olidan (Götaälv), Porjus (Luleälven) and Älvkarleby (Dalälven) – were all built in the early 20th Century with the main purpose of supplying power to the railways and local industries.

Dalälven river runs through the very heart of Sweden's mining industry. Many mills have been built along the river. The river has also been used for log-driving on a large scale.

Älvkarleby power plant is located eight kilometers from the point where Dalälven river flows into the Baltic Sea. Älvkarleby was already an important settlement back in the Bronze Age. People were probably drawn to the area by its salmon-fishing, and the river is still popular for sport fishing, even after construction of the power plant.

The purpose of Älvkarleby power plant was to supply central Sweden with electricity. The power plant was designed by the architect Erik Josephson, who also designed Olidan power plant. Älvkarleby originally had an installed capacity of 70 MW but its capacity has increased over time and is now 125 MW.

The Älvkarlebyfalls are divided by the two islets Flakön and Laxön in three branches, called from the left Kungsådran, Mellanfallet and Storfallet. In the three river branches there are dam constructions, mainly made in concrete. Between 1986 and 1992, new concrete and embankment dams were replaced as compensation for older dams that were tear down. Embankment dams can be found at the left land attachment of the Mellanfallet as well as at the two land brackets of the Kungsådran. There is also an embankment dam along the Laxön beach that connects the dams in the Mellanfallet and Kungsådran. Two machine stations with a total of six aggregates are on the right side of the river.

Technical details

GENERAL

Owner	Vattenfall Vattenkraft AB
Purpose	Hydropower
Location	Älvkarleby Municipality, Uppsala County
River	Dalälven
Drainage basin area	– km²
Mean annual flow	348 m³/s
100-year flow	1 850 m³/s
Year of construction	1911–1915

POWER FACILITIES

Rated head	22,5 m
Maximum discharge capacity	700 m³/s
Installed power	125 MW

RESERVOIR

Lake name	Älvkarleby reservoir
Operating range	– m
Surface area	1,5 km²
Storage capacity	– Mm³

DAM

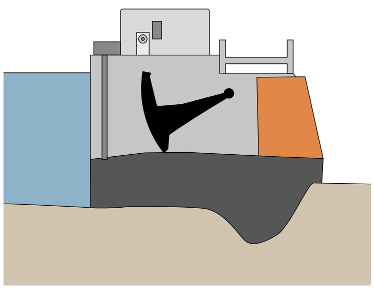
Type	Concrete
Height	18 m
Crest length	1 500 m
Foundation type	Rock

SPILLWAY

Type	Surface spillway
Maximum discharge capacity	– m³/s

MAJOR MODIFICATIONS

1987–1992	New concrete dams and spillway gates



Overview. Photo: Jennie Pettersson, Vattenfall.

Photo: Jennie Pettersson, Vattenfall.

Photo: Matz Almbrandt, Vattenfall.

Lilla Edet

Lilla Edet power plant is situated on the Göta River in the southwest part of the country.

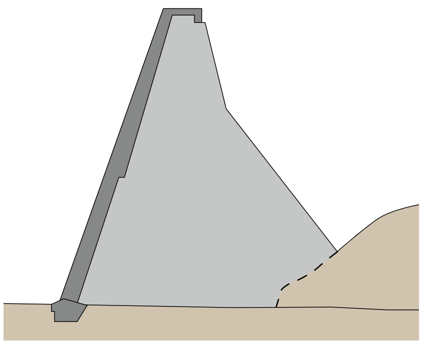
Lilla Edet power plant is situated on the Göta River in the southwest part of the country. The construction of the facility started in 1916. The purpose was to supply the western main railway line between Stockholm and Gothenburg with electricity. However, due to the recession after the war, it took more than ten years until the commission of Lilla Edet in 1926. The dam is a concrete dam founded on rock. The dam is equipped with eight spillways.

Choosing Lilla Edet as the site for a hydropower plant had both advantages and disadvantages. One of the advantages was that the Göta River is Sweden's most water-rich river, with an average flow rate of 550 m³ per second. The main drawback at the time was the low head – only four meters. However, in connection with the construction of a floodgate in the municipality of Trollhättan, a dam was also built in 1916 that increased the head at Lilla Edet to 6.5 meters.

Lilla Edet was the first Swedish power plant to use Kaplan turbines, and the Kaplan turbine built as unit 1 was the largest in the world on completion. As the Swedish experience with the Kaplan turbine was limited at this time, Lawaczeck turbines were selected for the other two units. However, one of them was later replaced with a propeller turbine. In 1982, a 13 MW bulb-type turbine was added as the fourth unit. Using four different turbine types in a single power plant makes the Lilla Edet power plant unique.

In 2021 Vattenfall started an extensive dam project in Lilla Edet to ensure renewable hydropower production for at least another 100 years. In this process, the current dam and part of the spillway section will be replaced. The replacement of four old spillways with new ones will provide additional spillway capacity so the dam meets the design flow requirements. Construction of the new dam is expected to be completed in 2026.

The Göta River was once one of the country's best rivers for salmon fishing. To improve the conditions for the salmon population and help the salmon swim upstream, a fish ladder was built early in Lilla Edet. It has been replaced in recent years by a new fishway on the eastern side of the river. The fishway is equipped with a counter that counts the salmon that migrate upstream. Downstream Trollhättan and Lilla Edet, Vattenfall releases 35,000 salmon smolt every year as a compensation for the natural spawning grounds that disappeared when the river was expanded.



Section through dam.

Technical details

GENERAL

Owner	Vattenfall Vattenkraft AB
Purpose	Hydropower
Location	Lilla Edet Municipality, Västra Götaland County
River	Göta älv
Drainage basin area	– km²
Mean annual flow	550 m³/s
100-year flow	1 320 m³/s
Year of construction	1916–1926

POWER FACILITIES

Rated head	7 m
Maximum discharge capacity	780 m³/s
Installed power	44 MW

RESERVOIR

Lake name	Lilla Edet
Operating range	1,05 m
Surface area	3,4 km²
Storage capacity	– Mm³

DAM

Type	Concrete dam
Height	25 m
Crest length	400 m
Foundation type	Bedrock

SPILLWAY

Type	Surface spillway and bottom outlet
Maximum discharge capacity	– m³/s

MAJOR MODIFICATIONS

2021–ongoing	Construction of a new dam and a spillway section

Overview. Photo: Romanas Wolfsborg, Vattenfall.

Kattstrupeforsen

Kattstrupeforsen dam is situated in the river Indalsälven, 6 km downstream of the Hissmofors power plant and about 20 km north of the city Östersund.

The plant was built between 1939 and 1942. The total length of the dam is about 1300 m, and the maximum height is 17 m. The dam consists of both fill dams and concrete dams.

Like some other contemporary dams built during this period, the fill dams were built with a core consisting of concrete. The core is 250 mm thick and reinforced, and at the foundation at the bedrock, the core was widened to the shape of a triangle. The concrete blocks were made in 12 m long sections, where every other section was made in the first stage. Intermediate sections were not made until two weeks later. The blocks were not provided with dilatation joints. Instead, the casting joints were provided with abundant amounts of reinforcement. Upstream of the concrete core, a layer of clay and till was placed. The supporting fill consists of sand, gravel, and stones. In the abutments, the concrete core was replaced with wood- or steel-sheet piles.

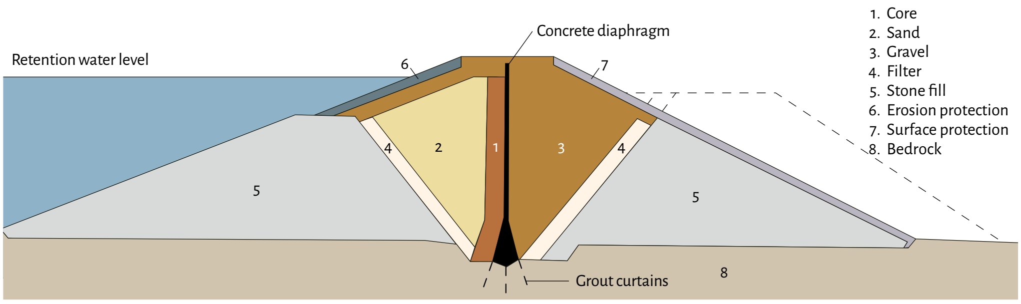
From the beginning, it was decided to carry out the dam over the mainstream as a fill dam with a vertical sealing core of concrete. In the course of the work, however, through the events of the war, such a change in the situation regarding the production of power in the country occurred that demands were made for the speedy completion of the power station. For that reason, this dam part was carried out as a concrete dam, which could be carried out in winter within heating sheds. A time gain in the completion of the plant of about four months could thus be achieved.

The concrete dam consists of a supporting solid dam body and, in front of it, a waterproof front plate made of reinforced concrete. The dam was constructed with eight monoliths, each 12 m long. The thickness of the front plate is about 25 cm in the upper part and 32 cm in the lower part. The total length is 150 m and, at most, 16 m high.

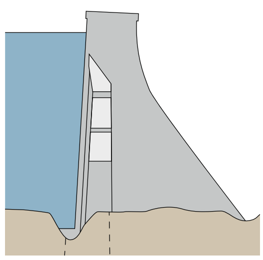
The concrete dam became one of the last dams in the country of this type. The decisive reason was that the costs of the dam type were so high that it became difficult to defend against other types of concrete dams, such as the buttress dam.

Technical details

GENERAL	
Owner	Jämtkraft AB
Purpose	Hydropower
Location	Krokom Municipality, Jämtland County
River	Indalsälven
Drainage basin area	12 144 km²
Mean annual flow	239 m³/s
100-year flow	980 m³/s
Year of construction	1939–1942
POWER FACILITIES	
Rated head	16 m
Maximum discharge capacity	445 m³/s
Installed power	61,5 MW
RESERVOIR	
Lake name	Kattstrupeforsen
Operating range	0,75 m
Surface area	5,4 km²
Storage capacity	4,3 Mm³
DAM	
Type	Concrete dam, earthfill dam
Height	16 m
Crest length	1 350 m
Foundation type	Bedrock of clayey slate
SPILLWAY	
Type	Bulkhead gates
Maximum discharge capacity	1 284 m³/s
MAJOR MODIFICATIONS	
1956	Installation of a third turbine
1990	Increase of crest height



Cross-section of the embankment dam.



Cross-section of the concrete dam.

Overview.

Concrete dam in foreground.

Burvattnet

The dam is the highest situated regulation in river Långan and is located in mountain terrain, on the border of bare mountains.

The dam is located in roadless land, and a boat or a snowmobile is used for access. At the dam, there is a barrack that allows staff to stay overnight. The reservoir consists of two parts of a lake connected by an excavated canal. The volume of regulation is 73 Mm³.

The left dam is a fill dam with a bottom outlet (a culvert through the dam). On the left dam, there is also a fish ladder. The right outlet is a surface spillway stepped of concrete. The bottom outlet is normally controlled by remote operation from the operating center in Östersund. The surface spillway and the fish ladder are regulated on-site.

The bottom outlet has so far consisted of a wooden culvert with embedded concrete elements. In 2021, work began on the rebuilding of the bottom outlet. After the refurbishment, the spillway capacity will increase. During the rebuilding of the left dam, a temporary cofferdam was built on the upstream side and a siphon was used for the temporary discharge of water.

Technical details

GENERAL

Owner	Indalsälvens Vatten-regleringsföretag (IVF)
Purpose	Hydropower
Location	Krokoms and Åre Municipality, Jämtland County
River	Långan/Indalsälven
Drainage basin area	117 km²
Mean annual flow	4,1 m³/s
100-year flow	75 m³/s
Year of construction	1942–1943

POWER FACILITIES

Rated head	– m
Maximum discharge capacity	– m³/s
Installed power	– MW

RESERVOIR

Lake name	Burvattnet
Operating range	5,9 m
Surface area	13 km²
Storage capacity	72 Mm³

DAM

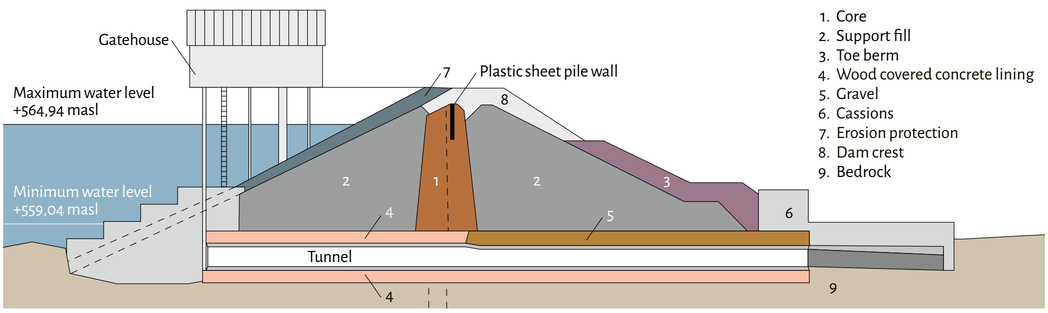
Type	Earthfill dam
Height	11 m
Crest length	230 m
Foundation type	Till

SPILLWAY

Type	Bottom outlet and surface spillway
Maximum discharge capacity	48 m³/s

MAJOR MODIFICATIONS

2009	New surface spilway, rip-rap and toe-berm
2021 >>	New bottom-outlet and Rebuilding of left dam. (ongoing work)



Cross section of the embankment dam at the bottom outlet.

Aerial overview.

The Burvattnet dam, completed in 1943, is an embankment dam with a wooden diaphragm.

View from upstream.

View from downstream.

Construction of new spillway.

Skallböle

Skallböle hydropower plant is a run-of-the-river plant situated in the river Ljungan, close to Sundsvall society.

Skallböle hydropowerplant was built to replace a smaller powerplant located upstream, due to greater demand of energy from the local industry.

The power station, the spillway, the concrete dam, and most earth-fill dams are founded on bedrock. The left earth-fill dam is constructed with a central impervious core with a wooden sheet pile. A filter of sand surrounds the core. The dam shoulders consist of previous material, and a layer of erosion protection is placed on the upstream slope. The right earth-fill dam is placed in an excavated trench into the right abutment and consists of an impervious core with a wooden sheet pile in the center. In 2018 the old sheet pile was improved, both on the dam's left and right side, by installing a plastic sheet pile with concrete fill. To increase the downstream stability of the dam, a coarse rock-fill berm is placed along the downstream toe of the left earth-fill dam. The earthfill dam has surveillance by pore pressure and leakage measurements.

To fulfill the demands of spillway capacity, one of the three existing spillways was reconstructed with a lower threshold and a new larger radial gate. The new spillway gate is 12 x 15 meters. The downstream area has been optimized due to the hydraulic flow situation. The left wall downstream of spillway 1 and the connected deflector has been increased and extended. Rock has been excavated from the left bank. The right wall downstream of Spillway 2 and the connected deflector has been increased, and the existing separation wall to the downstream channel of turbines 1 and 2 has been extended. Rock has been excavated at the bottom and concrete slab downstream of Spillway 3. A new diagonal and inclined guiding wall joins the increased separation wall and limits the concrete slab on the right. To optimize the design of these improvements, a hydraulic model test was performed at the Technical University at Munich. The model was built in scale 1:40.

The stability of the concrete dam is improved by installing steel tendon. The forces in the tendons are monitored.

Technical details

GENERAL

Owner	Statkraft Sverige AB
Purpose	Hydropower
Location	Sundsvall Municipality, Västernorrland County
River	Ljungan
Drainage basin area	12 076 km²
Mean annual flow	126 m³/s
100-year flow	1 010 m³/s
Year of construction	1949–1950 (3rd turbine 1980–1982)

POWER FACILITIES

Rated head	21,5 m
Maximum discharge capacity	265 m³/s
Installed power	46 MW

RESERVOIR

Lake name	Stödesjön
Operating range	0,27–0,60 m
Surface area	18 km²
Storage capacity	5,2–11,3 Mm³

DAM

Type	Concrete dam, earthfill dam
Height	27 m
Crest length	208 m
Foundation type	Bedrock

SPILLWAY

Type	Surface spillways with radial gates
Maximum discharge capacity	1 575 m³/s

MAJOR MODIFICATIONS

2018–2020	Increased discharge capacity, increased stability and persistence towards internal leakage in the earthfill dam, increased stability in the concrete dam and optimization of hydraulic flow in the downstream area.

Overview. Photo: Statkraft Sverige AB.

Rebuilt spillway 2.

Granfors

Granfors dam and power station are situated along Skellefteälven, approximately 30 km northwest of Skellefteå.

The dam serves as short-term regulation for hydropower purposes. The dam consists of a 100 m long earth-fill dam that connects the intake structure to the northern shore. Between the intake structure and the southern shore, the dam consists of a concrete buttress dam. The concrete is directly connected to the relatively steep natural rock slope at the south abutment.

The spillways consist of two segment gates and one sector gate. There are also three bottom outlets under one of the segment gates. The bottom outlets have not been in service since the construction phase when they were used to pass flows during construction.

The remnants of previous log-driving in the river can be viewed on the left of the spillways. The outdated timber chute, used to transport logs from the upstream to downstream side of the dam, remains. The former timber spillway is now blocked by a concrete wall, and its old gate has been removed. Such remnants of the past are commonly visible throughout the river.

Technical details

GENERAL

Owner	Skellefteå kraft AB
Purpose	–
Location	Skellefteå Municipality, Västerbotten County
River	Skellefteälven
Drainage basin area	11 110 km²
Mean annual flow	144 m³/s
100-year flow	– m³/s
Year of construction	1952 (completion)

POWER FACILITIES

Rated head	18,7 m
Maximum discharge capacity	240 m³/s
Installed power	39 MW

RESERVOIR

Lake name	Granfors reservoir
Operating range	1,0 m
Surface area	1,0 km²
Storage capacity	1,0 Mm³

DAM

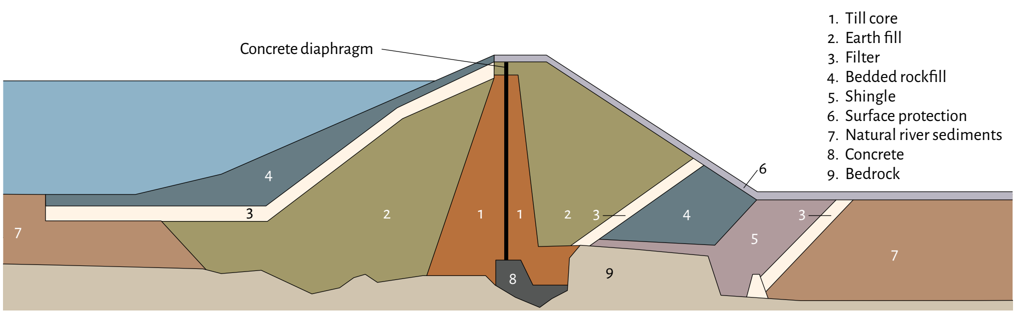
Type	Concrete buttress dam
Height	33 m
Crest length	283 m
Foundation type	Bedrock

SPILLWAY

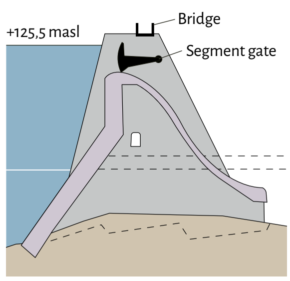
Type	Surface spillway and bottom outlet (not in service)
Maximum discharge capacity	690 m³/s

MAJOR MODIFICATIONS

2003	Heightening and reinforcement of crest



Cross-section of the embankment dam.



Cross-section of the spillway.

Overview.

View from the air. Photo: John Eliasson.

Lake Lisjön - Kovik Dam

The Lisjön reservoir in the tributary Svartälven of the river Gullspångsälven is used for long-term (annual) regulation with an amplitude of 6,20 meters.

The storage basin was created by increasing the capacity of the previous Old Reservoir, 3 Mm^3 to Lisjön of 45 Mm^3. A large bog area, including a few smaller lakes, was inundated. The power station, a regulating dam, and four saddle dams were constructed between 1949 and 1952.

The original Kovik dam is an earth fill dam of a somewhat unusual design. The foundation of till is partly covered with a layer of peat. The dam has a broad core of dense material, but no downstream filter. The upstream face is, and the crest was covered with a layer of peat to prevent leakage if settlements in the peat would occur.

Cracks and partial landslides occurred on the upstream face early, and the slopes were repaired and reinforced in 1952. Another unforeseen problem was the debris of peat detaching from the bottom of the reservoir, creating large floating islands that can block the intake or spillways.

The original spillway, a bottom outlet, has a capacity of 25 m^3/s. Early on, it was evident that only one spillway was not safe enough. In 1960, a new surface spillway of 20 m^3/s was constructed. The first Dam Safety Evaluation of the dam in 1999 raised concerns about the overall construction of the dam and compaction skills in the fifties. In connection with this evaluation, the probable maximum flood was calculated, and the discharge capacity was found insufficient compared to the requirements.

In late 2000 an incident occurred at the bottom outlet wooden channel. After a period with high inflow and continuous discharge, the channel failed and a deep erosion cavity quickly formed in the downstream area of the dam. The surface spillway was suddenly vital. Repairs, fill of the cavity, and a new concrete channel, were completed within 13 days.

During 2001–2003, the dam was reconditioned. A third surface spillway with a 24 m^3/s capacity was constructed, and the freeboard was raised to 1.50 meters. A rockfill toe berm increased the dam's stability, and the upstream surface was improved with a rockfill cover and riprap. New leakage measurements were installed, and the flow in the four drainage wells is now continuously monitored remotely.

Technical details

GENERAL

Owner	Karlskoga Vattenkraft AB
Purpose	Hydropower
Location	Ludvika Municipality, Dalarna County
River	Svartälven/ Gullspångsälven/Göta älv
Drainage basin area	177 km^2
Mean annual flow	2,6 m^3/s
100-year flow	32 m^3/s (inflow)
Year of construction	1950–1952

POWER FACILITIES

Rated head	33 m
Maximum discharge capacity	9,7 m^3/s
Installed power	2,2 MW

RESERVOIR

Lake name	Lisjön
Operating range	6,20 m
Surface area	14 km^2
Storage capacity	45 Mm^3

DAM

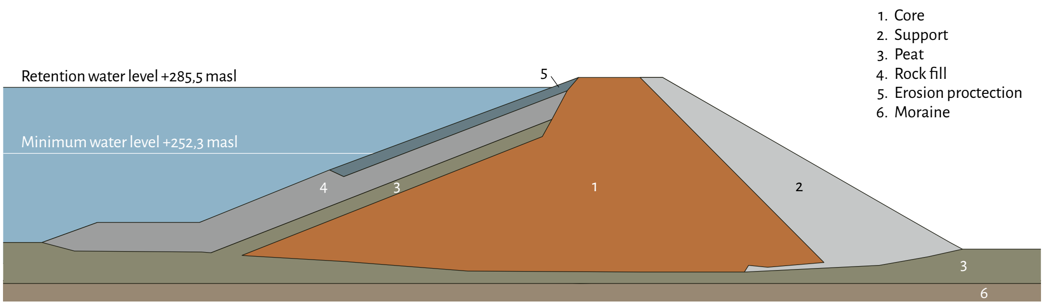
Type	Earth fill
Height	10 m
Crest length	615 m
Foundation type	Till and peat

SPILLWAY

Type	Bottom outlet and surface spillways
Maximum discharge capacity	69 m^3/s

MAJOR MODIFICATIONS

2001–2003	Upgrading of spillways, riprap, toe berm and instrumentation



Section through the original Kovik dam (before reconditioning) completed in 1951.

Overview left side of dam, bottom outlet. Low reservoir. Photo: Norconsult.

Overview right side of dam, incoming peat. Photo: Norconsult.

Storfinnforsen

Storfinnforsen hydropower plant is located at reservoir Storfinnsjön in Västernorrland County, Sollefteå Municipality, 24 km upstream of the Ramsele community.

The dam is a part of the hydropower complex in the river Faxälven, downstream of Lövön hydropower plant and upstream of its sister facility Ramsle hydropower plant.

The facility consists of three main dams. The left dam is a 25 m high, 350 m long earth fill dam connecting to a concrete buttress dam. The buttress dam is 40 m high and almost 700 m long. Farthest to the right is a 150 m long and 8 m high concrete gravity dam.

The dams have undergone major upgrades between 2008 and 2017:

Increased stability of the concrete dam

- Pre-tensioned rock anchors through the buttress.
- New drainage in bedrock downstream of the front plate.
- Insulation of the concrete buttress dam and installing heating, ventilation, lighting, and new inspection passages on two levels in the enclosed area.
- Renovation of all accessible concrete surfaces.
- New sensors and monitoring program.

Increased safety of the earth fill dam

- New rockfill toe berm.
- New downstream drainage system with seepage measurement system.
- New vertical chimney drainage consisting of drilled and sand-filled holes placed 7 m downstream of the core through the support fill.
- New sensors and monitoring program.

Renovation and recommission of the bottom outlet

- New temporary gate, installed at 40 m depth.
- New gate in stainless steel.
- New outlet channel.

Rock stabilization in the outlet channel to mitigate safe energy dissipation.

Technical details

GENERAL

Owner	Sydkraft Hydropower AB
Purpose	Hydropower
Location	Sollefteå Municipality, Västernorrland County
River	Faxälven/Ångermanälven
Drainage basin area	6 791 km²
Mean annual flow	124 m³/s
100-year flow	543 m³/s
Year of construction	1948–1954

POWER FACILITIES

Rated head	49,5 m
Maximum discharge capacity	270 m³/s
Installed power	112 MW

RESERVOIR

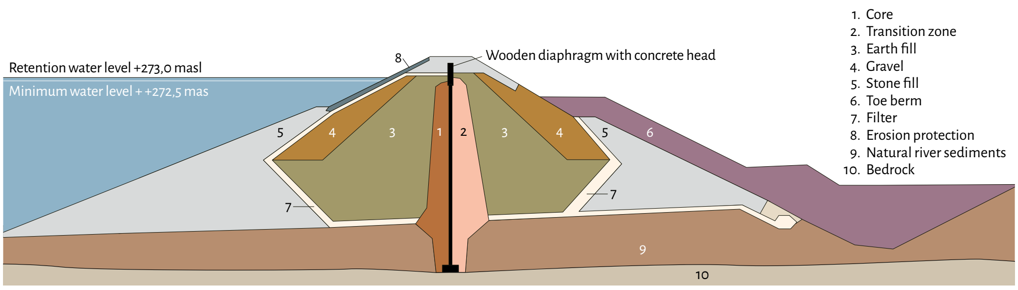
Lake name	Storfinnforsen
Operating range	0,5 m
Surface area	26,3 km²
Storage capacity	6,5 Mm³

DAM

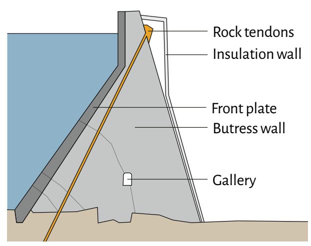
Type	Earth fill dam and concrete buttress dam
Height	40 m
Crest length	1 198 m
Foundation type	Bedrock

SPILLWAY

Type	Surface spillway and bottom outlet
Maximum discharge capacity	1 170 m³/s at RL



Cross-section of the earth fill dam.



Cross-section of a buttress.

Overview. Photos: Uniper.

During installation of chimney drains.

Bergeforsen

Bergeforsen hydropower plant is situated at the downstream end of the river Indalsälven, some 10 km from where the river meets the Baltic Ocean.

The plant is located in Timrå County, just north of Timrå and about 20 km north of Sundsvall. Bergeforsen kraft AB (BKAB), a company jointly owned by Vattenfall and Uniper, owns and operates the Bergeforsen power plant.

Construction of the plant began in 1949, the operation of units 1–3 started during 1955-1956, and the operation of a fourth unit started in 1960. The four generators with a rated head of 23 m are designed for a total water flow of 840 m³/s, providing an output of 174 MW. The Bergeforsen has no storage capacity as the water surface is kept constant at +23.0 m.a.s.l.

The dam facility consists, from the left, of a 25 m wide spillway that was put into operation in 2014, a 230 m long earthfill dam, a 158 m long concrete dam with three spillways and an intake to the power station, and a 126 m long earthfill dam. The dams are mainly founded on rock.

Unique to Bergeforsen from a dam safety perspective is Alnöit, a rock with relatively low strength, which is found in the bedrock at and around the dam. During 2011-2014, a new spillway was built for debris management. However, finding a suitable location for the new spillway was not easy. The Alnöit makes it inappropriate to construct the spillway at the right bank or near the existing spillways. Therefore, the new spillway was constructed at the left bank. Construction on this side meant no problem with Alnöit, but resulted in the redemption of houses and a hotel.

The design of the spillway includes a new 10x25 m² segment gate. The gate, which is the largest gate in the Nordic region, is operated by two centrally located hydraulic cylinders. The design of the channel was determined through model experiments at Älvkarleby and involved major rock and concrete work. The dam was reinforced with a downstream support berm in 2002-2003. This support berm aims to increase drainage capacity and improve slope stability.

Technical details

GENERAL	
Owner	Bergeforsen Kraft AB
Purpose	Hydropower
Location	Timrå Municipality, Västernorrland County
River	Indalsälven
Drainage basin area	–
Mean annual flow	446 m³/s
100-year flow	2 160 m³/s
Year of construction	1949–1955

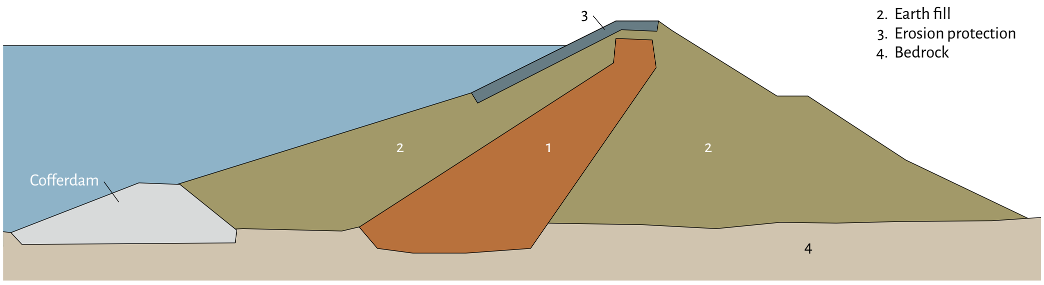
POWER FACILITIES	
Rated head	23 m
Maximum discharge capacity	840 m³/s
Installed power	174 MW

RESERVOIR	
Lake name	Bergeforsen
Operating range	0 m
Surface area	19 km²
Storage capacity	–

DAM	
Type	Earthfill dam
Height	37 m
Crest length	544 m
Foundation type	The dam's core is founded on rock

SPILLWAY	
Type	Surface spillway
Maximum discharge capacity	–

MAJOR MODIFICATIONS	
2002–2003	Rip-rap, toe berm and instrumentation
2011–2014	New spillway



Section through dam.

Aerial overview.

Upstream view powerplant. Photo: Niclas Johansson, Vattenfall.

Spillway A-C.

Spillway D.

Yngeredsfors

Yngeredsfors HPP is located in the southwest of Sweden, approx. 100 km southeast of Gothenburg.

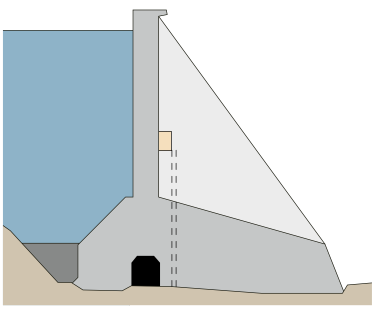
It is one of Unipers 5 HPPs in river Ätran, which starts in the central parts of southern Sweden and ends in the Ocean (Kattegatt) in Falkenberg. Uniper's hydropower plants in Ätran have small storage basins and act like run-of-the-river plants. However, river Ätran is partially regulated by five smaller dams that control the outflow from lakes Sämsjön, Fegen, and Åsunden.

Yngeredsfors dam is a concrete dam founded on bedrock. The abutments are designed as gravity dams, and the central part is a buttress dam. The spillway consists of 2 large radial gates with a discharge capacity of 160 m³/s each at RT, and approximately 250 m³/s each at dam crest level, which gives that the design flood can be discharged with an upstream level of a little above RT but with a satisfying margin to the crest level of +75,0 m.

The power station is located at the right abutment of the dam. A tailrace tunnel discharge the water from the turbines approximately 1,5 km downstream of the dam.

Seepage control is installed on both sides of the intake. There are no piezometers or settlement monuments installed at Yngeredsfors.

As a result of the dam safety evaluation 2011, 6 posttensioned anchors were installed to increase the stability of the dam. The anchors were installed with a force of approximately 3 000 kN each.



Cross-section of buttress

Technical details

GENERAL

Owner	Uniper
Purpose	Hydropower
Location	Falkenberg Municipality, Halland County
River	Ätran
Drainage basin area	2 571 km²
Mean annual flow	41 m³/s
100-year flow	255 m³/s
Year of construction	1964

POWER FACILITIES

Rated head	28,5 m
Maximum discharge capacity	75 m³/s
Installed power	18,1 MW

RESERVOIR

Lake name	Ätran
Operating range	0,5 m
Surface area	1,1 km²
Storage capacity	3,1 Mm³ at Retention Level (RT +73,0 m)

DAM

Type	Concrete buttress dam
Height	20 m
Crest length	102,5 m
Foundation type	Bedrock

SPILLWAY

Type	2 radial gates
Maximum discharge capacity	320 m³/s at RT, 510 at dam crest

MAJOR MODIFICATIONS

2016	Installation of 6 post-tensioned anchors in three monoliths to increase sliding frictional resistance.

Upstream overview.

Downstream overview.

Discharge.

Trängslet

The Trängslet dam is the highest dam in Sweden.

The Trängslet dam is the highest dam in Sweden. The dam is built as a rockfill dam with an impervious core of till. The construction was carried out by Stora Kopparberg during 1955–1960. The present owner of Trängslet power station is Fortum. The dam height is 125 m, the crest length 900 m, and the crest width 10 m. The dam is founded on bedrock. The bedrock is of varying quality and consists of syenite, porphyry, and, at some locations, diabase. The inclined impervious core made of till is surrounded by three filter layers. The dam consists of 4,5 million m^3 of rockfill, 1,2 million m^3 filter, and 1,5 million m^3 till. The total volume of masses used is 7,2 million m^3. The three filters between the impervious core and the rockfill have different characteristics; coarse, medium, and fine.

Trängslet power station is located in the bedrock beneath ground level. It is equipped with three units with separate intakes and three penstocks lined with concrete and steel. The penstock has a diameter of 4,8 m and a length of 150 m. The turbines are of Francis type and equipped with throttle valves. Three different draft tubes join into one tailrace tunnel with a cross-sectional area of 140 m^2. The length of the tail race tunnel is 4,3 km. The tunnel also has a surge chamber, 3 000 m^2.

The dam was equipped with two segment gates with a total discharge capacity of 876 m^3/s. Since the dam was constructed, two projects with a focus on dam safety. In the first dam safety project, the height of the dam and the impervious core was increased by 1,5 -2 m.

In an ongoing dam safety project, a bottom outlet is built that will increase the discharge capacity. At the downstream side, a dam toe berm is built to make the dam even more able to withstand a hypothetical situation with internal erosion and leakage.

Technical details

GENERAL

Owner	Fortum
Purpose	Hydropower
Location	Älvdalen Municipality, Dalarna County
River	Dalälven
Drainage basin area	4 518 km²
Mean annual flow	64 m³/s
100-year flow	930 m³/s (inflow)
Year of construction	1955–1960

POWER FACILITIES

Rated head	142 m
Maximum discharge capacity	280 m³/s
Installed power	330 MW

RESERVOIR

Lake name	Trängsletsjön
Operating range	35 m
Surface area	37 km²
Storage capacity	880 Mm³

DAM

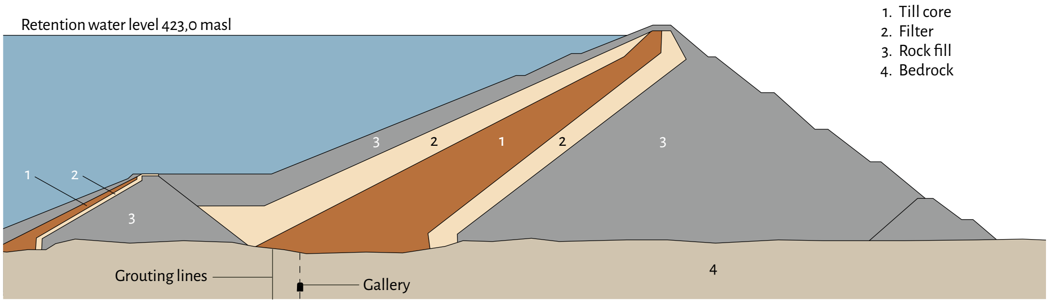
Type	Rockfill dam
Height	125 m
Crest length	900 m
Foundation type	Bedrock

SPILLWAY

Type	Surface spillway with segment gates
Maximum discharge capacity	876 m³/s

MAJOR MODIFICATIONS

1999	Dam safety
2019–ongoing	Dam safety project



Cross-section of the original dam.

Overview. Photo: Fortum.

Overview. Photo: Fortum.

Höljes

Höljes power plant is located in Klarälven, Torsby Municipality in Värmland County. Close to the border between Norway and Sweden.

Höljes is the northernmost plant in the river Klarälven on the Swedish side of the border to Norway. In 1957, construction began of the dam and the work was completed in 1961. The lake Höljessjön is the reservoir for the Höljes power plant, originating in Norway and then stretches about 12 km north-south to the plant site in Höljes. Nowadays the main purpose of the reservoir is hydro power but historically the lake has also been used to facilitate log driving and became a holding site for logs from Norway until 1991 when the log driving ceased.

The dam in Höljes is a zoned earth- and rockfill dam with a height of 81 meters. The crest length is about 400 m and the width about 10 m. The impervious core of till is founded on rock, while parts of the supporting material are founded on natural river sediments. There is a grout curtain in the rock foundation beneath the core. The supporting fill material consists of gravel and rock.

The power plant in Höljes is located underground on the left bank of the river. The water is led via intake penstocks to two Francis-type turbines. The outlet tunnel is four km long, and the outlet channel is one and a half km long.

In 2005 a safety evaluation of the dam (SEED) was initiated. In 2006, the result from the SEED was reviewed by an advisory board which led to further extended investigations including setting up a physical model in order to find the best solution for a new spillway and stilling basin. In 2012 a legal permit for proposed project was achieved and a dam safety rehabilitation and improvement project started and lasted until 2016. The main activities in the project was to:

- Remove the old rafting spillway and construct a new radial gate in addition to the two existing outlets to increase spillway capacity to meet the design inflow.
- Install a larger stilling basin to protect the spillway area from erosion.
- Raise the core with pvc-trench.
- Place a layer of rock riprap on the upstream slope in order to protect the slope from erosion.
- Stabilize the dam with a toe berm on the downstream side.
- Install instrumentation in order to evaluate the performance of the dam and detect early signs of unwanted changes in behavior.

Technical details

GENERAL

Owner	Fortum
Purpose	Hydropower
Location	Torsby Municipality, Värmland County
River	Klarälven/Göta Älv
Drainage basin area	6 002 km^2
Mean annual flow	93 m^3/s
100-year flow	740 m^3/s
Year of construction	1957 – 1961

POWER FACILITIES

Rated head	88 m
Maximum discharge capacity	182 m^3/s
Installed power	139 MW

RESERVOIR

Lake name	Höljessjön
Operating range	34 m
Surface area	16 km^2
Storage capacity	270 Mm^3

DAM

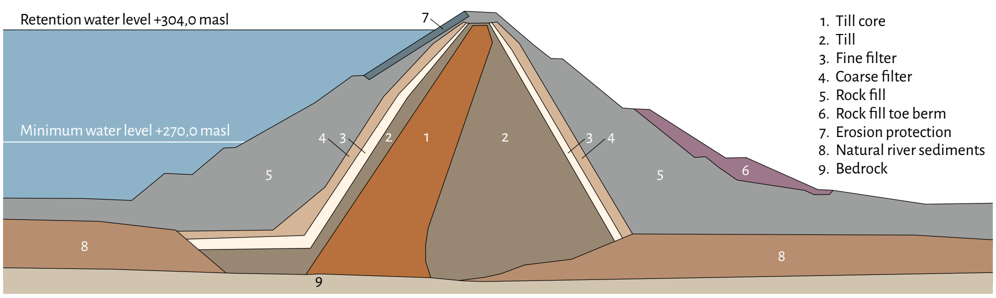
Type	Earthfill dam
Height	81 m
Crest length	400 m
Foundation type	Bedrock

SPILLWAY

Type	Surface spillway and bottom outlet
Maximum discharge capacity	2 004 m^3/s

MAJOR MODIFICATIONS

2012–2016	Dam safety project



Cross-section of the dam.

Overview.

Surface spillway with cofferdam upstream of left gate.

Surface spillway with radial gates.

Damcrest and upstream rip-rap.

Storjuktan

Storjuktan's regulation reservoir includes the lakes Storjuktan and Fjosokken.

The dam is an earthfill dam with a central core of morain surrounded by filters and with a sealing blanket on the upstream side. The spillway consists of a bottom outlet equipped with two gates and a downstream open channel. Previously there was a gate for timber, but this is now clogged.

The right earth dam is founded on soil, with a blanket on the upstream side. A supporting berm has been placed on the downstream side of the dam. The spillway and the left dam are founded on bedrock.

The part of the dam, which is founded on soil, is equipped with several leakage measuring points and a relatively large number of water level pipes. This is to monitor the leakage in the underground. There are large variations in leakage and water pressure on the downstream side of the dam, and there is ongoing work to evaluate the dam safety and if dam safety measures have to be performed.

The gates can be operated remotely from the operations center in Östersund. During larger flows, the dam is staffed.

After the construction of the Juktan power station, which was commissioned in 1979, the minimum required water flow (3 - 6 m³/s) was discharged through the spillway of the dam.

Technical details

GENERAL

Owner	UVF (dam) and Vattenfall Vattenkraft AB (power station)
Purpose	Hydropower
Location	Sorsele Municipality, Västerbotten County
River	Juktån/Umeälven
Drainage basin area	1 670 km²
Mean annual flow	28 m³/s
100-year flow	380 m³/s
Year of construction	1961–1963

POWER FACILITIES

Rated head	59,5 m
Maximum discharge capacity	50 m³/s
Installed power	25 MW

RESERVOIR

Lake name	Storjuktan
Operating range	14 m
Surface area	69 km²
Storage capacity	548 Mm³ (580 including Fjosokken)

DAM

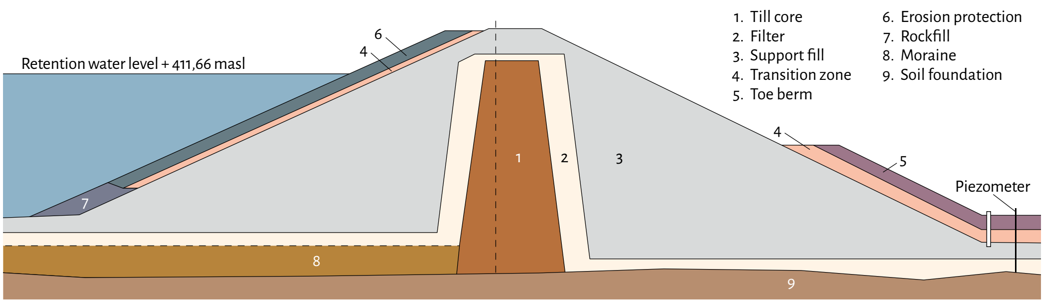
Type	Earthfill dam
Height	20 m
Crest length	900 m
Foundation type	Till, bedrock

SPILLWAY

Type	Bottom outlet
Maximum discharge capacity	430 m³/s

MAJOR MODIFICATIONS

2006–2017	Upgrading of spillway, rip-rap, toe berm and instrumentation



Cross-section of dam.

View from upstream.

View from downstream.

View of the dam.

Håckren Dam

The Håckren Dam is situated in the tributary Storån of the river Indalsälven, to the east of the mountain range that forms the border between Norway and northern Sweden.

The storage basin of 700 Mm^3 has been created by the four lakes Aumen, Hottöjen, Gesten, and Håckren. The reservoir is used for long-term (annual) regulation with a regulation amplitude of 26,9 m. It is also used for short-term regulation for the power station Sällsjö which was constructed at the same time as the dam. When the reservoir was commissioned, the fleeting of timber in Storån ceased and was replaced by truck transport on new roads built by IVF.

The dam is an earthfill dam with a central core of till surrounded by several zones of sand and gravelly sand and shoulders of gravel and rock. The original spillway is designed as a morning glory spillway and also with a low-level outlet. The latter is only intended to pass flows in case the powerhouse is shut down and the reservoir water level is below the sill level of the morning glory.

In the years 2006-2009, the dam was upgraded with an additional surface spillway, new rip-rap protection on the upstream slope, and a downstream rockfill berm. The old spillway's theoretical capacity was considered sufficient, but its real discharge capacity was questioned mainly because of the hydraulic performance of the discharge tunnel. Therefore a new spillway was constructed and placed in the left part of the dam on bedrock. It is equipped with two radial gates. It has a discharge channel with a stilling basin at its end. The discharge capacity of the new spillway is 470 m^3/s, as much as the original spillway.

At the same time, the rip-rap protection on the upstream slope was improved by an entirely new and improved rip-rap. The stones were placed individually in a two-layer system outside a layer of filter/transition.

Technical details

GENERAL

Owner	IVF (dam) and Skellefteå kraft (power station)
Purpose	Hydropower
Location	Åre Municipality, Jämtland County
River	Storån/Indalsälven
Drainage basin area	1153 km^2
Mean annual flow	25 m^3/s
100-year flow	240 m^3/s
Year of construction	1962–1965

POWER FACILITIES

Rated head	193 m
Maximum discharge capacity	110 m^3/s
Installed power	152 MW

RESERVOIR

Lake name	Håckren
Operating range	26,9 m
Surface area	44 km^2
Storage capacity	700 Mm^3

DAM

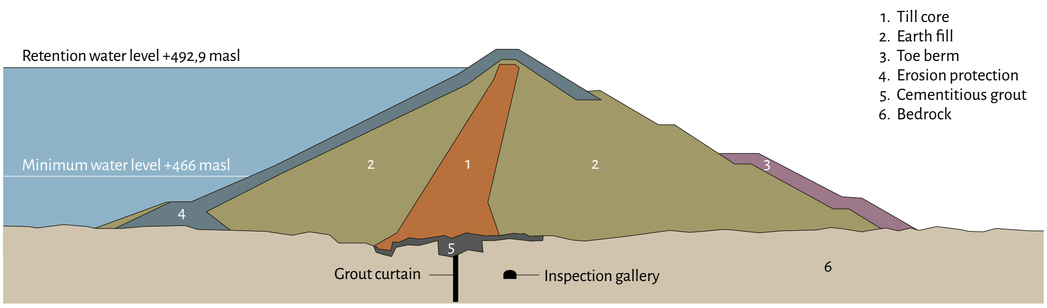
Type	Earthfill dam
Height	67 m
Crest length	860 m
Foundation type	Bedrock of clayey slate

SPILLWAY

Type	Surface spillway, morning glory spillway and bottom outlet
Maximum discharge capacity	935 m^3/s

MAJOR MODIFICATIONS

2006–2009	Upgrading of spillway, rip-rap, toe berm and instrumentation.



Cross-section of dam.

Aerial overview.

Overview.

View from upstream.

Morning glory spillway.

Construction of new spillway.

Dabbsjö

The Dabbsjö dam is situated in the tributary Saxån of the river Ångermanälven.

The storage basin is 380 Mm³. The reservoir is used for longterm (annual) regulation with a regulation amplitude of 25,5 m.

The main dam is a 530 m long and 6,5 m wide rockfill dam founded on bedrock. It's 45 m high and the crest is at elevation + 420,00 m. The rockfill dam is constructed with a central core made of till, slightly tilted in the downstream direction. The core is surrounded by filters of sand, transitional bearings and rockfill material.

Discharge is possible through either of the two surface spillways or by the overflow threshold. The two surface spillways have a flat gate each and are separated by a concrete monolith. The threshold of the overflow spillway is at +417 m which is the same as the retention water level.

Two model tests were performed at NTNU in Trondheim, Norway, 2011. One focused on discharge capacity for the surface spillways and the other focused on the overflow threshold.

2012-2015 the dam safety has been increased by:

- Rebuilding of existing surface spillways and an increased discharge capacity.
- Building a new overflow dam (overflow threshold) and increasing discharge capacity.
- Reinforcements of the rockfill dam.
- Reinforcement of tunnel from the bottom outlet.
- Instrumentation and automation of the dam monitoring.
- New road to access the dam from the right side.

Technical details

GENERAL

Owner	Statkraft
Purpose	Hydropower
Location	Dorotea Municipality, Västerbotten County and Strömsund Municipality, Jämtland County
River	Saxån/Fjällsjöälven/Ångermanälven
Drainage basin area	862 km²
Mean annual flow	30,4 m³/s
100-year flow	292 m³/s
Year of construction	1969

POWER FACILITIES

Rated head	50 m
Maximum discharge capacity	74 m³/s
Installed power	26 MW

RESERVOIR

Lake name	Dabbsjön
Operating range	25,5 m
Surface area	18,3 km²
Storage capacity	380 Mm³

DAM

Type	Earthfill dam
Height	45 m
Crest length	659 m
Foundation type	Bedrock

SPILLWAY

Type	Surface spillway, bottom outlet and overflow threshold
Maximum discharge capacity	1 300 m³/s

MAJOR MODIFICATIONS

2005	Improved rip-rap protection upstream.
2011–2015	Upgraded existing surface spillways, building a new overflow threshold spillway, reinforcement of downstream slope, widening of the crest and instrumentation.
2022	Completion of existing instrumentation.

Overview. Photo: Statkraft Sverige AB.

Overflow threshold. Photo: Statkraft Sverige AB.

Hällby

Hällby hydropower plant is located on the River Ångermanälven, 30 km north of Junsele town, 20 km downstream of Åsele power plant, and 10 km upstream of Gulsele power plant.

The central section comprises the powerhouse and spillways and the dam closure to each abutment are embankments. Buttress dams form the transitions between the powerhouse, the spillways, and the embankment dams. The spillway section consists of two main radial gates with Creager profile ogees, one timber flume gate, and one bottom outlet. The bottom outlet was used to bypass water during construction and after the first impoundment was taken out of operation. In 2019, the bottom outlet was refurbishment, including the construction of a new spillway, and the bottom outlet is now fully operational.

A sinkhole was found in the left abutment embankment dam on 11 September 1985. The surface had settled about 0.7 m, and the volume of the settled fill was about 7 m³. The seepage flow had increased from about 20 l/min to about 200 l/min. A grouting program was performed during 1985 - 86 and comprised of grouting of fill using the tube-a-manchettes method, contact grouting between fill and rock/concrete, and finally, bedrock grouting. The total amount of grout used was approximately 400 m³.

As a result of the comprehensive dam safety evaluation year 2000, a supporting rock fill berm was constructed to the full height of both embankments during 2003-04. At the same time, a fully automated leakage measurement system for the right embankment was installed.

In 2008 the upstream riprap improved on both embankment dams. The new riprap was placed on a rock-fill berm built underwater. The new riprap has performed flawlessly to date.

Technical details

GENERAL

Owner	Sydkraft Hydropower AB
Purpose	Hydropower
Location	Sollefteå Municipality, Västernorrland County
River	Ångermanälven
Drainage basin area	10 685 km²
Mean annual flow	159 m³/s
100-year flow	1 150 m³/s
Year of construction	1970

POWER FACILITIES

Rated head	29 m
Maximum discharge capacity	325 m³/s
Installed power	84 MW

RESERVOIR

Lake name	Hällbymagasinet
Operating range	0,8 m
Surface area	40 km²
Storage capacity	30 Mm³

DAM

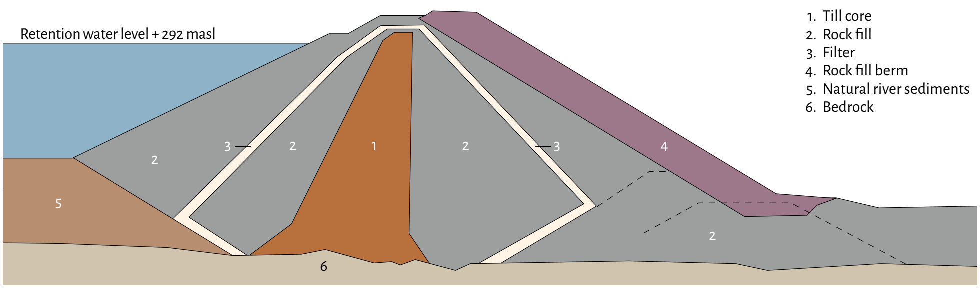
Type	Buttress and embankment dam
Height	30 m
Crest length	470 m
Foundation type	Bedrock

SPILLWAY

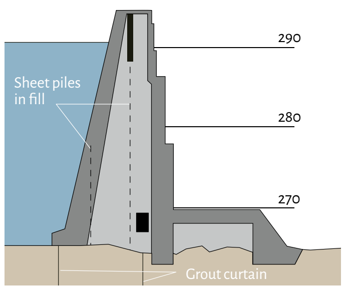
Type	Surface spillway and bottom outlet
Maximum discharge capacity	2 150 m³/s

MAJOR MODIFICATIONS

1985–1986	Grouting of embankment dam and bedrock close to the buttress dam
2003–2004	Leakage measuring system for right embankment
2003–2004	Rock fill berms for both embankments
2008	New riprap
2019–2021	Refurbishment of bottom outlet and new chute



Cross-section of the embankment dam.



Cross-section of the concrete dam.

View from downstream.

Upstream view during construction.

Upgrade of riprap.

Bottom outlet discharge.

Grundsjön

The Grundsjön reservoir is located in the upper parts of the river Ljusnan.

The reservoir is used for long-term (annual) regulation with an amplitude of 23,5 m and a reservoir capacity of 284 Mm^3. In addition, the reservoir is connected to the reservoir Övre Särvsjön, 44.7 Mm^3, via a 5 500 m long tunnel, area of 7.5 m^2. The reservoir holds the intake for power station Långå, Unit 2, with a head of 216 m and a capacity of 50 m^3/s. Unit 1 in Långå HPP is supplied from reservoir Lossen.

The facility was constructed during 1970-1972 and consists of two dams. The main dam is a 1 800 m long and 44 m high earth and rockfill dam with an inclined till core on a rock foundation. The minor dam has a central till core. The bottom outlet is a tower outlet with a cylinder gate and outlet tunnel under the main dam. The surface spillway has two flat gates.

In 1990 the lower part of the main dam experienced sink holes which led to a reconstruction of a part of the dam and installation of instruments for monitoring pore pressure, earth pressure and temperature. Since then, no incidents of that kind have taken place. During 2005-2008, the main dam was upgraded with upstream rip-rap, downstream toe berm and instrumentation. In 2022 the spillway chute for the surface spillway was extended to reduce the risk of backward erosion. Retaining walls and concrete slab was prolonged 20 meters.

Technical details

GENERAL

Owner	Ljusnans Vattenregleringsföretag
Purpose	Hydropower
Location	Härjedalen Municipality, Jämtland County
River	Mittån/Ljusnan
Drainage basin area	728 km^2
Mean annual flow	10,8 m^3/s
100-year flow	280 m^3/s
Year of construction	1970–1972

POWER FACILITIES

Rated head	216 m
Maximum discharge capacity	50 m^3/s
Installed power	92 MW

RESERVOIR

Lake name	Grundsjön
Operating range	23,5 m
Surface area	20,3 km^2
Storage capacity	284 Mm^3

DAM

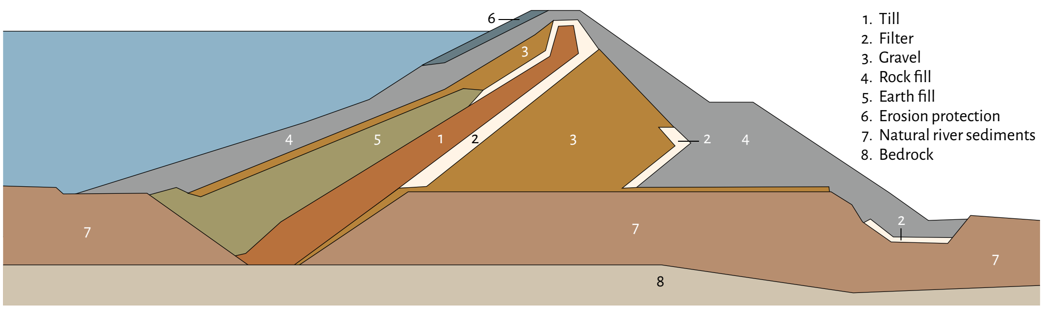
Type	Earthfill dam
Height	43 m
Crest length	2 000 m
Foundation type	Bedrock

SPILLWAY

Type	Surface spillway and bottom outlet
Maximum discharge capacity	570 m^3/s

MAJOR MODIFICATIONS

2005–2008	Dam safety actions including upstream rip-rap, downstream toe berm and instrumentation



1. Till
2. Filter
3. Gravel
4. Rock fill
5. Earth fill
6. Erosion protection
7. Natural river sediments
8. Bedrock

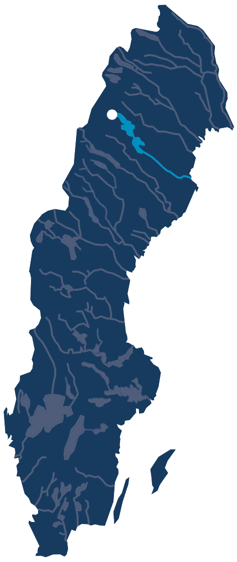
Section through dam.

Overview.

Surface outlet.

Rip-rap installation.

Sädvajaure Dam



Lake Sädvajaure was first regulated in 1941 when there was a need for electricity to a lead mine in Laisvall, close to the dam site.

The mining company Boliden built a dam and a power station, which were used to regulate the lake by approximately 6 m until 1983, when the construction of the current dam started. The old dam structure can still be seen when the reservoir level is close to its lowest level.

The Sädvajaure dam was commissioned in 1985 and is primarily used for long-term regulation to provide thirteen downstream power stations with water. The dam is situated at the east end of lake Sädvajaure, with an equal distance (70 km) to Arjeplog Municipality and the Sweden-Norway border. The dam can easily be seen from public road number 95, which passes only a few meters from the downstream toe.

The dam is a zoned rockfill dam with a central core of till, two filters of sand and gravel, and a support fill of slate rockfill from blasted canals and tunnels. The upstream face riprap is made of blasted slate, whilst the downstream toe berm is made of granite.

When the dam was built, it had only a bottom outlet with a blasted tunnel under the foundation of the dam. New design flood calculations conducted in the middle of 1990 showed that the spillway capacity was insufficient, and because of that, an additional surface spillway was built in 1999. Radial gates control both spillways; the bottom gate is driven by gear racks and the surface gate with a hydraulic cylinder.

The material used for the support fill has shown to be sensitive to weathering, and a considerably decreased fraction size and decreased permeability are observed. That, combined with a relatively steep downstream slope, led to a dam reinforcement with a 15 m high toe berm in 2015. To avoid problems with weathering, carefully tested granite was used instead of the material from the bedrock in the area surrounding the dam.

From the reservoir, there are intake structures to two power stations, both owned by Skellefteå Kraft AB. Ringsele power station is a mini-hydro situated at the dam toe and is used for the prescribed minimum discharge of 2.6 m³/s to the original river path. Sädva power station is supplied with water through a 1.6 km tunnel. It has a discharge capacity of 70 m³/s and a gross head of 45 m. Installed capacity is 31 MW (one turbine).

Technical details

GENERAL

Owner	Dam: Skellefteälven Water Regulation Company (SVF)
Purpose	Hydropower
Location	Arjeplogs Municipality, Norrbotten County
River	Skellefteälven
Drainage basin area	1 444 km²
Mean annual flow	37 m³/s
100-year flow	557 m³/s
Year of construction	1985

POWER FACILITIES

Rated head	–
Maximum discharge capacity	–
Installed power	–

RESERVOIR

Lake name	Sädvajaure
Operating range	16,3 m
Surface area	43,5 km²
Storage capacity	605 Mm³

DAM

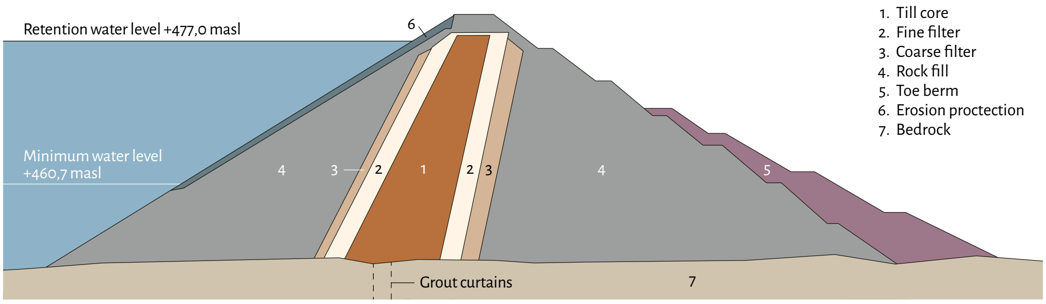
Type	Rockfill
Height	31 m
Crest length	604 m
Foundation type	Bedrock (slate) and soil (till)

SPILLWAY

Type	Surface spillway and bottom outlet, both with radial gates
Maximum discharge capacity	625 m³/s

MAJOR MODIFICATIONS

1999	Surface spillway added.
2015	Toe berm and additional drainage with weirs.



Section through dam.

Overview from downstream. Photo: Markus Alnqvist.

Site visit during construction. Photo: SVF.

View from downstream. Photo: Patrik Isaksson.

Overview from upstream. Photo: Markus Alnqvist.

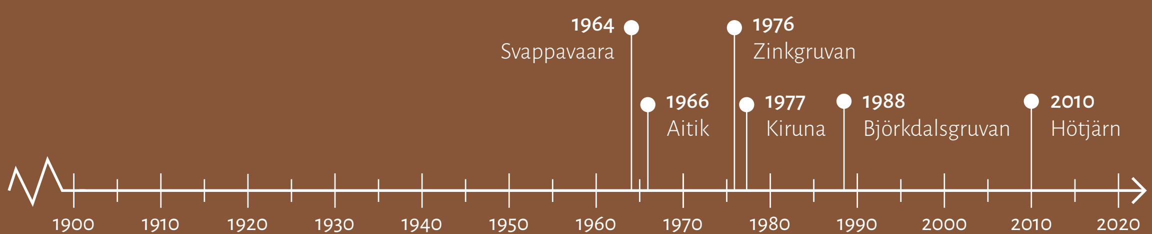
A2. Dams for the mining industry

This annex presents a collection of tailing storage management facilities used in the mining industry, carefully selected by their owners.

As mentioned in Chapter 4.2, Sweden has nine active tailing storage management facilities. To this annex, dam owners in the mining industry have selected a collection of six facilities to present in more detail. Each facility is presented with informative text, technical data, photos, and, in many cases, drawings, all provided by the dam owners. The dams are presented in chronological order to highlight the development of dam design over time.

Location

Year of construction



Svappavaara

Deposition of tailings in Svappavaara started in 1964. The tailings pond is an impoundment of a natural valley.

Initially only one embankment for the clarification pond was constructed. The strategy was that tailings were deposited from the southern part of the valley, with the intention that the tailings would settle before reaching the clarification pond in the north. However, already in1967, new embankments were built to prevent tailings from settling in the clarification pond.

Between 1967 and 2012 the tailings pond was operated as an impoundment with impermeable outer embankments and significant amount for free water in the pond. Tailings were deposited from a single discharge pint with a low solids content (about 5 % - 10 % by weight). This was combined with different types of internal walls, to support additional clarification. The surrounding embankments where constructed either with till core and support fill or as homogeneous till embankments.

In 2012, the system was changed to increase available volumes. Thickened tailings was introduced with the intention to create a cone with a significant slope on top of the existing tailings surface (tailings deposited with a solids content of approximately 65 % by weight, to achieve a non-segregating slurry). This transition also included a significant reduction of free water being deposited in the pond.

Today the tailings surface has the shape of a single cone (slope of approximately 1:30) with its highest elevation in the east (natural high terrain). The amount of free water in the tailings pond has been reduced to a minimum (the initial clarification is still in use for clarification and water storage). The majority of the surrounding embankments have been transformed form impervious to draining structures, through raises with only filters and rock fill, to allow for drainage of the deposited tailings.

The long-term plan for the facility is to continue building the tailings cone from the natural hill in the east, combined with downstream raises of the surrounding embankments. All internal embankments will eventually be completely removed (i.e. covered with tailings).

Technical details

GENERAL

Owner	LKAB
Location	Kiruna Municipality, Norrbotten County
Ore type	Iron ore
Mining method	Open pit
Tailings production	0,6 Mt/year
Recipient	Liukattijoki
Drainage basin area	Tailings pond: 2,2 km² Recipient pond: 0,6 km²
100-year flood	Tailings pond: 1,6 m³/s Recipient pond: 4,0 m³/s
Design flood (~1/10 000 y)	Tailings pond: 5,3 m³/s Recipient pond: 9,2 m³/s

TAILINGS STORAGE FACILITY (TSF)

Year of construction	1964
Footprint area	2,2 km²
Storage capacity	23 Mm³
Rate of rise	– m/year
Consequence classification	Highest: B
Deposition method	Thickened tailings deposited as a cone from natural high terrain
Closure plan	Dry cover with till

DAM

Type	Downstream dams
Height	Max. 24 m
Crest length	Tailings pond dams: 6 km Recipient dam: 1 km

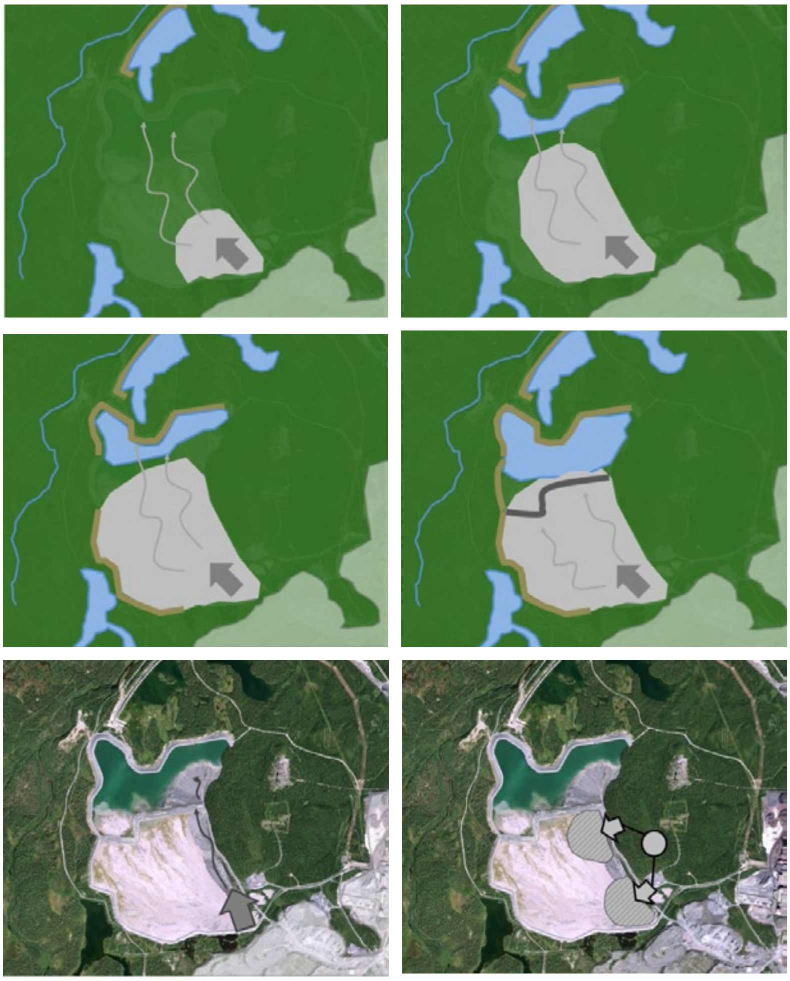
SPILLWAY

Type	Bottom outlet, culvert spillway and overflow spillway

CLARIFICATION POND

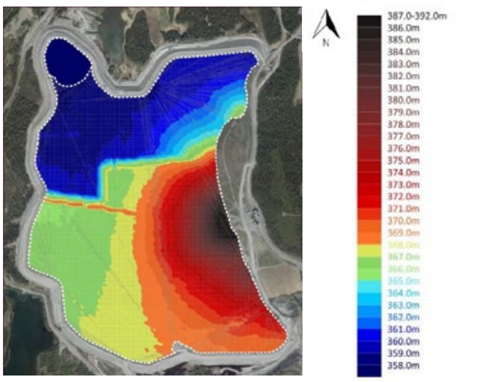
Footprint area	0,22 km²
Storage capacity	0,4 Mm³

Photo: LKAB



Historical overview of the development of the TSF in Svappavaara, from the start in 1964 (top left) to year 2012 (bottom right).

Overview of Svappavaara TSF.



Tailings surface in 2020-06-23.

Aitik

The Aitik TSF was constructed in 1966 and the production started in 1968.

The dams were constructed as downstream dams with till. Some sections of the dams were initially raised with the upstream method and some sections with the downstream method, with till as construction material. The tailings were deposited through single point discharge from the east side of the TSF.

Clearing of the water did initially occur in the western part of the tailings pond. However, the clarification surface decreased with time as more tailings were deposited in the pond. Hence, a clarification pond was constructed west of the tailings pond in 1985.

Since 2003, all dams in the tailings pond are raised with the upstream method with tailings as construction material. The tailings were deposited through cyclones from the northwest side of the TSF and through single point discharge from the east side between year 1990 and 2003. The deposition method spigotting was introduced in Aitik in 2003, where the tailings could be spigotted from all the tailings dams.

A new pond was constructed in 2015-2016, called the HS-pond, located southeast of the tailings pond. The pond is used for separate deposition of tailings with a high sulfur content.

Today, two different deposition methods are used for tailings deposition. Primarily, the tailings are deposited through spigotting, but also through single point discharge.

The general design includes upstream construction along with significant buttressing to meet necessary requirements on stability. The dams towards the eastern part of the facility is integrated with the waste rock dump, while the design of the western dams includes an annual buttressing plan. Reoccurring investigations and evaluations of the tailings characteristics are included in the control program for Aitik, which informs the buttressing plan.

Technical details

GENERAL

Owner	Boliden
Location	Gällivare Municipality, Norrbotten County
Ore type	Cu, Au, Ag
Mining method	Open-pit
Tailings production	42 Mt/year (2020)
Recipient	Vassara älv/Lina älv /Kalixälven
Drainage basin area	23.9 km²
100-year flood	Tailings pond: 10,6 m³/s
Design flood (~1/10 000 y)	Tailings pond: 30,6 m³/s

TAILINGS STORAGE FACILITY (TSF)

Year of construction	1966
Footprint area	12,4 km²
Storage capacity	590 Mm³
Rate of rise	2-3 m/year
Consequence classification	Highest: B
Deposition method	Spigotting, single point and mechanical deposition (only if necessary)
Closure plan	Dry cover and wetland cover

DAM

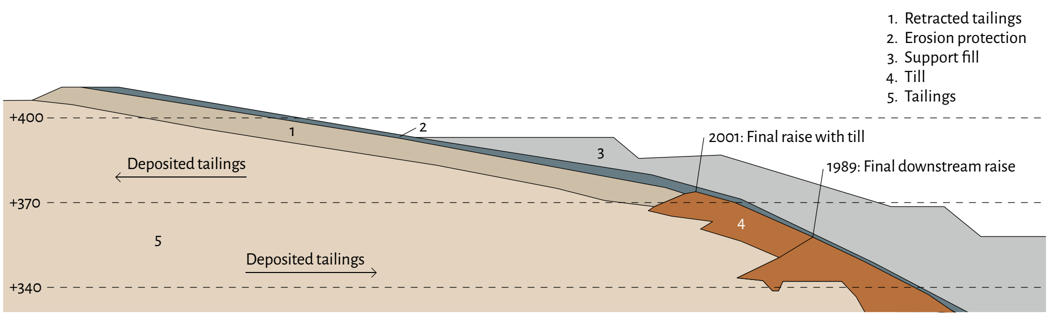
Type	Tailings pond: Upstream dams Clarification pond: downstream dams
Height	Ca 80 m
Crest length	Tailings dams: 10 km Clarification dam: 2 km

SPILLWAY

Type	Open channel outlet (tailings pond), gated spillway (clarification pond)

CLARIFICATION POND

Footprint area	1,8 km²
Storage capacity	18,3 Mm³



Typical cross section of dam E-F, Aitik TSF (2020).

Detail, buttress on dam E-F, Clarification pond to the left, TSF to the right (2021).

Overview of Aitik TSF.

Zinkgruvan

The Zinkgruvan mine comprises an underground mine with shaft and ramp access, feeding two processing plants.

The zinc/lead plant has a nominal capacity of 1.0 million tonnes per annum (Mtpa) and the copper plant a capacity of 0.3 Mtpa. A new SAG mill installation has recently been completed to simplify the primary comminution at the mine and enable an increase in total throughput to 1.35 Mtpa (1350 Project). From the approximately 1.4 million tonnes per year of tailings produced, approximately 40 % is used to produce cemented paste backfill to support the mining operations (44 % in 2019 and 38 % in 2020).

The remaining tailings (0,8 Mton) are pumped approximately 4 km to the nearby tailings storage facilities (TSF) from which water is reclaimed via the clarification pond (Klarningssjön) water storage facility before reuse in the mill processes.

The tailings storage facilities comprise the Enemossen TSF and the Enemossen East TSF. The Enemossen TSF is at capacity and a new facility, Enemossen East TSF, constructed downstream of the existing facility is currently operating. Permitting for Enemossen East and a new operating license for the entire Zinkgruvan operation was received in February 2015, construction was undertaken in 2017 and the facility has been operated for more than three years. Overview picture (from the air) The Enemossen East TSF was designed to replace the Enemossen TSF which reached permit limits in late 2017. The Enemossen TSF is currently operated under a care and maintenance program. The Stage 1 Enemossen East TSF was constructed to a minimum crest elevation of + 175 mRL with construction completed by early Q4 2017. Stage 2, utilising a centreline construction methodology, was commissioned in November 2019 and was constructed to a minimum crest elevation of +180 mRL by raising the East and North Embankments (KP 2020). In 2020 the design was changed to a downstream raise method and raised in 2021 to 182,5 m.

All water within the TSF basin and water management ponds are pumped directly into the Enemossen TSF basin, and after settlement of solids lead to the clarification pond.

Technical details

GENERAL

Owner	Lundin Mining Corporation
Location	Askersund Municipality, Örebro County
Ore type	Zn, Pb, Cu, Ag
Mining method	Underground
Tailings production	0,8 Mt/year
Recipient	Ekershyttebäcken/Salaån
Drainage basin area	– km²
100-year flood	EE 0,3 m³/s
Design flood (~1/10 000 y)	EE calculated 0,9 m³/s, design 0,11 m³/s

TAILINGS STORAGE FACILITY (TSF)

Year of construction	Enemossen (E), 1976, Enemossen East (EE), 2016
Footprint area	1,5 km² E+EE
Storage capacity	E 12 Mm³, EE 7,4 Mm³
Rate of rise	– m/year
Consequence classification	B/2
Deposition method	EE modifyed spigotting
Closure plan	Dry cover

DAM

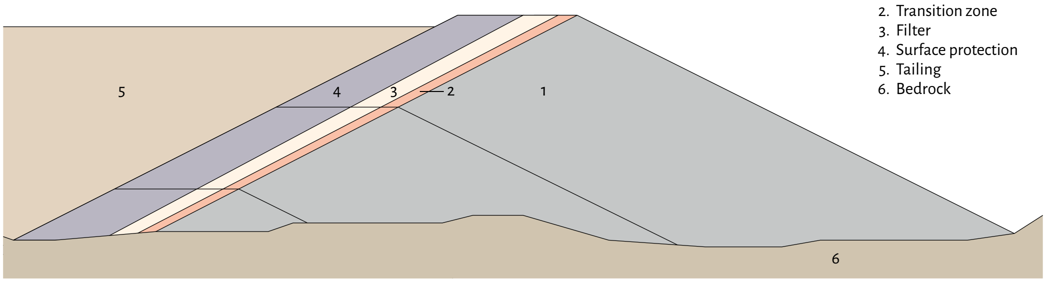
Type	EE Downstream construction
Height	EE 15 m
Crest length	EE 1 000 m

SPILLWAY

Type	Decant tower

CLARIFICATION POND

Footprint area	0,12 km²
Storage capacity	0,250 Mm³



Enemossen East 2021 showing Sections of planned downstream construction on Enemossen East to full height.

Photos: Olof Slatte.

Kiruna

LKAB's tailings pond in Kiruna was initially built as an impoundment of a natural valley.

A clarification pond was also constructed by the tailings pond. Initially, the tailings pond basically resembled an artificial lake, into which the tailings were deposited with a very low solid content (around 5 percentage by weight of tailings). The surrounding embankments were constructed with an impermeable core to enable impoundment of water.

Over the years, as the embankments were gradually raised, the impermeable core reached its technical limit with regards to hydraulic pressure at the foundation level. Hence, the embankments have thereafter gradually been rebuilt to more draining structures. This idea of large volumes of free water has been abandoned, and today the tailings pond surface is mainly dry. This transition been included a changed of deposition method, from a single point discharge with a low solids content to spigotting with a higher solids content.

In combination with spigotting, the dams in the north have been partly raised with the upstream method. However, a transition has recently been made to raising the northern dams with the downstream method instead.

A complicating factor regarding the TSF design in Kiruna is the public railway that goes along the eastern side of the facility. The railway is in fact founded on the former tailings footprint. To enable the construction of the railway, it was necessary to excavate a considerable amount of tailings in combination with building a new dam along the whole eastern side.

The long-term strategy for the tailings pond includes combining placement of waste rock with dam building to achieve cost-efficient downstream dams.

Technical details

GENERAL

Owner	LKAB
Location	Kiruna Municipality, Norrbotten County
Ore type	Iron ore
Mining method	Underground mining
Tailings production	3 Mt/year
Recipient	Mettä-Rakkujärvi
Drainage basin area	Tailings pond: 5,6 km^2 Clarification pond: 4,1 km^2
100-year flood	Tailings pond: 5,9 m^3/s Clarification pond: 9,0 m^3/s
Design flood (~1/10 000 y)	Tailings pond: 13,7 m^3/s Clarification pond: 22,6 m^3/s

TAILINGS STORAGE FACILITY (TSF)

Year of construction	1977
Footprint area	5,9 km^2
Storage capacity	36 Mm^3
Rate of rise	Approx. 1m/year
Consequence classification	Highest: B
Deposition method	Primarily spigotting
Closure plan	Dry cover with till

DAM

Type	Downstream dams
Height	Max. 19 m
Crest length	Tailings dams: 8 km Clarification dams: 2 km

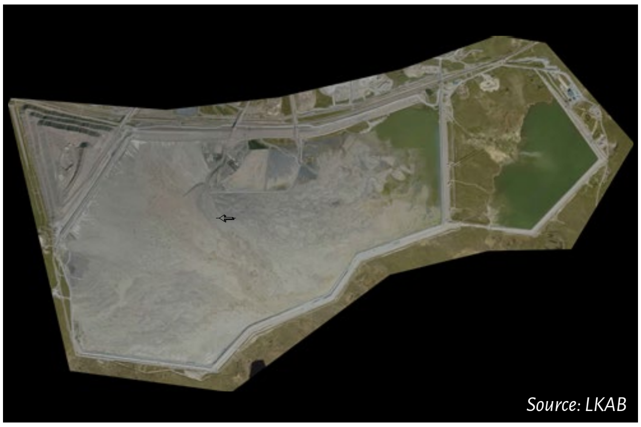
SPILLWAY

Type	Culvert spillway (tailings pond), 2 bottom outlets (clarification pond), overflow spillways (clarification pond and KS pond)

CLARIFICATION POND

Footprint area	1,5 km^2
Storage capacity	2,3 Mm^3

Photo: Fredic Alm, LKAB.



Source: LKAB

Photo: LKAB

Photo: Hans Berggren, LKAB

Björkdalsgruvan

The TSF in Björkdalsgruvan, see figure 1, was constructed and taken into operation in 1988. Currently there are two perimeter dams (a third under construction) at the TSF and a couple of internal embankments as well.

During the start, the tailings were deposited from west to the east through direct discharge. Back then, a clarification pond and dam called K1 was located furthest east where the most fine-grained particles could settle before diversion of the water. In 2001 a new outer dam called VSD was created further west, allowing deposition of tailings both east and westward. In the late 90's the deposition method was changed from direct discharge to cycloning with a central placement of the cyclone. Cycloning is still today the current deposition method and the intention with cycloning in Björkdal is to build up a sand cone in the central zone with the underflow (coarse fraction of the tailings), divert the overflow (fine fraction) against the outer dams in west (dam VSD) respectively east (dam K1) and to gradually tilt the tailings surface towards the east.

In 2014 a new clarification pond was constructed east of the existing dam K1. Dam K2, see figure 2. The K1 pond was therefore repurposed as a tailings storage pond and pre-clarification step before routing water to the K2 pond. When water from the K2 pond enters the spillway, some are re-used and pumped back to the concentrator plant and the rest is discharged.

Recent years, work has focused on increasing the capacity of the TMF to support the new LOM plan. Focus is also to simplify the previously complex layout of the faciliy (runoff towards both west and east, multiple internal embankments and spillways) by decommissioning internal embankments and spillways and also tilting the tailings surface towards the east. The measures includes raises of both dam K1 and VSD (see figure 3) with about the same time interval. Both dams have a similar history: starting as impervious till core embankments, changing to pervious upstream- or centerline raising techniques and the latest raises have all been done with the downstream raising method.

Dam K1´s latest raise is still under construction and is quite an extensive raise, see figure 4. In addition to raising the existing 700 m long embankment, a new spillway (leading water to K2) and about 1 km of new embankment is also constructed. About 400 m of the new embankment is constructed on top of bedrock, which have led to challenges in both excavation and preparing the surface for the till core.

Technical details

GENERAL

Owner	Mandalay Resources
Location	Skellefteå Municipality, Västerbotten County
Ore type	Gold ore
Mining method	Open pit and underground mining
Tailings production	1,3 Mt/year
Recipient	Mörttjärnmyrbäcken – Lillträskbäcken - Kågeälv
Drainage basin area	3,75 km²
100-year flood Design flood (~1/10 000 y)	K2: 18 m³/s - K1: 19 m³/s K2: 35 m³/s - K1: 54 m³/s

TAILINGS STORAGE FACILITY (TSF)

Year of construction	1988
Footprint area	1,74 km²
Storage capacity	20 Mm³
Rate of rise (m/y)	–
Consequence classification	Highest: B
Deposition method	Cycloning
Closure plan	Embankments will be excavated to achieve full drainage potential. The tailings is inert and hence a thin layer of till will be placed to facilitate for plants to grow.

DAM

Type	Upstream and downstream dams
Height	Max. 20 m
Crest length	Tot. 4,2 km

SPILLWAY

Type	Pumping wells, overflow spillways and drop inlet spillways.

CLARIFICATION POND

Footprint area	0,10 km²
Storage capacity	0,3 Mm³

Figure 2. The new clarification pond with dam K2 and the spillway in the front. Dam K1 and the central parts of the TSF with the sand cone can be seen further back in the picture. Photo: Jonas Westling.

Figure 4. Construction of new embankment on top of bedrock at dam K1 extension. Clarification pond K2 can be seen in the background. Photo: Jörgen Oscarsson, JOCM konsult AB.

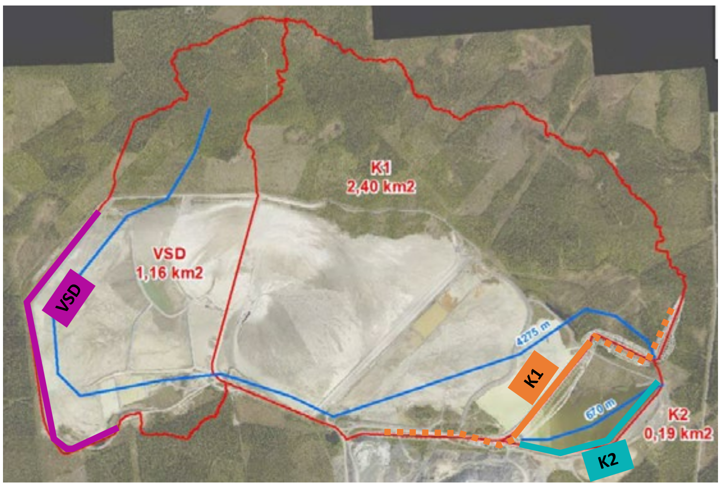


Figure 1. An overview of the TSF at Björkdalsgruvan with the three larger embankment dams VSD, K1 and K2 marked out. The red areas are the drainage basin area and the blue line illustrates the water flow through the drainage basin towards the spillway dam K2.

Figure 3. Dam crest and upstream area with the tailings overflow at VSD.

Hötjärn

In the Boliden area, Boliden currently operates the underground mines Renström, Kristineberg and Kankberg.

Deposition of tailings on the site has been ongoing from 1974 when the old TSF Gillervattnet was taken into operation. Gillervattnet was in operation until 2011 and has since then been remediated with a combination of dry cover/ wetland cover.

Currently tailings are deposited in the TSF Hötjärnsmagasinet, where the dams are built in two stages, containing appx. 10 Mm^3 per stage. The starter dams were built in 2008-2010 and raised during 2017-2019. Deposition started in 2011.

Hötjärnsmagasinet is limited by two downstream constructed dams (H and F), as well as the old facility Gillervattnet. Dam H and F are low permeable till dams with horizontal bottom drainage systems. The design criteria is to allow subaqueous deposition during operation as well as a water cover/ wetland cover at closure. The design intent has been to obtain long term stable dams.

The TSF contains internal dykes to separate process water of different quality. A purification plant (Fenton process) is used for water treatment before the water is recirculated to the process or discharged to the recipient.

Technical details

GENERAL

Owner	Boliden Mineral AB
Location	Skellefteå Municipality, Västerbotten County
Ore type	Zn, Cu, Pb, Au, Ag, Te
Mining method	Underground mines (3)
Tailings production	2.0 Mton/y
Recipient	Brubäcken/Skellefteälven
Drainage basin area	11,2 km^2
Design flood (~1/10 000 y)	14,7 ^{3}/s

TAILINGS STORAGE FACILITY (TSF)

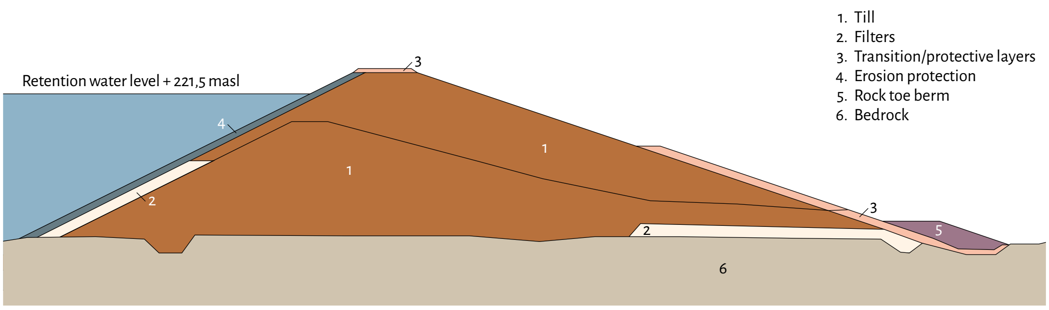
Year of construction	2008–2010, 2017–2019
Footprint area	2,6 km^2
Storage capacity	20 Mm^3
Rate of rise	– m/year
Consequence classification	Highest: B
Deposition method	Subaqueous single point discharge
Closure plan	Water cover/wetland

DAM

Type	Downstream construction, low permeable till
Height	22 m
Crest length	3,9 km

SPILLWAY

Type	Gated spillway for normal operating conditions. Owerflow weir (bedrock) as emergency spillway.



Cross section, dam H.

The clarification pond. Photo: Ronnie Furberg.

Damm H. Photo: Ronnie Furberg.

New spillway. Photo: Ronnie Furberg.

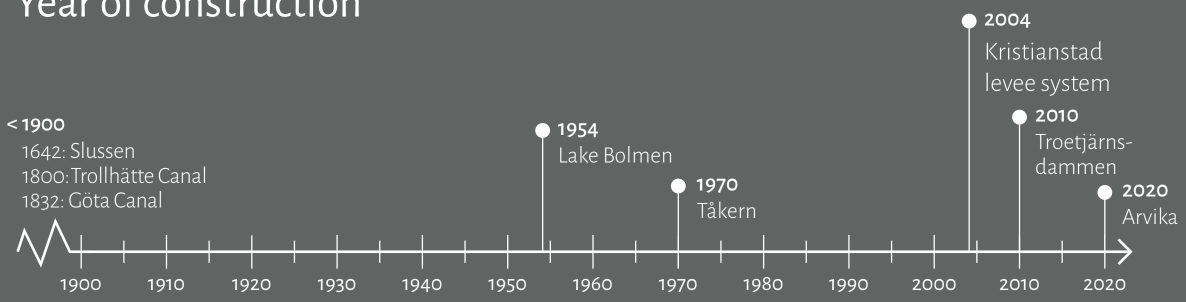
A3. Dams for other purposes

This annex presents a selection of dams used for a variety of purposes beyond hydropower and mining, including flood protection, snow production, wetlands, and canals.

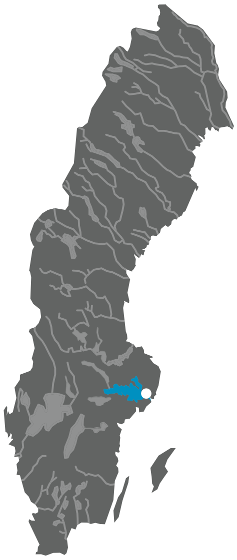
The owners of these dams have handpicked four facilities for presentation, and we, as editors, have added another four. Each dam is accompanied by informative text, technical data, photographs, and, in some cases, drawings, all provided by their respective owners.

Location

Year of construction



Slussen



Lake Mälaren is a significant freshwater lake located in central Sweden and ranks as the third largest in the country.

With an area of approximately 11,000 square kilometers, Lake Mälaren provides a critical transportation route through the Stockholm archipelago and the Södertälje Canal to the Baltic Sea. Mälaren is surrounded by several cities and towns, including the capital city of Stockholm and Uppsala, Sweden's fourth largest city, and serves as a source of freshwater for about 2 million inhabitants in several of these communities. Slussen in Stockholm is critical for the regulation of the water level in Lake Mälaren.

The lock system at Slussen in central Stockholm has a long history, with multiple upgrades and renovations to accommodate the city's growing demands and the surrounding area.

- Queen Kristina Lock was the first lock built in 1642 to facilitate shipping and trade in Stockholm.
- One hundred years later, the Christopher Polhem Lock was built due to the first lock's insufficient size.
- In the mid-1800s, the Nils Ericson Lock was built to accommodate steamboats.
- The Karl Johan Lock was built to address the issue of traffic chaos in Stockholm caused by the bridges at Slussen being the only route linking north and south Stockholm. With a population of 420,000 residents in 1920, a new lock became imperative.
- The Nils Ericson Lock was rebuilt to serve as a drainage channel for Lake Mälaren, and the previous Polhem Lock channel was filled in.
- The new Karl Johan Lock was opened in 1935, and its cloverleaf design allowed traffic to flow into different levels, reducing congestion and improving the situation for the increasing number of car users in Stockholm.

Today, more than 80 years since the last reconstruction a complete rebuild of the worn out Slussen area is ongoing to meet the needs of modern residents. The new Slussen will prioritize safety for pedestrians, cyclists, and public transportation, protect Stockholm from flooding and the region's drinking water reservoir from salt water intrusion. The local plan for the area became legally binding in 2013, and work began in 2016.

The new lock, this time named Victoria Lock after Sweden's crown princess, will reduce the risk of flooding by increasing the discharge capacity from Lake Mälaren and protecting important infrastructure and buildings. After a six-year consultation process, a new regulation for the water level of Lake Mälaren has been agreed on. With the reconstruction and new regulation, the discharge capacity will increase from 800 cubic meters of water per second to 2000. The new Slussen will also be adapted to the changing climate and environmental factors, considering the necessary environmental permits. This will ensure that the new Slussen is functional and environmentally responsible.

Technical details

GENERAL

Owner	–
Purpose	Multipurpose
Location	Stockholm Municipality, Stockholm County
River	–
Drainage basin area	22 650 km²
Year of construction	1642

LAKE

Lake name	Mälaren
Surface area	1 073 km²
Volume	14.3 km³
Shoreline	44.3 km
Length	120 km
Width	65 km
Average depth	12.8 m
Maximum depth	66 m

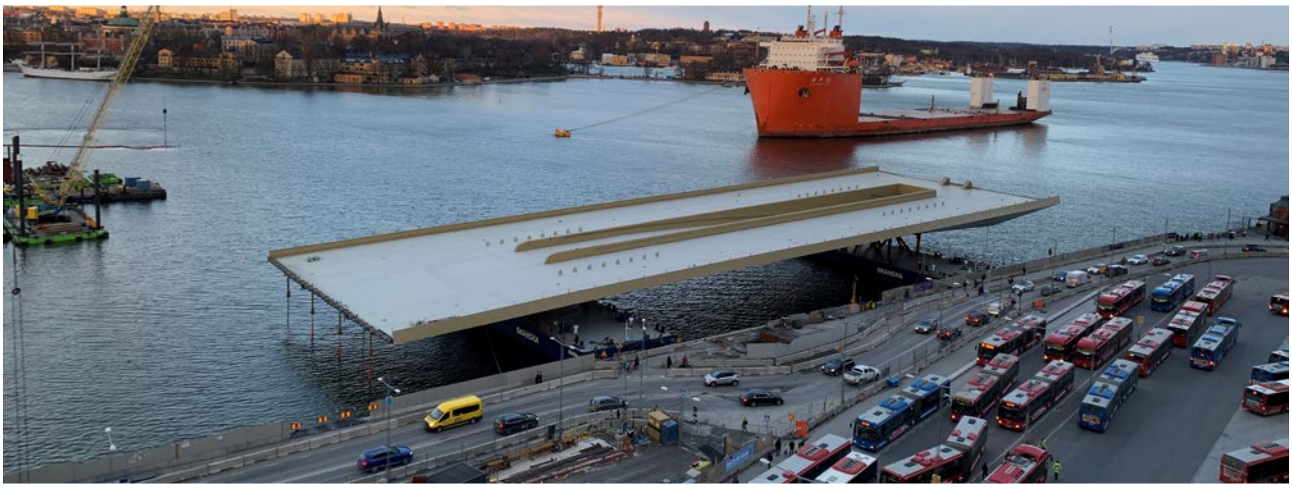
MAJOR MODIFICATIONS

1755	Christopher Polhems lock
1850	Nils Eriksson lock
1935	Karl Johan Lock

Ongoing renewal of Slussen 2023.

Ongoing renewal of Slussen 2020.

Slussen 1901. Photo: Hugo Edlund.



The new Golden Bridge arrives to Slussen in 2020. Photos: Maria Bartsch.

Trollhätte Canal

The Trollhätte Canal is a waterway connecting Lake Vänern to the Göta River and the Sea.

The Trollhätte Canal was built in the late 1700s and early 1800s to provide a navigable route for transportation of goods and people between the two bodies of water. The construction of the canal was a massive undertaking, requiring the use of manual labor and primitive tools to dig through the rugged Swedish landscape. Despite the challenges, the canal was completed in a relatively short period of time, due in part to the determination and ingenuity of the Swedish engineers and workers involved in its construction.

The original purpose of the Trollhätte Canal was to provide a convenient route for the transportation of goods and people between Lake Vänern and the Göta River. Over time, the canal has also been used for power generation, with several hydroelectric power stations located along its route. The canal is particularly important for boat transportation and the industries around Lake Vänern, providing a crucial link for the movement of goods and people between the lake and the surrounding regions, making it a critical component of the region's economic prosperity.

Today, the Trollhätte cnal is a popular tourist destination, attracting visitors from around the world for recreational boating and scenic views. In addition, the canal is still used for transportation of goods and people, and continues to play an important role in the local economy.

In recent years, the Trollhätte Canal has undergone several renovations and upgrades aimed at preserving its historic character and improving its usefulness and accessibility for modern travelers. This includes the restoration of locks and other infrastructure, as well as the creation of new visitor facilities and amenities. In the coming years, further renovations are planned, including the expansion of the hydroelectric power generation capabilities of the Göta River and the installation of new locks and other infrastructure to support increased boat traffic.

However, finding locations for the construction of new locks while keeping the canal open for commercial boat traffic has posed significant challenges. The canal is narrow in many places, and the surrounding landscape is rugged and densely populated, making it difficult to find suitable sites for new locks.

The up-and-coming renovations will require careful planning and coordination to ensure that the canal remains open for commercial boat traffic and that the new locks are installed without causing undue disruption to the local communities and environment. Nevertheless, the end result will be a more modern and accessible Trollhätte Canal that continues to play a vital role in the region's economy and cultural heritage for generations to come.

Technical details

GENERAL

Owner	–
Purpose	Canal
Location	Västra Götaland County
River	Göta älv
Year of construction	1800

WATERWAY DIMENSIONS

Maximum boat length	88 m
Maximum boat width	13.2 m
Maximum boat sraft	5.4 m
Maximum boat air draft	27 m

MAJOR MODIFICATIONS

1844	New locks
1916	New locks

Boats of various types pass through the locks of Trollhätte Canal. Photos: Sjöfartsverket.

Göta Canal

The Göta Canal is a historic waterway that connects The Stockholm area and the Baltic Sea in the east with the Gothenburg area and the North Sea.

The construction of the Göta Canal is one of the largest construction projects ever carried out in Sweden. It was built between 1810 and 1832, with construction efforts primarily relying on manual labor and horse-drawn carts to transport materials. It stretches from Sjötorp on Lake Vänern to Mem at Slätbaken and is 190 km long with 58 locks. Of the route, 87 km is dug, by hand, by about 58,000 Swedish soldiers. You could say that the idea for the canal was born out of anger, where one of the main reasons was to avoid the Danes' high customs duties. After 300 years of various investigations and canal proposals, it was Baltzar von Platen who finally succeeded in realizing the dream of a waterway across Sweden.

The canal was designed to provide a faster and more efficient route for the transportation of goods and people between the two cities, reducing travel time from several weeks to just a few days.

Today, the Göta Canal is a popular tourist destination, attracting visitors from all over the world for recreational boating and scenic views. The canal is lined with charming villages and historic landmarks, offering visitors a unique glimpse into the culture and history of Sweden. In recent years, the canal has undergone several renovations and upgrades, aimed at preserving its historic character while also improving its usefulness and accessibility for modern travelers.

One of the key renovations in recent years has been the restoration of locks and other infrastructure along the canal. These efforts have helped to ensure that the canal remains a functional and reliable waterway for boats and tourists, while also preserving its historic character. In addition to these renovations, new visitor facilities and amenities have been created to enhance the experience of travelers and tourists along the canal.

Overall, the Göta Canal is a remarkable engineering feat. Its historical significance, combined with its stunning natural beauty, make it an ideal destination for anyone looking to explore the rich heritage and cultural legacy of Sweden. Whether you are interested in boating, history, or simply scenic views, the Göta Canal is a must-visit destination for anyone traveling to Sweden.

Technical details

GENERAL

Owner	AB Göta kanalbolag
Purpose	Canal
Location	Östergötaland and Västra Götaland County
River	–
Year of construction	1810–1832

LAKE

Lake name	–
Length	190 km
Number of locks	58
Maximum height above sea level	91.8 m

WATERWAY DIMENSIONS

Maximum boat length	30 m
Maximum boat width	7 m
Maximum boat sraft	3.82 m
Maximum boat air draft	22 m

The locks at Borenhults. Photo: Svenska kraftnät.

The locks at Borenhults. Photo: Svenska kraftnät.

Kungs Norrby aqueduct. Photo:Svenska kraftnät.

The canal and the alley of over 10,000 trees that runs alongside it in Östergötland. Photo: Svenska kraftnät.

Lake Bolmen

Lake Bolmen is the 10th largest lake in Sweden, located in Ljungby Municipality, Kronoberg County. It covers an area of 173 km² and acts as a multi-purpose reservoir.

The Skeen hydropower plant, put in operation in 1954, regulates the lake. In addition, Lake Bolmen is an important source of drinking water for the southern part of Sweden, a popular destination for recreational activities, and crucial for the local flora and fauna.

In the mid-1960s, the growth of several cities in West Scania was causing concern over insufficient water resources for the increasing population and industry. To solve this problem, the municipalities merged to form Sydvatten, which aimed to secure the water supply in the region. One solution was to fetch water from Lake Bolmen via a freshwater tunnel from Bolmen. The construction started in 1975, and the tunnel was put into operation in 1987.

The tunnel starts with its intake near the Skeen hydroelectric power plant and ends in Äktabode in Klippan Municipality. The tunnel, 82 kilometers long and with a cross-sectional area of 9 m², is the world's 5th longest tunnel in all categories. It transports water in two parallel wooden tubes with a diameter of 1,200 mm. This water flows naturally, thanks to the 90-meter height difference.

The water is transported to Ringsjöholm near the Ringsjön lake. From Ringsjöholm, the water is pumped to the Ringsjöverket treatment plant, from where it is distributed to the municipalities. Of the 15 shareholder municipalities that receive water from Sydvatten, eight municipalities (Bjuv, Helsingborg, Höganäs, Kävlinge, Landskrona, Lomma, Svalöv, and Ängelholm) are entirely supplied by water from Bolmen through the Ringsjöverket, four (Eslöv, Lund, Malmö, and Staffanstorp) are partially supplied, and the remaining 3 (Burlöv, Svedala, and Vellinge) are supplied by water from Vombsjön lake through the Vombverket.

Technical details

GENERAL

Owner	–
Purpose	Multipurpose
Location	Ljungby Municipality, Kronoberg County
River	Lillån
Year of construction	1954/1987

LAKE

Lake name	Bolmen
Operating range	–
Surface area	173 km²
Volume	29.1 million m³
Shoreline	334 km
Average depth	5.4 m
Maximum depth	36 m

Skeen Hydropower station. Photos: Statkraft.

Tåkern

Few lakes are so characterized by the cultural landscape and social development as lake Tåkern.

From being the base for households through its rich supply of fish and birds, 200 years ago the lake was considered an obstacle to development that should preferably be drained to create more arable land. However, after such initiatives, the lake changed into a bird lake and today Lake Tåkern is considered one of northern Europe's foremost bird lakes. Thousands of migrating birds stop here every spring and autumn, and large numbers of birds area also found here all year round. The reason for the lake's popularity is its depth, or rather lack of depth.

It was the modernization of agriculture that became Tåkern's destiny. In order to dreate more arable land for the local farmers the "great lake lowering project" started in the 1840s. By 1845, the lake had been lowered 1.7 m and 1100 hectares of seabed and waterlogged soil had been drained. A shallow lake, with an average depth of less than 1 meter, had been created. This was a drastic change, but things didn't turn out the way they were intended. Reeds started to grow on the shores of the lake and some of the land turned out to be unfit as arable land. Instead this meant fantastically rich conditions for bird life.

Large differences in water level between dry years and flood events remained a problem around Tåkern. This was solved in the 1960s by building a small dam in the river Mjölnaån. Since then the lake's water level is regulated with the help of gates.

Today Tåkern is a 12 km long and 8 km wide lake with an average depth of only 0.8 m. In total, over 270 bird species are frequent visitors, of which around a hundred species also nest in the lake. In 1975, Tåkern Nature Reserve, consisiting of the whole lake and its surrounding wetland and beaches, was established and in 2012 a modern visitor centre, Naturum, designed by famous Swedish architect Gert Wingårdh, was inaugurated.

Technical details

GENERAL

Owner	–
Purpose	Bird lake
Location	Ödeshög, Mjölby and Vadstena Municipality, Östergötland County
River	Mjölnaån and Disevidån
Drainage basin area	146,53 km²

LAKE

Lake name	Tåkern
Surface area	44 km²
Volume	29.1 million m³
Shoreline	44.3 km
Length	–
Width	–
Average depth	0.8 m
Maximum depth	1.9 m

Dam at lake Tåkern. Photos: Svenska kraftnät.

Kristianstad levee system

Kristianstad is a town located in the north-eastern region of Skåne province in Sweden, bordering Lake Hammarsjön and the River Helge Å.

The town is situated in a low-lying area, with its lowest point reaching 2.41 meters below sea level, making it very vulnerable to extreme weather and effects of climate change such as sea level rise. The River Helge Å flows through Lake Hammarsjön and eventually mouths into Hanöbukten Bay to the south of Åhus.

When Kristianstad was founded in 1614 it´s location was considerad to be ideal as it had natural protection by water courses and marshland. But when the city grew there were new demands. In the 1860s Dam Hammarlundsvallen was build in order to drain part of Lake Hammarsjön, to create new farmland.

Starting from the early 20th century the drained land was used also for buildings, and today a significant portion of central Kristianstad, approximately 60%, lies on what was once the seabed.

In 2002, the town faced severe flooding due to heavy rainfall and high tides, which caused significant damage to properties and infrastructure. The Hammarvallen embankment was at risk of failing, and if it had breached, the consequences would have been severe, with thousands of people affected and several important public services.

To avoid a repetition of this near catastrophe, the municipality decided to upgrade Hammarslundsvallen and at the same time construct an additional embankment just inside the existing one, and new additional levees to protect other parts of the city from the River Helge Å during future extreme flood events and high sea water level.

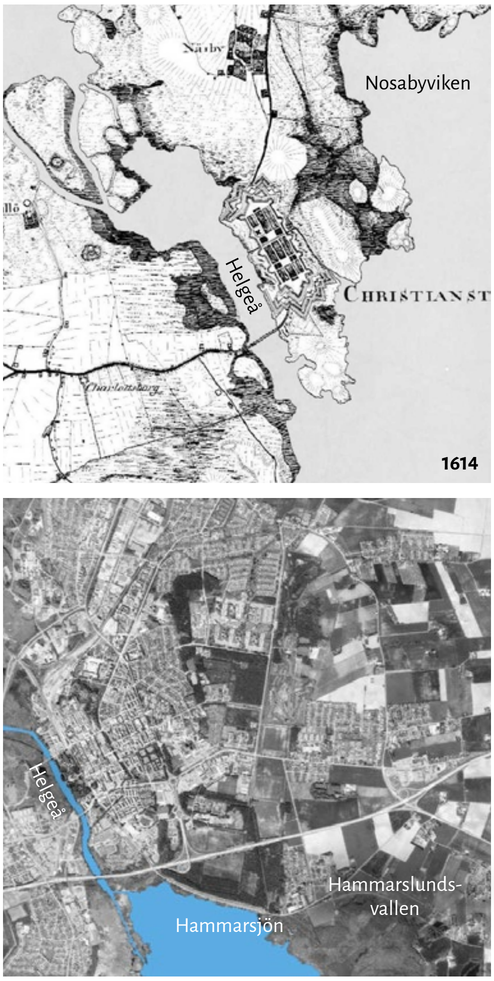
The project to reinforce and construct new embankments is expected to be completed by 2025, and in total, 10 km of embankments will be constructed and a total of 6 pumping stations. These renovations are an important steps towards ensuring the safety and security of the town and its residents, and provide an effective and sustainable solution for flood protection in Kristianstad. However, already today it is foreseen that the embankments may have to be raised further to meet the effects of climate change.

Technical details

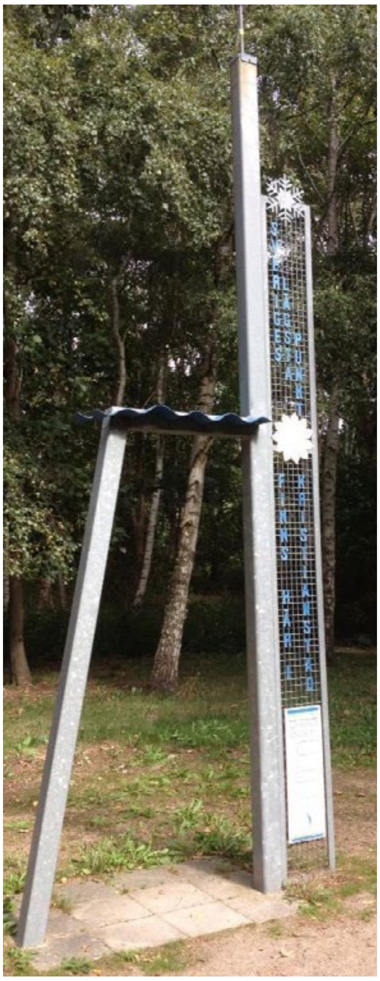
GENERAL

Owner	–
Purpose	Flood protection
Location	Kristanstad Municipality, Skåne County
River	–
Year of construction	2004

View of some of the levees. Photo: Maria Bartsch.



Kristianstad in 1614 and today.
Source: Kristianstad Municipality.



Monument on Sweden's lowests point, located in Kristianstad. Photo: Maria Bartsch.

View of some of the levees. Photo: Maria Bartsch.

View of some of the levees. Photo: Maria Bartsch.

Troetjärnsdammen

Björnrike is a ski area run by Skistar. Since the beginning of the 2000s, Skistar has made major investments in lifts and accommodation at Björnrike.

These investments in the area place great demands on snow availability, i.e., the ski slopes should be available early in the season. To meet this demand, Skistar has built a dam at the top of Björnrike's ski area to ensure water availability to the snow cannon system.

The construction of the dam was completed in 2010. The dam can create a reservoir containing 250,000 m^3 of water at the retention water level. This water volume can be used to create enough snow to cover the entire ski area in only 100 hours at temperatures below -4 degrees Celcius.

Due to the dam's remote location in the middle of the mountains, material from the reservoir was used as the building material. Utilizing material from the removed material had two main benefits, it increased the reservoir volume and minimized the need for material transport. No impervious material was available in the area near the dam. Therefore, a dam type with a geomembrane was chosen. This design is more expensive than a traditional dam with a till core, but it is less sensitive to the quality of the building materials involved. Hence, this dam type is well suited for facilities where access roads are limited.

Pumping and abstracting water is done via two pipes from a well at the bottom of the reservoir to a pump housing downstream of the dam. The snow cannon system is connected and pressurized from the pump housing with self-pressure. Usually, the reservoir is filled by pumping water from the valley during September and October to reach the reservoir's retention level just before the temperatures allow for snowmaking. During the remaining time of the year, the reservoir is empty.

Technical details

GENERAL

Owner	SkiStar AB
Purpose	Water storage for snowmaking
Location	Björnrike, Jämtland
River	–
Drainage basin area	0,23 km²
Mean annual flow	0,004 m³/s or 4 l/s
100-year flow	–
Year of construction	2010

RESERVOIR

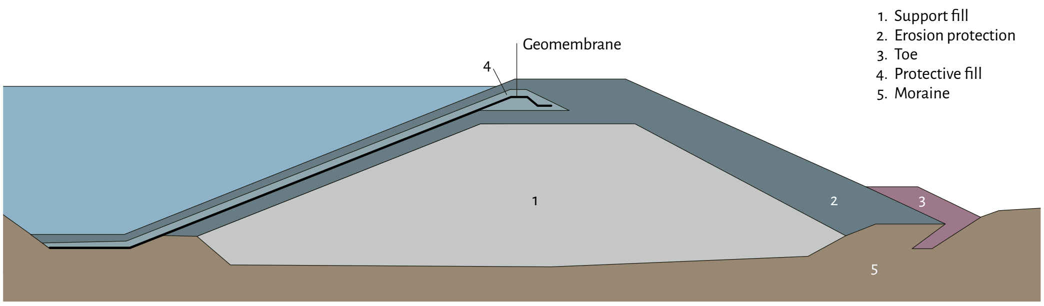
Lake name	Troetjärnsdammen
Operating range	About 5 m
Surface area	12 000 m²
Storage capacity	0,25 Mm³

DAM

Type	Fill dam with a tightening geomembrane
Height	7 m
Crest length	400 m
Foundation type	Till

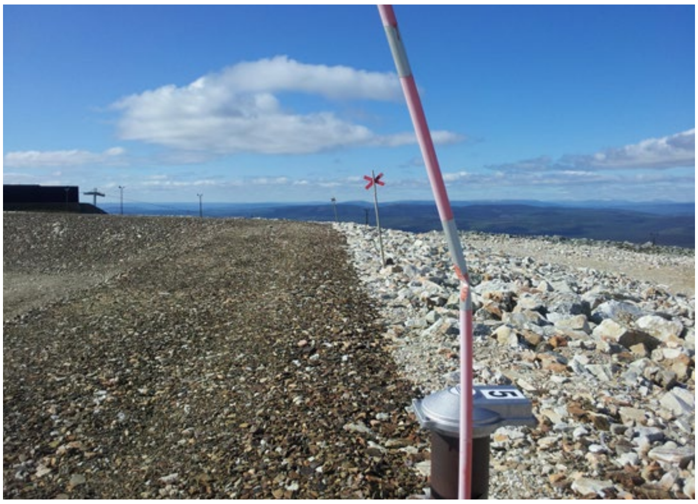
SPILLWAY

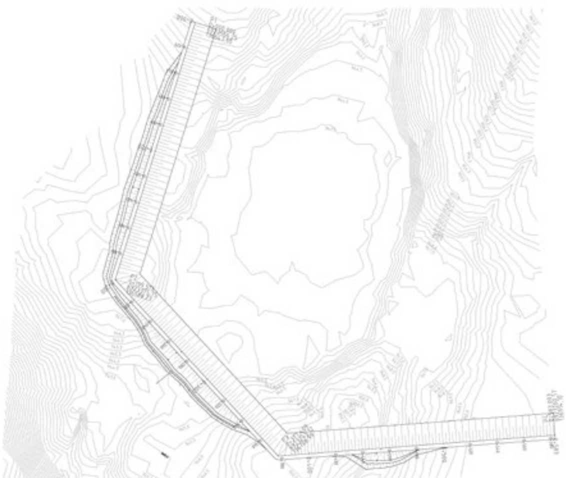
Type	Fixed overflow
Maximum discharge capacity	0 m³/s at DG 4 m³/s at top of geomembrane



Cross-section of the dam.

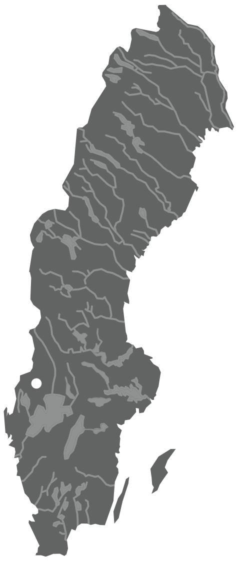
Overview. Photos: David Geijer.





Situation plan. Source: Sweco.

Arvika flood protection dam



Arvika town is situated by the shore of Kyrkviken bay, with a history of floods. In the year 2000, the town experienced severe floods. In the aftermath of these floods, a project was initiated to build new flood protections.

The resulting flood protection scheme was completed in 2020 and consists of three dams:

- the main dam in the narrow strait between Kyrkviken bay and Lake Glafsfjorden (constructed 2016-2020)
- the east barrier (constructed 2015)
- the west barrier (constructed 2016)

At the end of 2020, only months after the completion of the last dam, the water in Kyrkviken bay reached critical levels, and the flood protection was used successfully for the first time.

At normal water levels in Kyrkviken bay, the main dam has two eight-meter-wide openings for boats and three seven-meter-wide openings ensuring sufficient water exchange between Kyrkviken bay and Lake Glafsfjorden. Smaller openings at varying depths allow fish and other species to pass the barrier. These openings are closed by mobile crane-operated steel gates before flood events. In case of extreme flood events, vertical steel beams and horizontal logs can be used to increase the level of the crest from +48 m a.s.l to +50.5 m a.s.l. With this increased crest level, the dam can, with a margin for climate change, protect Arvika from a worst-case scenario (PMF equivalent).

Five pumps with a total capacity of 30 m³/s are integrated inside the dam to ensure runoff behind the barriers can be passed. The water level in Kyrkviken bay is limited to +47 m. The grid power approximately 60 % of the total pump capacity. In case of a power outage, or extreme inflow where maximum pumping capacity is needed, up to three mobile generators, with a total capacity of 1,9 MW, can be used.

Technical details

GENERAL

Owner	Arvika kommun
Purpose	Flood protection
Location	Arvika Municipality, Värmland County
River	Byälven/Götaälv
Drainage basin area	142 km²
Mean annual flow	1,6 m³/s
100-year flow	25 m³/s (inflow)
Year of construction	2016–2020

PUMP FACILITIES

Rated head	4 m
Maximum discharge capacity	30 m³/s
Installed power	1,7 MW

RESERVOIR

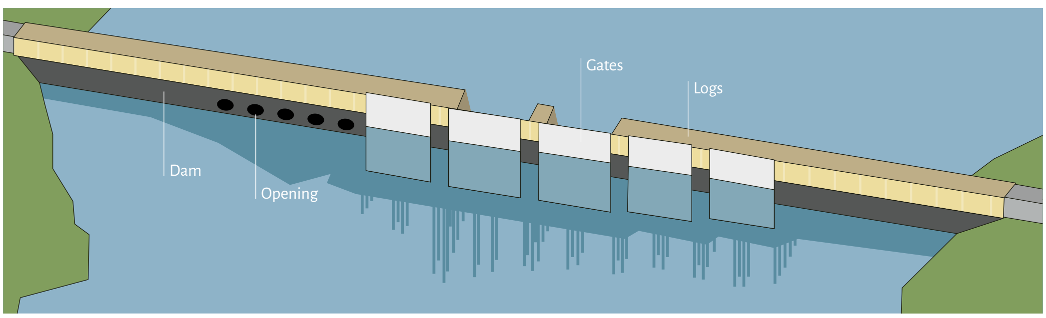
Lake name	Kyrkviken
Operating range	–
Surface area	6 km²
Storage capacity	–

DAM

Type	Concrete buttress dam
Height	8,5 m (extendable to 11 m)
Crest length	110 m
Foundation type	Bedrock/piles to bedrock

SPILLWAY

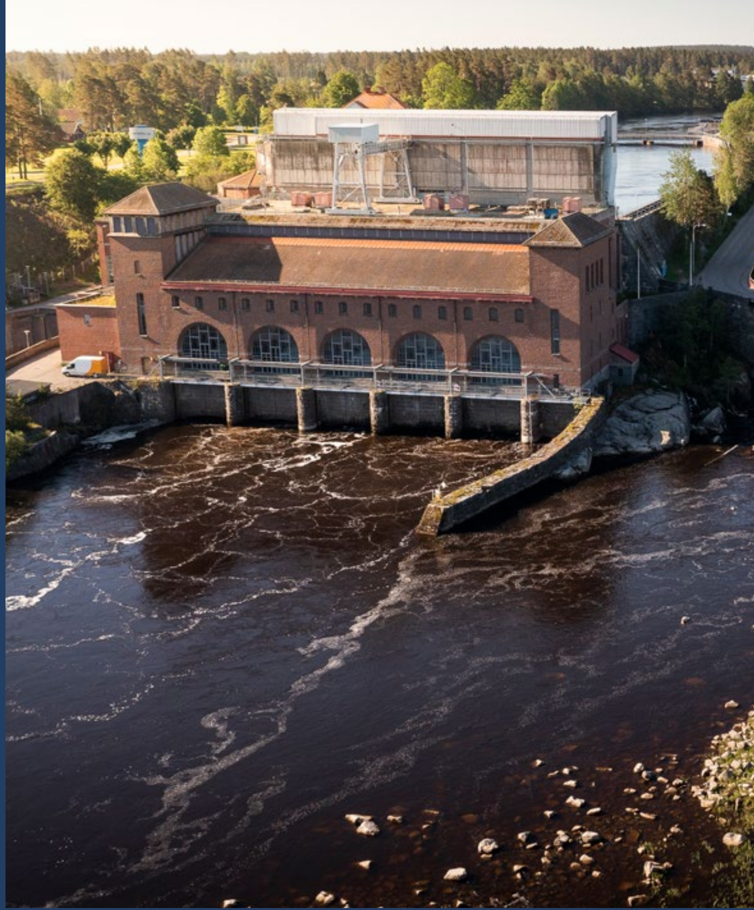
Type	Pumps
Maximum discharge capacity	30 m³/s



Main dam with extended crest.

Main dam successfully mobilized for the first time 31 December 2000.
Arvika town and Kyrkviken bay in the background. Photo: Arvika kommun.

Main dam with openings for boats, view from Glafsfjorden. Photo: Arvika kommun.



This book, titled “Book on Dams – The Swedish Experience”, is being published in conjunction with ICOLD’s 91st annual meeting in Gothenburg, organized by SwedCOLD. The book consists of two parts:

- The main text, which tells the general story of Swedish dams from a historical and geographical perspective, supported by maps, pictures, and timelines.
- An annex that presents a selection of around 40 dams. These dams are significant to Sweden for various reasons and illustrate the development of dams in the country.

Together, they offer an overview of the evolution of Swedish dams and dam safety, from the construction of the earliest large dams in the beginning of the last century to the current challenges of managing an aging dam portfolio, raising tailings dams, and constructing levees for flood protection.

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