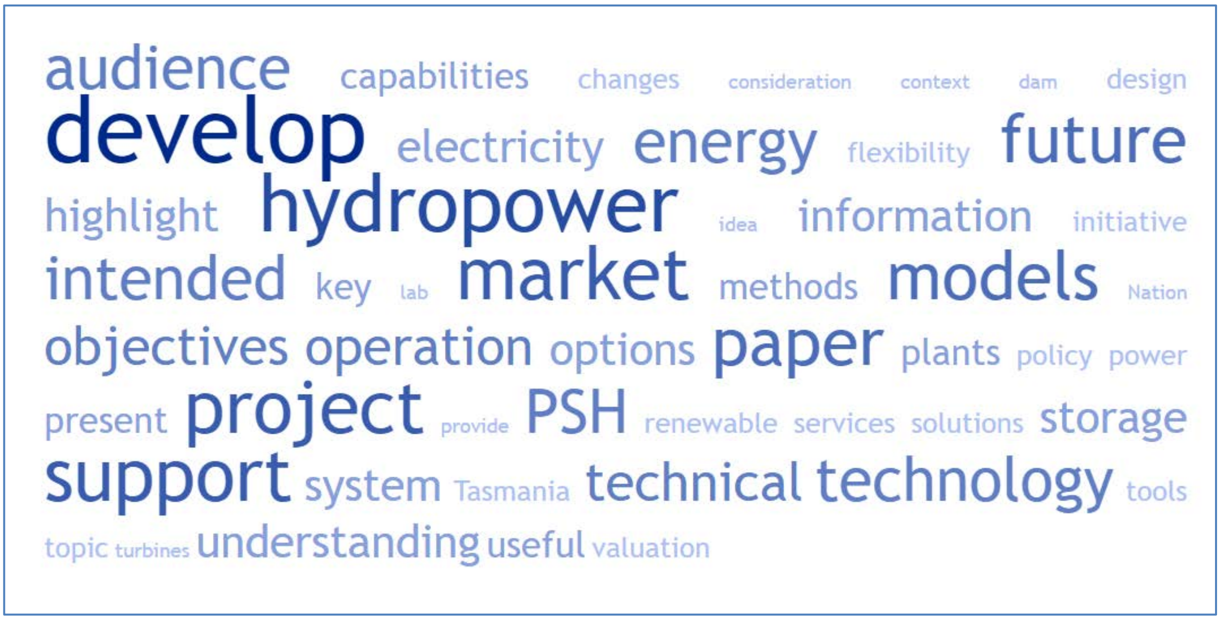
THE INTERNATIONAL ENERGY AGENCY TECHNOLOGY COLLABORATION PROGRAMME ON HYDROPOWER

IEA Hydropower

Hydropower providing flood control and drought management services under changing climate scenarios: Case studies

September 2022



This document provides a short description of the case studies in member countries relevant for the work of the joint task in IEA Hydro between Annex IX and XII related to valuing hydropower services. The project descriptions are provided both by members of IEA Hydro and invited experts. The activity has been kicked off during a workshop and the projects have been collected by the authors via mail held by the International Energy Agency on the flood and drought management services provided by powered dams and on potential changes to those services due to climate change.

Collected by Atle Harby, Operating Agent for IEA Hydro Annex IX and Jorge Damazio, Operating Agent for IEA Hydro Annex XII. Edited by Mauro Carolli, SINTEF Energy Research

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Preface

Historically, many dams were constructed to store water, and in doing so reduced the impacts of flood events in downstream areas. More recently, dams with hydropower were often designed to provide multi-purpose services, including flood control and drought management. The first phase of Annex IX covered ways to value both energy and water management services.

Much more recently, it has been recognized that one of the future important roles for hydropower facilities is in providing flood control and drought management services under changing climate scenarios. For hydropower to be recognized for climate change services, an understanding is needed of:

- How hydropower's characteristics affect adaptation and resiliency to climatic change
- Hydropower's role in managing water resources in future climate scenarios
- Assessing hydropower's value in managing risks in a changing climate
- Investigating hydropower design and operation scenarios to best manage climate change challenges

This report provides case studies from member countries on this subject with relevant examples provided both by members of IEA Hydro and invited experts. This activity is a joint effort between two of the Hydropower TCP Annexes, namely Annex IX Phase 2 on *Valuing Hydropower Services* and Annex XII on *Hydropower and the Environment*.

Starting with a kick-off workshop in 2019, case studies were collected by the authors of this report. The scope of work covered flood and drought management services provided by powered dams and the potential changes to those services due to climate change.

A previous deliverable on this subject was a Communique titled: *Climate Change: Adaptation, Resilience and Valuation of Hydropower Services,* dated December 2019. This can be found on www.ieahydro.org.

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Introduction

IEA Hydro is working collaboratively with industry and governments to understand how hydropower has contributed to flood control and drought management, and how the need for these services will be under future climates. This report presents examples and case studies on how hydropower has contributed to these climate scenarios. Overall, the scope of this study was to investigate "The role of hydropower in managing risks associated with a changing climate with a focus on flood control and drought management"; the work plan having two main components

- The role of hydropower services in adaptation and resilience (A&R) to climatic change covering methodologies for assessment.
- Understanding the value that hydropower provides in managing the risks associated with a changing climate with a focus on flood management and drought control

On this basis, the report presents examples and case studies on how hydropower has contributed to these climate services. This will be followed by consideration on how the needs for such services will change in the future, and by valuing the services hydropower provides to the society for flood control and drought management. Thirteen case studies, from all around the world, have been gathered, each showing how hydropower reservoirs and operation have contributed to different climate changes services. These case studies cover a wide range of contributions to the topic, such as: How hydropower plant characteristics and hydrological regimes affect the level of adaptation and resilience to climatic changes of its services from the viewpoint of business, security and socio-environmental issues;

- The role of hydropower for managing water resources in different countries in todays and future climate scenarios;
- The value that hydropower provides in minimizing or mitigating risks associated with a changing climate;
- How hydropower design and operation can best be adapted to minimize or manage climate change challenges.

The tables in the section titled "Summary of Case Studies" provide information on the contribution of each case study to the provision of flood control and drought management services under changing climate scenarios.

The IEA Technology Collaboration Programme on Hydropower

The IEA Technology Collaboration Programme on Hydropower (IEA Hydro) is a working group of International Energy Agency member countries and others that have a common interest in advancing hydropower worldwide. Current members of the IEA Hydro TCP are Australia, Brazil, China, EU, Finland, Japan, Norway, Switzerland and the USA. Sarawak EB is a sponsor. Member governments either participate themselves, or designate an organization in their country to represent them on the Executive Committee (ExCo) and the working groups (Annexes), through which IEA Hydro's work is carried out. Some activities are collaborative ventures between the IA and other hydropower organizations.

Vision

Through the facilitation of worldwide recognition of hydropower as a well-established and socially desirable energy technology, advance the development of new hydropower and the modernization of existing hydropower

Mission

To encourage through awareness, knowledge, and support the sustainable use of water resources for the development and management of hydropower.

To accomplish its Mission, the Executive Committee has identified the following programme- based strategy to:

- Apply an interdisciplinary approach to the research needed to encourage the public acceptance of hydropower as a feasible, socially desirable form of renewable energy.
- Increase the current wealth of knowledge on a wide array of issues currently associated with hydropower.
- Explore areas of common interest among international organizations in the continued use of hydropower as a socially desirable energy resource.
- Bring a balanced view of hydropower as an environmentally desirable energy technology to the worldwide debate.
- Encourage technology development.

IEA Hydro is keen to promote its work programmes and to encourage increasing involvement of non-participating countries. All OECD and non-OECD countries are eligible to join. Information about membership and research activities can be found on the IEA Hydro website www.ieahydro.org

The Authors

The case studies have collected by the Operating Agents of IEA Hydro Annex IX and XII, Atle Harby at SINTEF Energy Research, Norway and Jorge Damazio at CEPEL, Brazil. This report has been edited by the Operating Agents in collaboration with Mauro Carolli at SINTEF Energy Research. Table 1 shows the list of individuals that has provided the case studies.

Case study	Country	Provided by	Affiliation
Tasmania irrigation schemes	Australia	Carolyn Maxwell and Greg Carson	Hydro Tasmania
Tyrol	Austria	Peter Bauhofer and Johannes Schöber	TIWAG
Paraiba do Sul River Basin	Brazil	P. Diniz, F.S. Costa & J.M. Damazio	National Grid Operator, State Univ. of Rio de Janeiro CEPEL
Columbia River Basin	USA - Canada	Nathalie Voisin, Simon Gore & Shih-Chieh Kao	Pacific Northwest National Lab. US DoE Oakridge National Lab.
Roßhaupten with Forggensee	Germany	Cornelia Häckl	Uniper
Schluschsee Basin	Germany	Orkan Akpinar	Schluchseewerke
Nukabira Dam	Japan	Murashige Hiroshi	Japan Electric Power Information Center
The Telemark hydropower system	Norway	Ånund Killingtveit	Norwegian University of Science and Technology
Rheinkraftwerk Schaffhausen	Switzerland	Klaus Jorde	KJ Consult
MINERVE flood forecast system in the Canton of Valais	Switzerland	Anton Schleiss	Ecole polytechnique fédérale de Lausanne
Atatürk HEPP & Dam, Southeastern Anatolia Project	Turkey	Furkan Yardimici	Elektrik Üretim A.Ş
Dibang multipurpose project	India	Abhay Kumar Singh & Deepak Saigal	NHPC Ltd
Tehri Dam as flood moderator	India	Rajiv Vishnoi	THDC India Limited

Summary of case studies

We collected 13 case studies from all the continents. The studies show that assets can be used to mitigate floods, droughts, or both, but how they provide these services depends on the local context they are operated within and how the scheme was designed.

It is assumed that all the facilities covered by the thirteen case studies were able to safely pass the Probable Maximum Flood (PMF) without significant damage to the structures. Flood routing can be provided through reservoir storage, discharge facilities or a combination. In modern hydropower facilities, providing flood control for downstream communities is a requirement, though this may not be the case in very old dams. However, any upgrade to manage extreme floods on old dams should also consider flood control for downstream communities. Of specific interest from these case studies are the approaches to flood control and drought management services under changing climate scenarios.

All the hydropower assets (mainly reservoirs), except for the Tasmania irrigation schemescase study, have been used to mitigate flood events. National and regional authorities in collaboration with the hydropower companies actively mitigate flood events in 9 case studies using a combination of reservoirs volume dedicated to flood control, gate operations and weather forecasts, to reduce and/or delay the flood peaks. Hydropower plants can support flood control systems by shutting down on the tributaries and reducing water release to prevent downstream floods (Austria, Inn River Basin) or by dedicating volume to flood control (Lake Forggensee, Germany, Lech River Basin). Hydropower reservoirs can reduce the impacts of floods: in Japan, the magnitude/duration of the flood peak induced by four consecutive typhoons was halved; in Turkey (Atatürk HEPP&Dam, Southeastern Anatolia Project (GAP)), hydropower reservoirs decreased the impacts of floods from the Tigris and Euphrates; and in Brazil, the series of reservoirs in the Paraiba do Sul River Basin have been used to mitigate a 200-years recurring flood. In one case (Schaffhausen), the weir (dam) for hydropower production passively prevents the floods in the downstream town.

In some case studies, decision support systems have been developed to mitigate floods in circumstances where the reservoir capacity is too small to allow the flood peak to be stored. For example, in the Upper Rhone Valley (Minerve System, Upper Rhone Valley), since 2002 a decision support system, based on weather forecasts and on a hydrological model, allows to define optimal preventive operation of powerplants and/or opening of bottom outlets in order to create storage in the reservoirs and to reduce flood wave in downstream Rhone river. Based on an agreement with the hydropower companies the latter are renumerated for doing preventive operation. The real-time operating system raised several warnings, but it has not been used up to now since now sever flood occurred. The management plan of a reservoir in India (Dibang multipurpose Project, Lower Dibang valley) includes mitigation of floods events up to 100-years return period through reservoir volume secured for flood mitigation that changes accordingly with the monsoon season. In a case study from Norway (Flood-forecasting and flood management in Skiensvassdraget, Norway), reservoirs are used to mitigate flood risk, but they have a limited capacity, thus they require an accurate forecast system, the Telemark flood forecasting model (FMTV). The model is divided in 5 sub-catchments, that are independently managed by 5 different organizations and centrally organized. The system has been used to produce scenarios and mitigate flood events in 2007. The Tehri Dam in India (Tehri Dam), even though it is primarily built for irrigation and hydropower production and not specifically for flood mitigation purposes, can retain a large volume of water and it has immensely helped in year 2013 to prevent a severe inundation of major downstream cities.

Four case studies reported use of the reservoirs to mitigate drought. We should distinguish between two different services, namely surface water for irrigation and drought mitigation, because the management of reservoirs and water distribution schemes is different for these two services, and the hydro-morphological processes involved are different as well. In the Turkish case, the reservoir scheme is used to improve the field irrigation in quantity (more water and more irrigated crops), but not specifically to mitigate extreme drought events. Other three cases (Australia, Canada – US and Brazil) actively use the reservoirs for drought mitigation. They have plans to mitigate drought events that have been successfully put in practice during extended dry periods in the last 10 years. During these events, reservoirs supplied water both for drinking and non-drinking purposes. In future scenarios, predictions for most case studies foresee a decrease in precipitation and an increase in water demand. The reservoirs managers plan to include these scenarios in the management. The Lake Forggensee managing company has a plan to use the reservoir to alleviate drought events. In case of low flows, they guarantee the minimum environmental flow. In case of low flow and low oxygen concentration, measured in different points, the company can release water from the reservoir.

Climate change is leading to a change in the management of the reservoirs due to the increase of extreme precipitation events as for the Japan case study, and it plays a role mainly in changing managing rules according with the precipitation forecasts. The snowline is raising in the mountain areas (e.g., the Alps), likely increasing flood events frequency and flood risk. In the Northern Alps, the intense and extreme precipitation events will increase, but the total precipitation will decrease, with consequently needs of the reservoirs to mitigate drought events. The managers of the Schluchsee reservoir (Schluchsee catchment area) changed the management plan and now they use the entire volume of the reservoir for hydropower production, but they can free volume for flood control in 50 hours following indications from the regional government precipitation model. In the Canada - US case study (Columbia River Basin), climate change is challenging the reservoirs' volumes reserved for managing flood mitigation, drought mitigation (water supply and environmental flow) and hydropower production.

The reports underlined that the reservoirs might impact or sustain additional ecosystem services. The reservoirs scheme in the British Columbia had effects on fishery, spiritual and cultural activities related to salmons, with annual celebration of the salmons' return in the river. From the report, it is unclear if these activities are going on nowadays, but they are less relevant than agriculture and hydropower production.

The Tasmanian irrigation scheme balances different water uses including also environmental requirements and recreational uses. They have a multi-purpose management of the water resources although the report does not specify how. An information that is missing in the reports is if the reservoirs must maintain environmental flows to support river ecosystems downstream and if they must guarantee the flow during drought events.

Tables

Each case study is summarized in this chapter in a table giving key information.

Reported by	Carolyn Maxwell and Greg Carson
Country	Australia
Case study	Tasmania irrigation schemes
Project responsible and partners	HydroTasmania
Short description	The irrigation scheme relies on several hydropower reservoirs to provide water supply. During wet years, water is stored in the reservoirs, and released in dry years. An extended dried period occurred between 2006 and 2008. The system also worked successfully in 2015 during a water shortage.
Flood control	No (or very limited). The existing schemes were not designed to mitigate floods
Drought mitigation	Water supply for agriculture and towns from hydropower reservoirs during droughts or water shortage periods.
Climate change	Although a decline in precipitation is predicted, the system remains operative and viable.
Technical details	Reservoirs: Lake Parangana - Sassafras/Wesley-Vale Irrigation Scheme, Arthurs Lake - Midlands Irrigation Scheme, Great Lake – Whitemore, Cressy-Longford and Southern Highlands Irrigation Schemes, Lake Paloona - Kindred / North Motton Irrigation Scheme. In the last 20 years, water use for irrigation in Tasmania increased from 240,000 ML to 850,000 ML and most of this is drawn from or below hydro-power reservoirs.
Other services	Aesthetics, recreational services, surface water supply for non-drinking uses, habitat-related services
Type	Reservoir volume

Reported by	Peter Bauhofer & Johannes Schöber
Country	Austria
Case study	Inn River basin
Project responsible and partners	TIWAG Tiroler Wasserkraft AG, Tyrol, Austria
Short description	The hydropower company TIWAG assets are part of the Tyrol's flood control system. During June 2019 flood event, two power plants (Kaunertal and Sellrain Sitz, reservoirs with pump storage) were shut down and the water wasn't released from the reservoir, preventing a 100-years flood in Innsbruck. The Tyrolean flood risk mitigation system combines forecasts, reservoirs, pumping storage plants, inter-basin tunnels.
Flood control	The hydropower system is used to prevent and/or mitigate floods.
Drought mitigation	No
Climate change	Increase of precipitation and rainfall events combined with a higher snow limit are predicted. However, the risk is increased mainly due to change in land use and big scale usage of soils.
Technical details	After the 2019 event, the Inn River discharge remained high in 2020 even after 1 month, with a mean flow of 670 m^3/s, 120 m^3/s higher than the second largest monthly mean flow. Downstream from Innsbruck, it resulted in floods compounded by groundwater levels.
Other services	No
Type	Combination of reservoirs, hydropower operations and forecast models.

Reported by	P. Diniz, F.S. Costa and J.M. Damazio
Country	Brazil
Case study	Paraiba do Sul River catchment area
Project responsible and partners	National Operator, State University of Rio de Janeiro CEPEL
Short description	The case study consists of a series of reservoirs and hydropower plants, with stations that pump the water in a different river basin. The inflow to the Santa Cecilia pump station has been reduced to mitigate the drought downstream in the Rio de Janeiro urban area.
Flood control	The reservoirs contributed to the mitigation of a 200-years recurring flood between December 2009 and January 2010.
Drought mitigation	The reservoirs guaranteed water supply during an extended drought (2014-2019) that caused water shortage in Rio de Janeiro and San Paolo urban areas.
Climate change	Due to climate change a general increase of precipitation is expected in the area. The area is densely populated and an increase in population is expected with a consequent increase of water demand.
Technical details	The total storage capacity in the catchment area is 4337 h cubic meters.
Other services	Surface water supply for drinking and non-drinking purposes (Climate change)
Type	Reservoir volume

Reported by	Nathalie Voisin, Simon Gore and Shih-Chieh Kao
Country	USA and Canada
Case study	Columbia River Basin
Project responsible and partners	Pacific Northwest National Lab., US DoE, Oakridge National Lab.
Short description	The Columbia River basin is a transboundary river basin with a complex management scheme. Hydropower reservoirs have been used to mitigate both floods and droughts and a multi-purpose use of the reservoirs is increasingly integrated in the management.
Flood control	During floods, the control of the operation in the US shifts from the hydropower producers to the US Corps of Engineers. In Canada, BC hydro manages both hydropower operations and flood control.
Drought mitigation	Bureau of Reclamation is responsible for the management of reservoirs for long term water storage and water supply availability during the irrigation season. Part of the Columbia River basin is a semi-arid agricultural region that heavily relies on diversion from the river, i.e. high vulnerability to droughts.
Climate change	A transition from snowmelt to rain-controlled flow regime (higher peaks in fall) challenges to seasonal coordination in reservoir operations and management of storage for 1) flood control, 2) water supply and 3) energy production.
Technical details	In the basin there are 250 reservoirs and 150 hydropower projects for an installed capacity around 35 000 Megawatts. The annual mean flow of the Columbia River is 7 500 m^3/s
Other services	Navigation, surface water for non-drinking purposes, recreational services, Natural and cultural heritage (salmons for local tribes), fishery
Type	Reservoir volume

Reported by	Cornelia Häckl
Country	Germany
Case study	Lake Forggensee, River Lech Basin
Project responsible and partners	Uniper Kraftwerke GmbH
Short description	The reservoir is used for hydropower production, flood and drought mitigation. In case the inflow in the reservoir exceeds 150 m^3/s, additional storage volume for flood management is used according with the water management authority. The flood risk upstream Augsburg has been decreased by the reservoir. The reservoir can be used to mitigate drought events and it releases water in case of low oxygen levels in the water. The reservoir guarantees minimum environmental flows.
Flood control	Additional storage volume for flood mitigation purposes. The reservoir retained a flood peak in February 2020.
Drought mitigation	The company has a plan to reduce drought events by releasing water. In case of low oxygen, to reduce impact on fish community the company may release water.
Climate change	For Bayern, an increase in extreme precipitation events and a decrease in average flow is predicted, with a need to mitigate short floods, but also mitigate longer drought events.
Technical details	Lake Forggensee, has a volume of 165 hcm. The reservoirs retained a peak inflow of 600 cms in February 2020
Other services	Recreational activities, habitat services, navigation (Danube River, winter only)
Type	Reservoir volume, weather forecasts

Reported by	Orkan Akpinar
Country	Germany
Case study	Schluchsee catchment area
Project responsible and partners	Schluchseewerk AG
Short description	Part of the volume of the reservoir is reserve for floods prevention. The hydropower managers changed the production scheme after a scientific assessment, and it does not reserve volume for flood management purposes. As a worst-case scenario, a forecast time of 50 hours, using the Baden-Württemberg prediction model is enough to lower the water level and use the Schluchsee to mitigate floods.
Flood control	The reservoir might be used to mitigate the floods
Drought mitigation	No
Climate change	No
Technical details	Reservoir capacity: 108 million m^3. The new scheme has been modelled with a 100-year recurring flood
Other services	No
Type	Short-term forecasts model

Reported by	Hiroshi Murashige
Country	Japan
Case study	Nukabira Hydropower Plants flood control management services and climate change impact
Project responsible and partners	JPower
Short description	Four typhoons attacked Hokkaido Island continuously in short intervals and brought record flood disaster in August, 2016. This was caused by rare pressure pattern and resulted in intense rainfall, exceeding 200mm. Late Gate Operation (LGO) at the Nukabira dam was based on rainfall predictions with remote sensing technology and outflow analysis to increase outflow before flood so that flood arrival time should delayed and that maximum outflow discharge be reduced. Rules for releasing water are now established in two steps, following different forecasting models.
Flood control	The reservoir might be used to mitigate the floods
Drought mitigation	No
Climate change	Yes
Technical details	Late Gate Operation is made to reduce flood impact Remote sensing technology and outflow analysis
Other services	No
Type	Forecasting models used to operate dam

Reported by	Ånund Killingtveit, Knut Alfredsen, Trond Rinde, Nicolai Østhus, Paul Christen Røhr
Country	Norway
Case study	Flood-forecasting and flood management in Skiensvassdraget
Project responsible and partners	5 different organizations
Short description	Reservoirs can reduce the flood risk, but they have a limited capacity, and they require an accurate forecast system, the Telemark flood forecasting model (FMTV). The system is complex: the catchment is divided in 5 sub-catchments, that are independently managed by 5 different organizations.
Flood control	It has been used to produce scenarios and mitigate flood events in 2007. A further step has been to combine the system with flood inundation maps.
Drought mitigation	No
Climate change	No
Technical details	There are 10 power plant. The total storage capacity of the system is around 4.250 billion of m^3.
Other services	The reservoirs were constructed at the beginning to help timber transport, and they were used for hydropower already at the beginning of 1900
Type	Reservoir volume and forecast model

Reported by	Klaus Jorde
Country	Switzerland
Case study	Rheinkraftwerk Schaffhausen
Project responsible and partners	Kraftwerk Schaffhausen AG
Short description	The weir on the Rhein River (7 meters high) has been upgraded in 1964 for power generation. After its upgrade, no floods occurred in the city of Schaffhausen.
Flood control	The backwater induced by the weir prevents floods in the city of Schaffhausen. Passive effect
Drought mitigation	No
Climate change	No assessment
Technical details	The installed capacity of the hydropower plant is 26 MW. The annual mean flow of the Rhein River is 370 m^3/s. The volume of the backwater is 48 billion m^3.
Other services	No
Type	Reservoir volume (passive)

Reported by	Anton Schleiss
Country	Switzerland
Case study	MINERVE System, Upper Rhone Valley, Rhone River
Project responsible and partners	Different hydropower companies, government of Valais
Short description	Since 2002 a complex flood forecast system coupled with a DSS has been established. The DSS defines measures for the hydropower plants (turbine and bottom outlet) to provide optimal flood routing and minimizing losses for hydropower companies. Based on the hydrological forecasts, automatic warnings, associated with four different thresholds at each control point, and preventive release strategies by operating powerhouses and/or opening of bottom outlets are provided to a governmental taskforce. This taskforce can require such preventive operations to the hydropower schemes owners to reduce potential flood damages, by creating additional storage in the reservoirs. The system produced warnings in 2006, 2011, 2012 and 2013. In 2013 preventive operations were suggested, but the storage volume available was sufficient.
Flood control	Flood management through a hydropower scheme using an advanced decision support system.
Drought mitigation	Some reservoirs are available for feeding traditional irrigation systems in Valais
Climate change	Likely included in the hydrological model (not specified)
Technical details	The system includes 21 reservoirs created by large dams and 24 plants, grouped into 10 independent hydropower companies. It has been validated by simulation of October 2000 flood. It has different control points on the Rhone River.
Other services	Some reservoirs deliver water for artificial snow production in ski resorts
Type	Mainly hydrological-hydraulic system model, decision support system

Reported by	Furkan Yardimici
Case study	Atatürk HEPP&Dam, Southeastern Anatolia Project (GAP)
Country	Turkey
Project responsible and partners	Elektrik Üretim A.Ş
Short description	The hydropower dam has been used to mitigate floods, protect from droughts and generate electricity
Flood control	Floods from Tigris and Euphrates Rivers decreased significantly after the construction of the dams with positive consequences on the local communities
Drought mitigation	Up to now, the dam has been used for irrigation purposes not for mitigation of extreme drought events.
Climate change	Predictions for the area show a reduction in precipitation and an increased evapotranspiration that will shift the beginning of the irrigation period from May to March
Technical details	Reservoir total volume: 48.7 billion m^3 Installed capacity: 2 400 MW (8 x 300 MW Francis turbines) Annual generation: 8,9 TWh Dam height: 169 m Dam length: 1 819 m
Other services	Surface water supply for non-drinking purposes (irrigation)
Type	Reservoir volume

Reported by	Abhay Kumar Singh (Chairman & Managing Director) and Deepak Saigal (General Manager)
Case study	Dibang Multipurpose Project, Lower Dibang Valley
Country	India
Project responsible and partners	NHPC LTD (Govt of India Enterprise)
Short description	Reservoir used to mitigate flood damages that sum up to 1.5 USD billions. The Project developers have a plan to adjust the reservoir level according to the monsoon flows. Simulations show that the reservoirs can decrease water level in the downstream section of the river from 3 to 6 m in the first 20 km and from 1 to 2 m beyond 20 km downstream of dam. A strip 2.7 km wide and 40 km length in the floodplain will not be flooded by a 100-year flood.
Flood control	Flood mitigation through reservoir's volume
Drought mitigation	No
Climate change	Not explicitly included in the plan
Technical details	Probable maximum flood is 26200 m^3/s, maximum observed flood 14000 m^3/s. Concrete dam diverts water to HP plants for 11200 GWh/y. Reservoir volume is 3510 million m^3.
Other services	Services related with land use (e.g. cultivated crops)
Type	Reservoir volume

Reported by	Rajeev Kumar Vishnoi (Technical Director)
Case study	Tehri Dam
Country	India
Project responsible and partners	THDC India Limited
Short description	The project consists in a multipurpose reservoir in the Upper Himalaya area (Gange River tributaries, Bhagirathi and Bhilangana). The reservoir has not been built primarily for flood mitigation, but the reservoir's volume can be used for that purpose. The advanced forecasting system allows to free volume for flood mitigation. In 2013 a severe flood impacted the basin upstream the reservoir. The Tehri Dam reduced the outflow from almost 7000 m^3/s to 500 m^3/s, preventing the inundation of the downstream cities such as Haridwar and Rishikesh, which were at the threshold of a large-scale inundation.
Flood control	Flood mitigation through reservoir's volume and forecasting system
Drought mitigation	No
Climate change	Not explicitly considered, but the dam has a large capacity to absorb the extreme precipitation events.
Technical details	Rock dam 261 m high, the catchment is 2328 km^2 snow-fed and 5183 km^2 rain-fed, with rainfall heavily skewed towards the monsoon season. The stored volume is 3540 million m^3. The reservoir is 44 km on river Bhagirathi and 25 km on river Bhilangana.
Other services	Water supply (drinking and non-drinking), recreational activities.
Type	Reservoir volume

Case studies

1. Tasmania irrigation schemes, Australia

By Carolyn Maxwell and Greg Carson, HydroTasmania

1.1. Drought management services and climate change impacts

1.1.1. Introduction

Tasmania's hydropower history dates back to the construction of the island's earliest schemes over 100 years ago, when concepts such as drought management or flood mitigation were far less understood than they are today. For example, development of the Waddamana power scheme in central Tasmania began in 1910 through a private company, before being commissioned by the Tasmanian Government in 1916. Approval for construction and operations included a riparian release down the Shannon River post-diversion, based on the understanding of the river's environment and hydrology at the time.

In the 1950s and 1960s there was a major hydropower development program across Tasmania, which included projects in the Derwent, Mersey, Forth and South Esk catchments. This infrastructure was not designed for flood mitigation.

Approvals for these schemes included provision of water for irrigation and other commercial uses. Over time these initial water allocations were fully subscribed. Demand for water continued to increase, however. In the past decade, there has been over $1 billion invested in irrigation infrastructure in Tasmania by the State and Australian Governments. Many of these developments draw their water either from hydro storages or below hydropower stations.

1.2. Assessment of drought services

1.2.1. System security

Lake Gordon and Yingina/Great Lake. During wet years when there is 'surplus' rainfall across the hydro-generation system, water can be stored in these lakes until needed in dry years, 'filling' and 'emptying' over an inter-annual storage cycle over multiple years. In this way, these major storages provide security of generation supply during times of drought (in combination with transfers across the 580MW Basslink interconnector between Tasmania and the Australian mainland).

Hydro Tasmania's also operates a range of medium-sized storages, which are usually the top lakes of a run-of-river chain. These storages can cycle over an annual or seasonal basis, feeding the storages that directly supply run-of-river power stations. These smaller lakes can theoretically cycle over a period of hours to days.

1.2.2. Irrigation development

Tasmania's first significant irrigation scheme development relying on hydropower infrastructure was the Cressy-Longford irrigation scheme. Commissioned in 1974, this draws its water from the Poatina power station tailrace and is capable of delivering up to 20 000 ML annually to irrigators.

In the mid-2000s, the Tasmanian Government established the Tasmanian Irrigation Development Board, now known as Tasmanian Irrigation, to develop irrigation infrastructure. This organisation has worked closely with Hydro Tasmania. Of Tasmanian Irrigation's 16 completed schemes, six draw their water either from hydro storages or downstream of hydro power stations, and are listed in the table below.

Irrigation scheme	Hydro Tasmania-managed water source
Sassafras/Wesley-Vale	Mersey River, downstream Parangana Dam
Midlands	Arthurs Lake
Whitemore	Poatina tailrace
Kindred / North Motton	Forth River, downstream Paloona power station
Cressy Longford	Poatina tailrace
Southern Highlands	Great Lake (Shannon River)

This list includes three of Tasmanian Irrigation's four largest irrigation schemes. The most significant is the Midlands Irrigation Scheme, which draws its water from Arthurs Lake, a high-altitude lake in the centre of the state. The scheme includes a pipeline/penstock that is over 50km long, to deliver water to the upper Macquarie River, from which point the water is either gravity-fed or pumped to irrigation areas. This scheme is capable of delivering up to 38 000 ML annually to irrigators.

Irrigation water consumption in Tasmania has increased from ~240 000ML to ~850 000ML per annum over the past 20 years, and is expected to continue to increase in the coming decades. The Tasmanian Government has a policy to increase the value of agricultural production from $1 billion in 2014 to over $10 billion by 2050. Access to more water is a key element of the program of works needed to achieve this target.

1.2.3. Recent drought experience

Tasmania experienced an extended dry period in 2006-08. During these years, Hydro Tasmania gained valuable experience of drought management. Irrigation schemes serviced by water drawn from hydro storages were able to draw their full allocations, however all other irrigation schemes in Tasmania experienced restrictions on water availability. Town water supplies and downstream environmental flows from hydro infrastructure were also maintained.

Spring 2015 was the driest spring on record for Tasmania. This coincided with an unplanned outage of the Basslink interconnector to Victoria, which meant that Tasmania's energy supply was isolated from the mainland during a period of water shortage. The knowledge gained during the earlier dry period informed our management of water storages. Once again, irrigation and domestic water supply obligations were met, and the integrity of nationally important wetlands was maintained.

1.2.4. Flood mitigation

While the various Tasmanian hydro-generation schemes were not designed to provide flood mitigation services, Hydro Tasmania's monitoring infrastructure provides important real-time data on rainfall and water flow. This is utilised by the Bureau of Meteorology and emergency services to provide warnings and advice on current and forecast flood conditions.

1.3. Climate change

Tasmania has experienced a decline in total annual rainfall since approximately 1975, and this trend has continued (Grose et al 2010). For many years, it was assumed the average yield of rainfall into the hydro generation scheme was equivalent to 10,000 GWh per year. Following a decade of lower than average rainfall to 2007, Hydro Tasmania reviewed these assumptions and conservatively revised its annual yield to 9 000 GWh annually.

The region supplying water to *yingina /* Great Lake is projected to experience a decline in net rainfall and a seasonal shift in water patterns under climate change scenarios (Bennett et al 2010). Modelling projects a decreased in runoff to this region of Tasmania in all seasons across all future periods to 2100. Despite this, the system remains viable over the long term.

The irrigation regions fed by this system are not projected to experience a significant change in annual rainfall. However, evaporation is projected to increase, especially during the irrigation season (up to 0.54mm per day in summer by 2099) and the region is projected to experience more 'summer days' above 25 °C (ACE CRC 2010). It is anticipated that as the impacts of climate change become apparent, there will be increasing demands for Hydro Tasmania to adjust our operations to provide confidence in future irrigation water supply.

1.4. Conclusions

Hydropower infrastructure can be used to supply services that mitigate the effects of drought. In new schemes (such as those contemplated with the Battery of the Nation initiative), these multiple uses need to be clearly considered, beginning at the design phase. Governance of these multiple uses must also be documented in the water management planning framework of each relevant jurisdiction.

Older systems, such as many of those still in operation in Tasmania, should not be relied on for flood management as they are not currently capable of fulfilling that purpose. Existing systems may be capable of providing drought mitigation services by retrofitting new engineering controls, and/or administrative frameworks that allow for clear-decision making, appropriate value attribution (including effective compensation) and clear prioritisation of water needs.

For over 100 years, Hydro Tasmania has been balancing the competing demands of irrigation, environmental stewardship, recreation and amenity values, along with hydropower generation. As climate change intensifies and water demand increases to support increasing industrial, agricultural and population growth, updated governance frameworks will be required to appropriately value and manage these competing requirements.

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2. Inn River Basin, Austria

Hydropower and Natural Hazard Management in Tyrol, Austria

By Peter Bauhofer and Johannes Schöber, TIWAG-Tiroler Wasserkraft AG, Tyrol, Austria

2.1. Introduction

The region of Tyrol is located in the heart of the eastern part of the Alps. The Tyrolean population has a long-lasting experience with natural hazards and in particular with flood events. In future even more than today, multifold driven meteorological and hydrological processes will likely be increased by climate change may cause more flood events due to rising zero-degree lines combined with heavy rainfall possibly occurring at the same time with strong snow and glacier melt. Currently, extreme hydrological events still range within the limits of observed flood series. However, the combination of flood risk together with increasing land use for buildings and large scale sealing of soils creates increasing vulnerability (e.g. Barredo 2007).

The Inn River's flood event of June 2019 is a consequent follow up to a series of remarkable events in the entire alpine region during the past 20 years. From a Tyrolean perspective, the events in 1999 (Lech River), in 2005 affecting the area of Paznaun and the Inn-valley, in 2013 affecting the greater area of Kitzbühel and in 2018 at the Drau River are of particular interest (e.g. Gattermayr, 2005; Blöschl 2013, Schöber 2014).

2.2. The Flood Event in 2019 and the role of Hydropower

In the first days of June 2019, the weather changed considerably from cold spring conditions to summer with very high temperatures. In consequence, the still enormous snow accumulation of the preceding winter resulted in extreme snowmelt rates. From the end of May to mid of June snow water equivalent in the order of 500-700 mm melted which corresponds to an average yearly precipitation sum in the Inn valley. From June 11 to June 13, thunderstorms with intense rainfall, strong wind and a zero-degree-line above 3000 m resulted in an exceptional flood event. High flows from the Engadin, Switzerland, and side valleys of the Inn valley cumulated in the Inn River in Tyrol. Once more, the capital of the region, Innsbruck, experienced flood damage.

On June 12, the Inn River was at the level of a 10-year flood, when passing the border from Switzerland. Flood flows on the tributaries lead from 50 up to 70 years floods until Innsbruck. On June 13, the Inn's water level in Innsbruck (Figure 1) reached 1350 m^3/s, the second largest flood flow in the records. Downstream from Innsbruck the Inn still reached the 30 years flood level (Figure 2). At Kirchbichl gauge, this event corresponds to the fourth largest flood in the time series (Figure 3).

Figure 1 River Inn at Innsbruck, close to the edge (Ref. TIWAG)

Figure 2 River Inn at Rattenberg downstreams of Innsbruck. Water level appr. 1m above level of the surroundings (Ref. TIWAG)

Statistical analysis of the runoff data of the Inn River makes evident, that the situation in June 2019 was extreme and nothing comparable can be found in the records starting in the year 1951. Mainly triggered by the extreme snowmelt due to high temperatures up to the highest elevations and additional heavy rainfall the resulting daily mean flow on June 12 enters the records as an all-time high. Moreover, in June 2020 the largest monthly mean flow with some 670 m^3/s was recorded being roughly 120 m^3/s higher than the second largest monthly mean flow. This monthly mean flow corresponds to the one-year flood recurrence level in Innsbruck. This permanent high-level situation had significant negative effects for areas with low depth to the groundwater table downstream of Innsbruck resulting in floods also caused by groundwater.

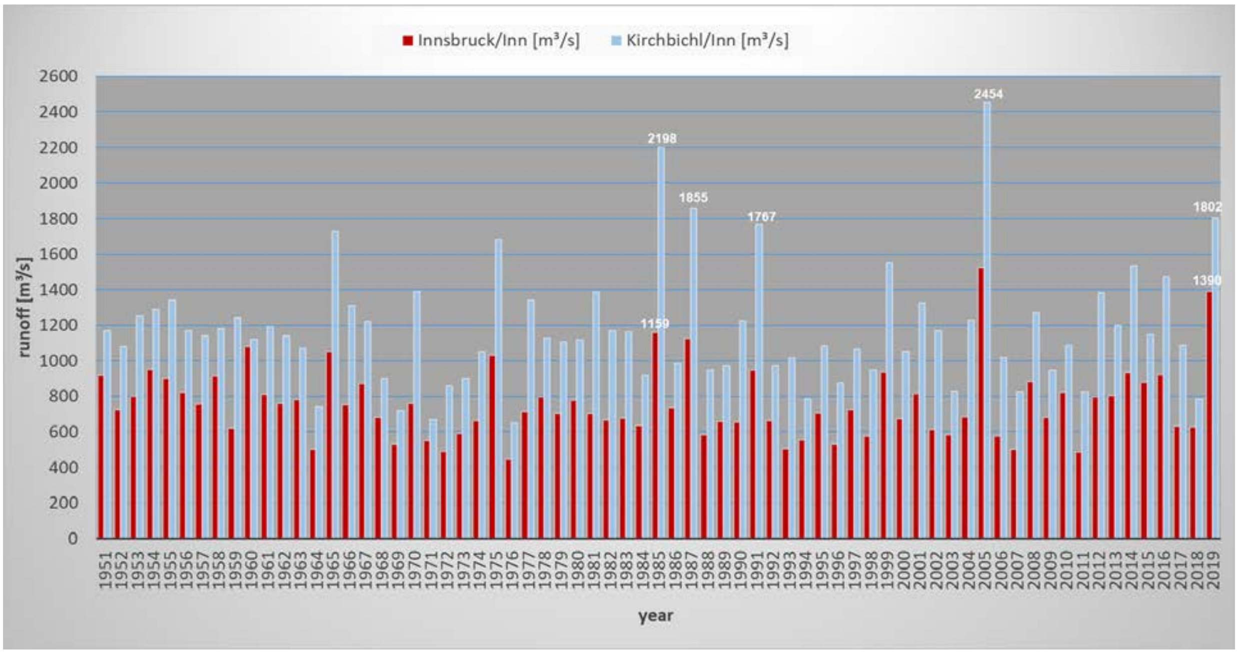

Figure 3 Annual maximum flood series at Innsbruck gauge and Kirchbichl gauge (Ref.: ehyd.gv.at, TIWAG 2019)

TIWAG's hydropower assets are an integrated part of Tyrol's flood management system. Seasonal storage power plants and pumped hydro storage together with high capacity diversion tunnels transferring water between neighbouring valleys. Combined with a flood forecasting system and early alert systems as well as a forward looking storage management efficiently helped to minimize flood damage for the benefit of the population and economy in Tyrol and the neighbouring Bavaria. Being aware of the imminent meteorological process the Kaunertal and Sellrain Silz power stations (both storage resp. pumped storage) were shut down before June 12 and thus further reduced water input to the Inn. Moreover, approximately 100 m³/s were continuously diverted to the reservoirs of the two power stations from June 11 to June 13. These measures effectively avoided floods in the Ötztal and the Stubaital, both side valleys of the Inntal, and flood damage for Innsbruck itself, since the water level of the Inn in Innsbruck was on the edge to the 100 years flood mark (Figure 1 and Figure 2).

2.3. Conclusions

Vast parts of Tyrolean valleys are densely populated and are intensively used for economy, in particular for an internationally oriented high-quality tourism. In a more general perspective hydropower assets of TIWAG and Verbund Hydropower once more significantly reduced flood hazards and finally flood damage in settlement areas of this region in the Alps.

Climate change effects combined with anthropological influences, likely increase the risk, that current 50 years or even 100 years flood events will have a significantly reduced frequency in future.

Thus, TIWAG's existing and new storage and pumped hydro storage power plants not only strongly support the regional and cross regional energy transition process of the ENTSOE-System by RES-integration and the improvement of system stability and security of supply but also provide effective habitat protection for the population and economy.

2.4. References

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3. Paraiba do Sul River Basin, Brazil

Flood Control and Drought Management Services Provided by Hydropower Plants in the Paraiba do Sul River Basin, Brazil

P. Diniz[1], F.S. Costa[2] J.M. Damazio[3]

[1]National Operator System, Rua Júlio do Carmo, 251, Rio de Janeiro, RJ, Brazil; [2]State University of Rio de Janeiro, Rua São Francisco Xavier, 524, Rio de Janeiro, RJ, Brazil; [3]Electric Energy Research Center, Av. Horácio Macedo, 354, Rio de Janeiro, RJ, Brazil

3.1. Introduction

The Paraiba do Sul River (PSR) basin is an interstate Brazilian river basin (Fig 1) spanning among three south-eastern Brazilian states: São Paulo, Rio de Janeiro and Minas Gerais. From its headwaters in the State of São Paulo, at 1,800 m of altitude, to its mouth, in northern Rio de Janeiro, PSR cover an approximate length of 1,150km. Its basin covering an area of 56,500 km^2, has an elongated shape, with a length about three times greater than the maximum width. The average long-term flows in the main stretches of the basin are approximately: high stretch, 150 m^3/s; medium stretch, 280 m^3/s; and low stretch, 810 m^3/s.

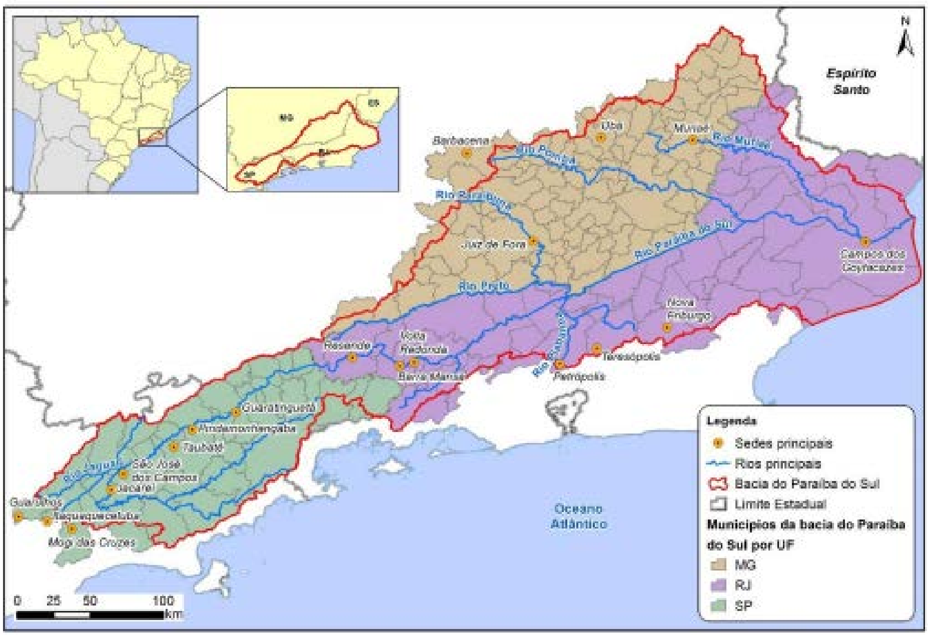


Figure 4 Paraiba do Sul River Basin.

PSR basin stands out on the Brazilian national scene for encompassing in its interior some of the main socio-economic poles of the country, implying a great diversity of interests related to its water resources. Ten to twelve percent of Brazilian GDP comes from the PSR basin, distributed in products from the service (56%), industrial (43%) and agricultural (1%) sectors. PSR population is estimated at 6.5 million inhabitants (92% living in urban zones) and water supply for approximately 19.3 million people (included the 12.8 million inhabitants of the Rio de Janeiro metropolitan region situated outside the basin) depends on its water (AGEVAP, 2016).

The PSR basin hydropower potential is estimated in 3,000 MW (Avelar, 2015). Hydropower development started in 1908 and a complex system is now in operation (Figure 5) with four upstream regulation reservoirs, 11 powerhouses and two pump stations, with a total generation capacity of 1,607.6 MW. The two pump stations (Santa Cecilia and Vigário) operate an inter-basin water transfer from Paraiba do Sul river basin to the neighbour Ribeirão das Lajes basin providing electricity generation and water supply to the Rio de Janeiro metropolitan area.

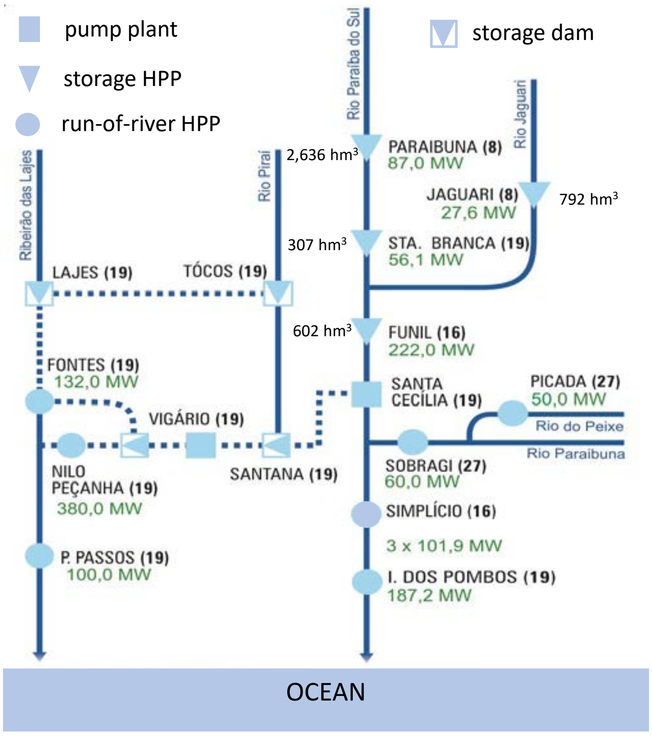


Figure 5 Paraiba do Sul Hydropower System (adapted from (Diniz, 2017)).

3.2. Assessment of Flood and Drought Services

The precipitation regime at the PSR basin presents a well-defined rainy period from November to January, when heavy rains cause large floods in PSR valley which may provoke substantial damages. The dry period occurs from June to August, and water shortage may impact industrial, agricultural activities and urban water supply. Figure 6 illustrates the PRS natural hydrological regime at a hydrometric station upstream of Sta. Cecília pump plant. Apart from the seasonal hydrologic variability, recurrent occurrences of extreme floods during the wet season and of extreme extended runs of dry years reflect the interannual hydrologic variability. Over the past 20 years, extreme floods occurred in the 2005/2006 and 2009/2010 wet seasons and a long dry spell from 2014 to 2019.

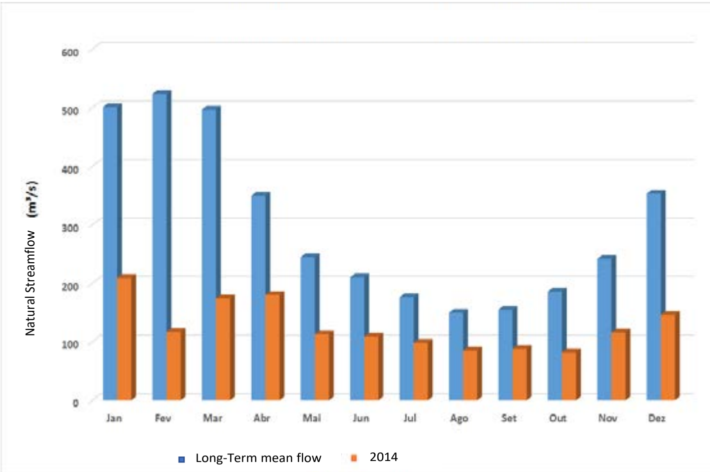
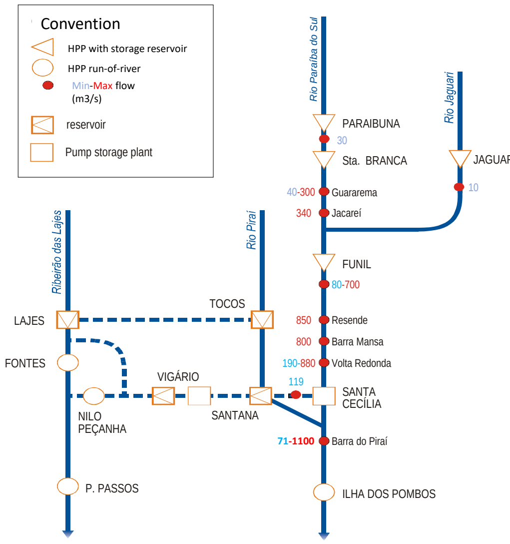


Figure 6 Natural long term mean streamflow at Sta Cecília hydrometric station. In red the drought of 2014.

The building of the four upstream storage HPPs (total water storage capacity of 4,337 hm^3) in Figure 5started at the end of the first half of the 20^{th} century and was completed in 1978 with the inauguration of the Paraibuna plant. The streamflow regularization provided by the coordinated operation of these upstream storages in the PSR basin have been providing flood control during the wet season and streamflow augmentation in drought periods with broad economic and social benefits for the region.

Since the 1970s the hydropower system in the PSR basin have its operation regulated through federal government agencies[1]ordinances which determine minimum and maximum discharge values downstream of the facilities and establish operating curves for reservoirs. Figure 7 presents flood control and drought management streamflow constrains at PSR control points considered in the operation of the system. The maximum discharges are associated with inundations in densely populated urban areas whereas minimum discharges are associated with industrial and municipal



[1] nowadays the Brazilian National Water Agency (ANA), which substituted in 2001 the Brazilian Department of Water and Electricity (DNAEE),

water abstraction facilities.

Figure 7 Flood Control and Drought Management Constraints (adapted from (ONS, 2019))

During the extended severe drought of 2014 to 2019 (Figure 6 shows the hydrograph of 2014), which the four PSR basin upstream reservoirs almost emptied. Water supply at PSR basin and at the metropolitan region of Rio de Janeiro, faced periodic outages. In the same period, water resources for megametropolitan region of Sao Paulo (21.7 million inhabitants) were also subjected to drought conditions and required emergency water from PSR basin. During this period, the operation rules for the whole water resource system of PSR basin were gradually improved by multiple resolutions of the Brazilian National Water Agency (ANA), aiming to reduce risks in the water supply and sewage dilution services provided by the hydropower infrastructure. The normal minimum discharges in Figure 7 have been changed to smaller values to be valid during water scarcity periods. The minimum inflow to Santa Cecília pump plant was reduced from 190 m^3/s to 110 m^3/s. Figure 8 shows the water augmentation in the inflows to Santa Cecília pump plant during the 2014-2019 drought obtained by the operation of the four upstream storage hydropower reservoirs. Note the relatively smaller streamflows during the rainy seasons of 2014 and 2015 and the larger streamflows in the subsequent rainy seasons. After the 2017 rainy season the reservoirs had been re-filled and the minimum inflow to Santa Cecília returned to 190 m^3/s.

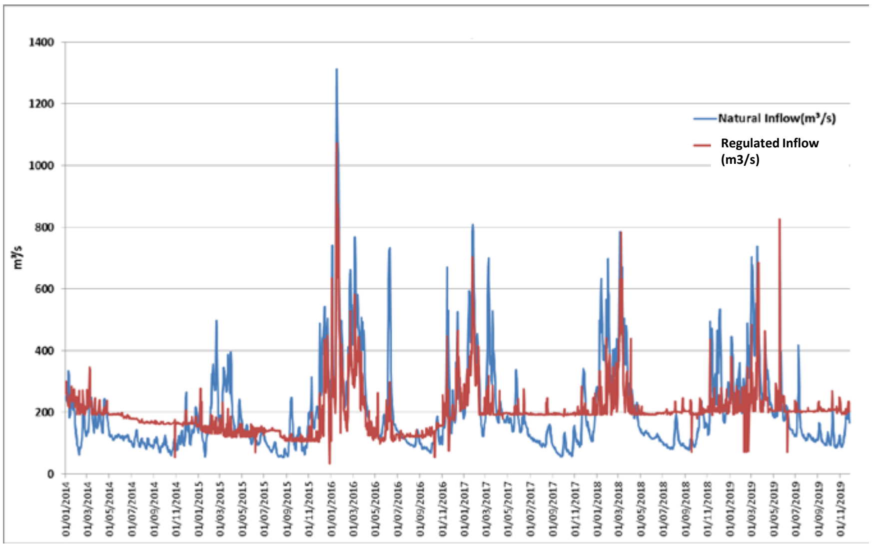


Figure 8 Water Augmentation in the inflows to Santa Cecília pump plant in the 2014-2019

The most recent exceptional flood event in the Paraíba do Sul river basin occurred between December 2009 and January 2010. This flood was characterized by verified streamflows upstream of the Paraibuna reservoir with a recurrence greater than 200 years. Figure 9 shows the natural flood abatement effect in the outflows of Funil Hydropower plant.

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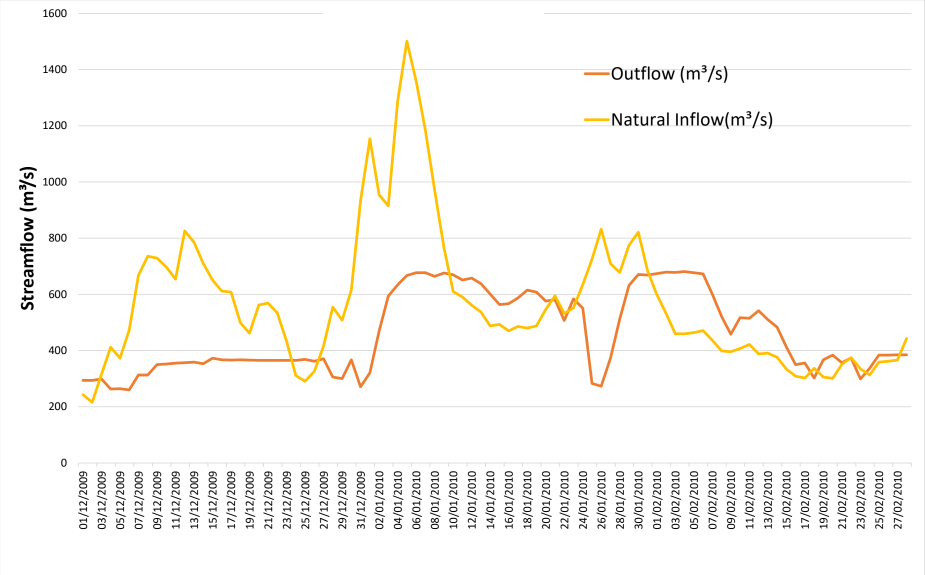

Figure 9 Natural Flood abatement effects in the outflows of Funil hydropower plant in the DEC2009-JAN2010 flood epsiode

3.3. Climate Change

Projections of the PSR basin climate for the 21st century were done by (AGEVAP, 2016) considering runs of 32 global climate models (GCMs) from phase 5 of the Coupled Model Intercomparison Project (CMIP5). The results show variations in the mean annual precipitation from 0 to +4%. Although this increase in water availability in the basin can help drought management, socio-economic development projections point to larger increases for water demands. Also, no information is available about changes in extreme precipitation frequency and intensity bringing new threats for the flood prone zones in the basin. Water resources infrastructure expansions and improvements in operating rules are planned to cope with the projected requirements of water supply and flood control for the future (AGEVAP, 2016).

3.4. Conclusions

The PSR basin, an important industrial Brazilian region, responsible for 10% of Brazilian GNP, encompass numerous municipalities which depends on its water resources. Decades of multipurpose operation of upstream hydropower regulation reservoirs had proved to be valuable in increasing basin water resources availability and reducing vulnerability against droughts in the basin and in the two metropolitan nearby regions (Rio de Janeiro and São Paulo). Valley vulnerability against floods had also been enhanced by proper allocation of flood control storage in the hydropower regulation reservoirs.

Climate change studies so far indicate that climate change is not able to provoke substantial stress on water resources management in the PSR basin. The main pressure on flood control and drought services in PSR basin comes from economic development. Medium term planning for the basin indicates the necessity of building more water storage capacity in the basin in order to cope with the increase of water demands in the remaining years of 21st century.

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4. Columbia River Basin, Canada and USA

Balancing Hydropower Generation, Flood Control and Drought Management Services Under a Changing Climate: A Columbia River Basin Case Study

N. Voisin[1], S. Gore[2], S.-C. Kao[3]

[1]Pacific Northwest National Laboratory; [2]Water Power Technology Office, Department of Energy; [3]Oakridge National Laboratory

4.1. Introduction

The Columbia River Basin (CRB) in the North American Pacific Northwest drains about 668,000 km^2 over the Provinces of Alberta and British Columbia in Canada, and seven states in the United States including almost all or large portions of Idaho, Montana, Oregon and Washington. The Columbia River is the fourth largest river in North America measured by discharge, with a mean annual flow of about 7,500 cms. The Pacific Northwest is home to over 13 million people in the U.S. with a large fraction of the population located in the Puget Sound Area, adjacent to the Columbia River drainage area (Figure 10). Over two third of the Pacific Northwest electricity demand is met by regional hydropower. Agriculture in the basin benefits the region, the nation, and international markets.

This case study aims to contribute to a workshop held by the International Energy Agency on the flood and drought management services provided by powered dams and on potential changes to those services due to climate change. We provide an overview of the hydro-climate regimes of the basin and the co-evolution of socio-economic dynamics associated with the powered dams' emergence and operations. We then present the existing flood and drought services and follow with how those services might be impacted by climate change. We finally discuss the regional priorities and challenges of balancing hydropower, flood and drought services under climate change. The scope of the case study is limited to the drought and flood management services after the dams were established.

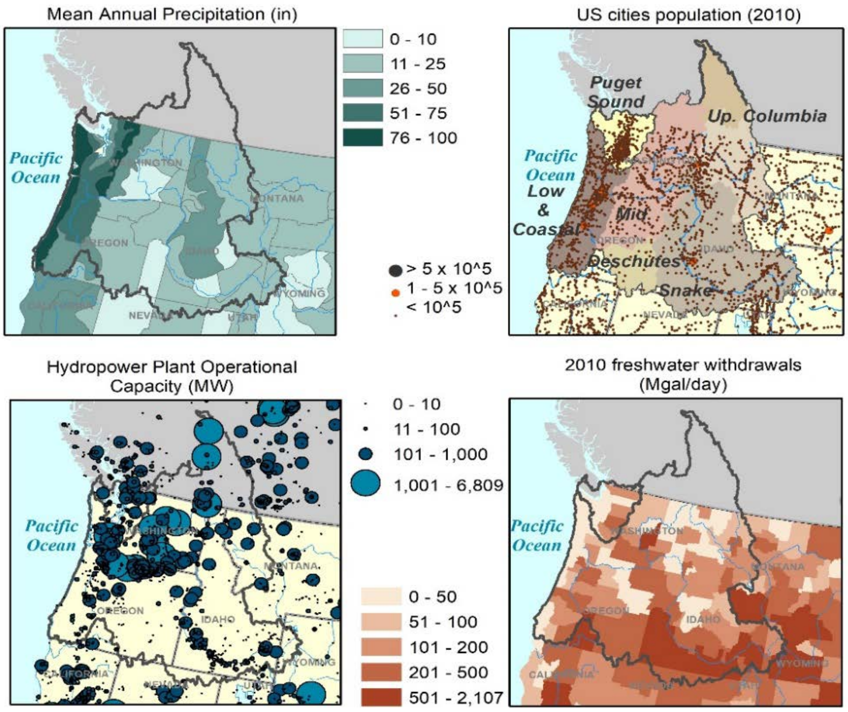

Figure 10 Overview of the Columbia River Basin. Top left panel: Mean annual precipitation by climate division (Source: Vose et al. 2014). Top right panel: U.S. population (Source: 2010 U.S. census) and sub-regions of the CRB, namely Canadian and U.S. Upper Columbia, Mid Columbia, Snake, Deschutes, Lower Columbia with coastal areas. Lower left panel: Hydropower plants are displayed according to their operational capacity (Source: Platts 2018). Lower right panel: 2010 total freshwater withdrawals (Source: Maupin et al. 2014).

4.2. Overview of Columbia River Basin

4.2.1. Natural climate and hydrology regimes

The CRB can be hydrologically divided into six hydrologic sub-regions: Canadian and U.S. Upper Columbia, Mid-Columbia, Snake River tributary, Deschutes River tributary, and the Lower Columbia which includes the Willamette River tributary and coastal areas. The Upper Basin lies in the Northern Rockies with a continental mountainous climate rely on land air mass transport from cooler northern lands and warmer southern lands. The Mid-Columbia lies in the rain shadow of the Cascades range, and is dominated by a semi-arid climate. The Snake River Basin with its headwaters in the Rockies is a continental mountainous climate while the lower Snake is semi-arid. The Deschutes River Basin is a semi-arid climate and a hydrologic regime controlled by groundwater reserves stored in volcanic soils. The Lower Columbia west of the Cascades has a temperate climate with ocean air masses providing more moderate seasonal temperature and precipitation changes throughout the year. The overall Columbia River basin has a seasonal hydrological regime tending to be snowmelt controlled with low flow through September - March and a massive freshet early Summer (May-July). However seasonal hydrological regimes vary throughout the basin from rain controlled, to rain-snow transition, and snowmelt controlled hydrological regimes (Figure 11).

4.2.2. Socio-economic activity in the basin

Fur trading[2] and fisheries[3] were the dominant industries until the early 1900s. Traditionally, salmon fishing has played a significant cultural and ecosystem role in the region. Historical estimates of annual salmon runs are 11 and 16 million returned to the river each year to spawn. Places such as Celilo Falls were once important trading centers for tribal livelihoods centered around salmon fishing and the river. Salmons also have significant religious and spiritual importance for tribes in the region, still marked today by the annual celebration of salmon returning to the river[4]. Agriculture developed aside the settlement of the region[5] in the 20th century. The 1930's drought and associated Great Depression motivated the development of large projects for water supply purposes[6], such as the construction of the Grand Coulee Dam, the largest concrete structure in the world until 2009 (Figure 11). Later, World War II motivated the need for further hydropower development to support energy-intensive manufacturing and production of weapons. Similarly, the aluminum industry developed in the region due to the abundant and low-cost hydroelectricity during WWII. Today, there are more than 250 reservoirs and about 150 hydroelectric projects in the basin[7] (Figure 10). The projects aggregate to a total nameplate capacity of 34,318 megawatts and produce, on average, 16,254 megawatts of electricity[8]. About 6% of CRB's mean annual flow is withdrawn to support 21, 000 km^2 of irrigated agriculture (Reclamation 1998). Data centers and transactions are the new-day industry looking for this abundant and low-cost electricity resource.

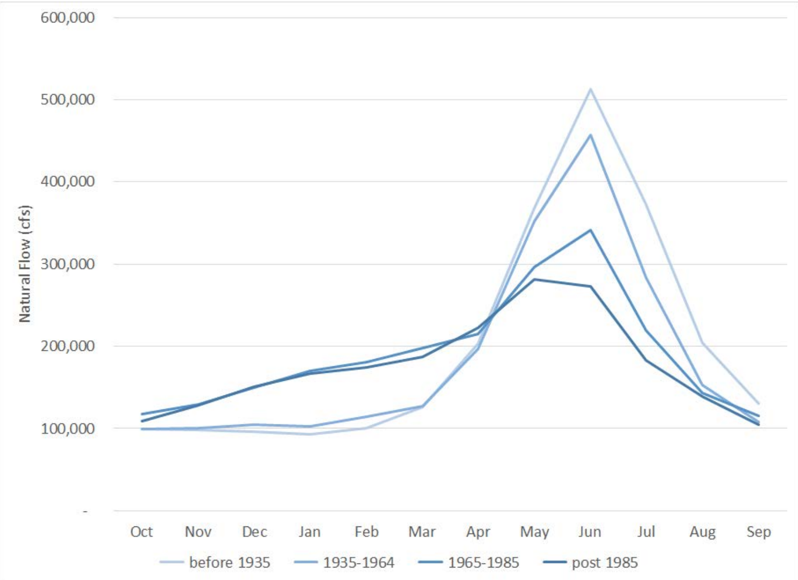

Figure 11 1878-2019 Columbia River mean monthly observed flow (cfs) at The Dalles over different periods of regulation by dams. (Source: USGS) Pre 1935 period had little flow regulation. U.S. dams were constructed in the late 1930s through 1950s. Canada's large storage projects were built upon the Columbia River Treaty in 1964 and finished in the 1970s. Post 1985 period reflects today's operations.

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[2] https://www.nwcouncil.org/reports/columbia-river-history/FurTrade

[3] https://www.nwcouncil.org/reports/columbia-river-history/commercialfishing

[4] https://www.critfc.org/salmon-culture/tribal-salmon-culture/

[5] https://www.nwcouncil.org/reports/columbia-river-history/irrigation

[6] https://www.nwcouncil.org/reports/columbia-river-history/DamsHistory

[7]https://www.nwd.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/475820/columbia-river-basin-dams

[8] https://www.nwcouncil.org/reports/columbia-river-history/DamsHistory

4.3. Hydropower Generation, Flood Control and Drought Management Services

As a transboundary basin, the CRB is a complex governance system. The Federal Columbia River Power System (FCRPS) comprises 33 projects while other dams are privately-owned entities. Most U.S. development happened between 1930 and 1950. Under the 1964 Columbia River Basin Treaty (the Treaty), additional storage was added in Canada to provide flood control services for the U.S.

Canadian flood control and hydropower operations are managed by BC Hydro as designated by the Treaty. A number of entities jointly manage U.S. waters (Figure 12); The Federal system is operated by the U.S. Army Corps of Engineers (USACE) and U.S. Bureau of Reclamation (Reclamation), both federal agencies under the Department of Defense and Department of Interior respectively. Bonneville Power Administration, a federal agency under the Department of Energy, markets the federal hydropower (non-profit). Reclamation and USACE operate the major storage reservoirs for flood control and water supply, while hydropower operations are coordinated with BPA to maximize the value of hydropower. Operations for the Federal system are effectively authorized by Congress where private entities are following the guidance of FERC licenses (Federal Energy Regulatory Commission), and both follow the biological opinions developed by NOAA Fisheries and U.S. Fish and Wildlife Service.

In times of floods, the USACE takes the lead on the coordination of flood control operations across US waters. Reclamation was established to protect, manage and develop water resources in the Western U.S. for the benefit and economic interest of the American public. While the Eastern U.S. follows riparian rights, like in Europe, the western U.S. established prior appropriation water rights. The senior water rights holders benefit from water supply equivalent to natural flow regimes to their water demands despite massive changes in river regimes associated with the new large river projects. Reclamation manages long term water storage and water deliveries through the irrigation season, complemented with groundwater-surface water interaction in the Snake River Basin with river flow enhancement.

Figure 12 Entities operating major reservoirs over the Columbia River Basin. Source: USACE (https://www.nwd.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/475820/columbia-river-basin-dams/)

4.4. Impacts of Climate Change

The Secure Water Act (SWA) of 2009 (Public Law 111-11) commissioned a comprehensive review and assessment of water security, specifically how "global climate change poses a significant challenge to the protection and use of the water resources of the United States". The Bureau of Reclamation is directed by the SWA to assess specific risks to water supply and analyze their impact on water services and related benefits (Reclamation 2016) while the Department of Energy is directed to assess "each effect of, and risk resulting from, global climate change with respect to (A) water supplies used for hydroelectric power generation; and (B) power supplies marketed by each Federal Power Marketing Administration" (Kao et al 2016). For a regional integrated assessment, the River Management Joint Operating Committee (RMJOC), comprised of BPA, USACE and Reclamation, has a mission to "continuously evaluate and anticipate vulnerabilities, risk and resiliency of the Federal Columbia River Power System (FCRPS). The RMJOC has partnered with universities to develop comprehensive assessments of water resources over the CRB under climate change and evolving water demands (Hall et al. 2016). The following assessments are extracted from those reports (RMJOC-1 2010, 2011; RMJOC-II, 2018). Since the 1970s, the air temperature has increased by .8°C and is expected to further raise by 0.6 to 2.2°C by 2030s. Spatial variations indicate larger warming in the interior of the basin, which is already a semi-arid climate. Projections of precipitation are uncertain, albeit with an indication for wetter falls and drier summers. Being a snowmelt driven basin, changes in the snowline elevation and more precipitation falling as rain impacts the overall snowpack storage inducing changes on the seasonality of the hydrograph throughout the basin (Figure 13). Transitional rain-snow basins are projected to become rain-controlled basins with a higher flood peak in the Fall rather than the Spring, and snowmelt-controlled basins are projected to become more rain controlled with a more proportionate flow peak in the Fall as in the Spring.

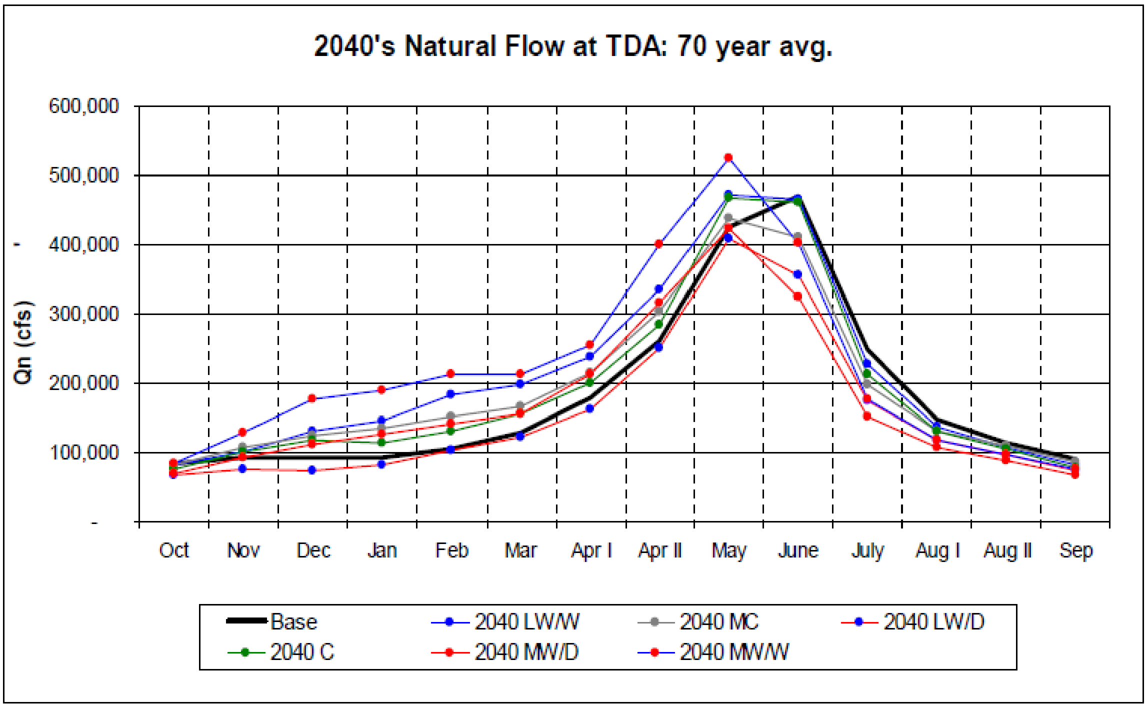

Figure 13 (Figure 12 in RMJOC-II part 1, 2018). Monthly natural flow averages from six scenarios used for the RMJOC-I Study for the 2040s at The Dalles, OR, relative to the long term modified historical flow means.

Considering future hydrologic and climate services, any new operational recommendation is first evaluated for maintaining flood control services, followed by water supply and energy services (NWPCC 2016). Advancements in seasonal and medium range flow forecasts are regularly considered for operations in order to benefit from scientific advances to allow for more robust multi-objective decision-making. With an overall earlier snowmelt with a lower volume, RMJOC reports conclude that the system would benefit from earlier drafts that could also be 10% lower. Several dams would also need to consider the increased chances of floods in the Fall (RMJOC-I part 3, 2011).

The Northwest Power Council evaluates electricity resources adequacy, leveraging the RMJOC reports (NWPCC 2016). The ongoing efforts for the new Northwest Power Plan will also include the impact of climate change on load and hydropower to guide recommendations on buildouts and capacity needs[9]. A recent study had demonstrated how lack of consideration of climate change on both electricity demand and hydropower at a seasonal scale could lead to substantial uncertainties in reliability metrics (Turner et al. 2019).

4.5. Discussions / challenges moving forward

River services over the Columbia River Basin include navigation, flood control, agriculture, fisheries, recreation and hydropower. Climate change impacts the availability of resources and is an ongoing concern for future planning and investment in the basin. The ability to adjust to changes and maintain services is a difficult exercise as tight coordination is needed along the entire basin to manage those services, and each service is managed by different institutions and stakeholders. While hydropower is perceived as a driving engine for providing river services, as demonstrated by the fact that BPA and BC hydro are leading the Columbia River Treaty, Federal and State environmental water laws and regulations have overlapping priorities and jurisdictions creating complex and fractured systems of water governance inherently challenging adjusting to climate change. Hydropower provides benefit to the region by providing “green” electricity source but also ensures water quality of reservoir releases such as maintained stream temperature and total dissolved gas while providing recreational, flood control, navigation and water supply services, which are all key to socio-economic welfare of the region.

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5. Lech River Basin, Germany

Hydropower plant Roßhaupten with Forggensee reservoir serving flood control and drought management to encounter climate change

By Cornelia Häckl, Uniper

5.1. Introduction

HPP Roßhaupten at lake

Figure 14 Catchment area river Lech © Umweltatlas Bayern

Uniper operates 23 hydropower plants along the River Lech, which is about 166 km long and has a catchment area of about 1594 1594 km². The discharge and the electricity production can be regulated by using its head storage facility lake Forggensee with a maximum storage volume of about 165 hm³ and its hydropower plant Roßhaupten. Since its construction in 1953 the artificial lake Forggensee has enhanced renewable demand-driven power production. In a regular year it provides around 150 GWh/a of CO_2-neutral electricity when it is needed, but it is also a multi-functional infrastructure. At the same time it serves the needs of flood protection, ecological flows in low water periods and touristic interests.The average inflow to lake Forggensee is about 65 m³/s, but varies between summer and winter (see

Figure 15). For the operation of the storage the following time frames are relevant: From 16th October to 31st May the storage lake can be operated between 780.50 and 765.00 m a.s.l. The long-term average of inflow during this period is about 50 m³/s. From 1st June to 15th October the lake level must be kept at 780.50 m a.s.l. to enable touristic activities except in flood situations. The long-term average of inflow during this period is about 85 m³/s.

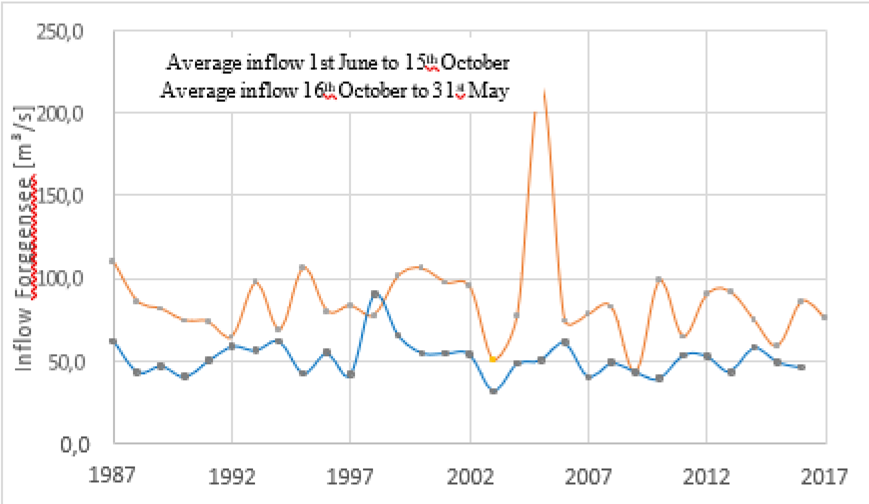

Figure 15 Average natural inflow orggensee between 1987-2017 differentiated between winter and summer operation

The following table Table 1 Hydrological data for several HPPs according to Deutsches Gewässerkundliches Jahrbuch, Donaugebiet 2006shows the hydrological data for several sites along river Lech from therggensee storage to the last major tributary (Wertach River) before it feeds into the River Danube.

Table 1 Hydrological data for several HPPs according to Deutsches Gewässerkundliches Jahrbuch, Donaugebiet 2006

Site	Km	Catchment area [km²]	MNQ [m³/s]	MQ [m³/s]	MHQ [m³/s]
Roßhaupten	166.2	1422			
Lechbruck	146.6	1708	17.7	70.9	359.0
Landsberg	85.4	2295	26.2	81.0	412.0
Haunstetten	50.4	2355	34.8	86.3	396.0
Augsburg	38.6	3800	47.4	114.0	561.0

5.2. Assessment of Flood and Drought Services

Figure 16 shows the contribution of the seasonal storage to partially hold back high inflows in the second quarter of the year and increase vital discharges during the low-flow period in winter. Mainly in May snowmelt is usually used to fill the reservoir up to the “summer level” supporting touristic needs.

In the dry winter period, the reservoir releases on average, 10 m^3/s to serve ecologic, energy and navigation needs downstream along the River Lech to the River Danube

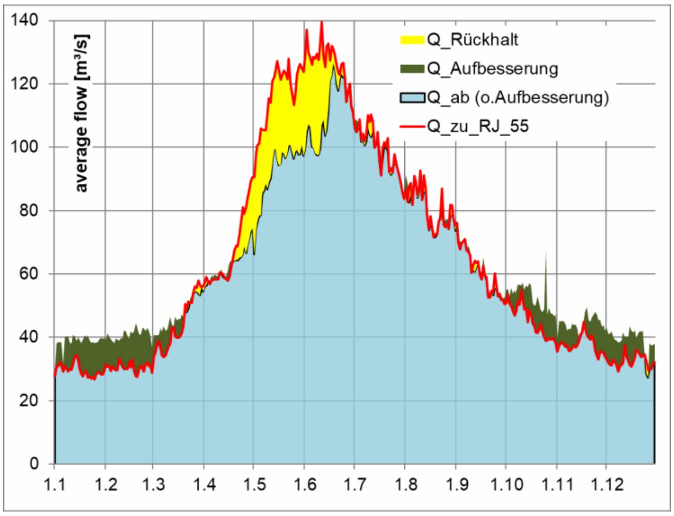

Figure 16 Average natural inflow to Forggensee versus released water to the Lech river below the reservoir (1955 – 2018)

5.3. Flood management

Flood management is a major purpose for the storage lake. The normal spring flood should fill the reservoir until 1st of June. In summer the enforced flood release spill gates and the additional flood storage volume can be used for flood protection. This is the case when the inflow to the reservoir exceeds 150 m³/s. The flood retention space lies between 780.70 m a.s.l. and 782.00 m a.s.l. Its operation must be aligned with the water management authority.

This flood retention space helps to mitigate the consequences of frequent floods and extreme floods. Due to the careful operation of the head storage, the areas alongside river Lech are rarely at risk to be flooded. Only the areas at the lower Lech between the city of Augsburg and the mouth into river Danube are slightly at risk in extreme flood events.

Figure 17 Flood risk areas alongside river Lech© Umweltatlas Bayern

For the purpose of safe operation during flood periods, Uniper has implemented detailed flood management plans, that ensure the safe operation during flood events. They contain information on the operation of all hydropower plants, on preparations during an upcoming flood and about the necessary communication with stakeholders along the river.

Figure 18 shows how frequent small floods were completely stored in Lake Forggensee during February 2020. Such inflows in the summer periods can only partly be stored in the retention space, but its capacity also provides protection for cities along the river, such as Augsburg, from peak flows.

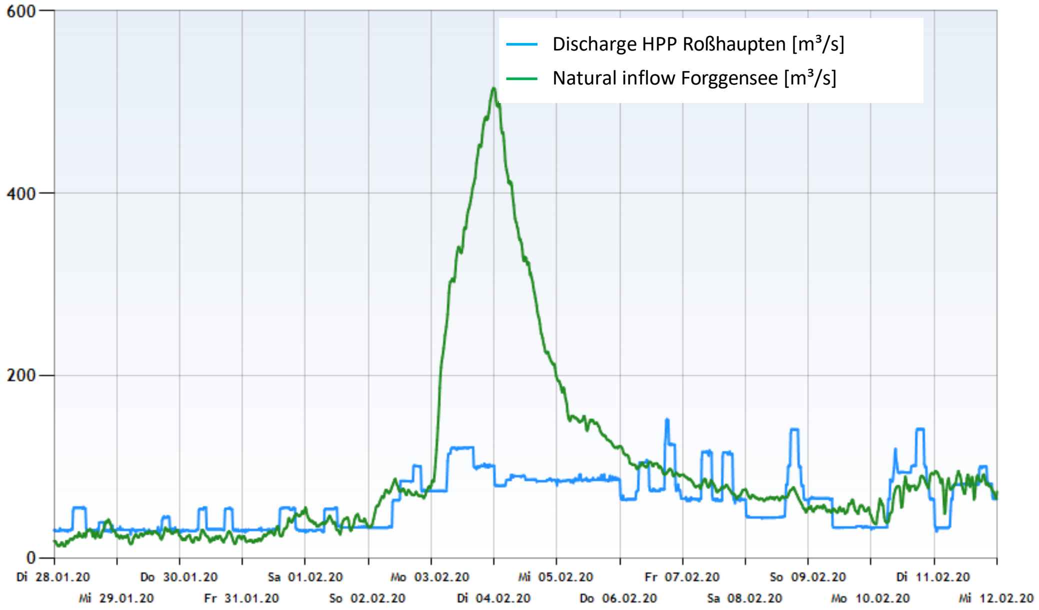

Figure 18 Frequent small floods can be stored in the Forggensee storage

Additionally, the storage capacity can help to influence the peak of flood events in river Danube, as there are only very limited flood retention spaces at other tributaries of river Danube in Bavaria.

5.4. Drought Services

Especially in winter when the inflow tends to be low, Uniper supports river Lech with water from the storage to ensure a minimum e-flow at the lower plants of river Lech.

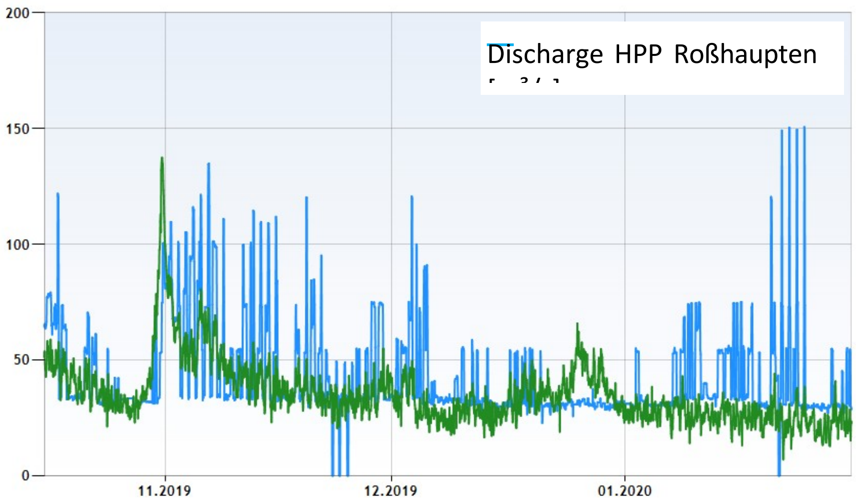

Figure 19 During winter discharge from the storage supports the river ecology

As a major tributary to the Danube River, the Lech also supports shipping at the Danube River during low flow periods. However, during dry periods in summer the interests of tourism do not allow the storage level to be lowered for ecological reasons. Uniper has implemented a drought management guideline to ensure the best possible operation during extreme situations. For instance, the guideline contains information about minimum required ecological flows to ensure survival of fish and other river organisms, highlights especially endangered river areas, and lists relevant stakeholders during drought periods. Oxygen measurements at several hydropower plants ensure the necessary level of dissolved oxygen in the water that allows fish to survive. In case of too low oxygen contents, the hydropower plants can support oxygen intake by using the weirs for water discharge. Some plants (for example at river Danube) also have the possibility to use technical oxygen enrichment valves at the turbines to support water ecology during low flow periods.

5.5. Climate Change

The ClimEx project has been researching on how climate change (in contrast to natural variability) will influence the frequency and impact of hydrological extreme events in Bavaria. For Bavaria the calculations of the models predict an increase of extreme precipitations north of the Alps, while at the same time the average discharge decreases by 20%. This means, that in general less water will be available in the rivers, while very heavy rain events can cause short floods. Also long heat periods will increase, causing more frequent and more severe drought events. Extreme weather situations as Vb-cyclones, that cause most of the severe flood events in Bavaria, will be increasing too. They will become more frequent in spring and winter and stronger in summer.

This means for the operation of the storage lakes in Bavaria that the role of ensuring a minimum ecological flow over long dry periods becomes increasingly important. Also, the need for short term storage of precipitation increases. Lake Forggensee already today perfectly serves these needs from 15th October to 31st May. In summer, when tourism is a very important economic factor in the region, the flexibility to use the available storage volume to balance natural extreme events is limited.

5.6. Conclusion

Storage facilities are rare but extremely important to fulfill different societal needs. Rivers are under immense pressures because of often conflicting interests. Storage facilities help to mitigate these pressures and serve many stakeholders. However, due to climate change the hydrological conditions become more challenging for all rivers in Bavaria, demanding the use of existing storage capacities with all of the flexibility they can offer. In addition, new storage options are needed to keep protecting humans living alongside rivers as well as the environment they are embedded in.

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5.8. Contact

Cornelia Häckl (cornelia.häckl@uniper.energy), Uniper Kraftwerke GmbH

6. Schluchsee catchment area, Germany

By Orkan Akpinar, Schluchseewerke

Flood prediction system for the Schluchsee catchment area

The „Schluchseewerk AG“ was found in 1928. In 1929/30 the Schluchsee dam was built followed by the first pumped storage hydro power plant auf Häusern in 1931. The Witznau power plant was finished in 1943, the Waldshut power in 1951. The three power plants form the „Schluchsee group“are arranged in a cascade. The lower basin of KW Häusern being the upper basin of Witznau and so forth. The Schluchsee lake has a capacity of 108 Mio. m³ and has a top water level of 930 m.a.s.l, and a theoretical minimum of 888 m.a.s.l. Due to restrictions of the permit, the lower water level is 924 m.a.s.l. from May to October and ramping up/down to 914 m.a.s.l. from December to March. The amount of stored energy is 133 GWh in theory and about 68 GWh in average within the limits and exceptions from the permit. After a ruling from the German federal supreme court in 2009, pumped storage hydro power plants were considered as end users when operating in pump mode thus being obliged to pay end user levies.

Figure 20

The final meter (929-930 m.a.s.l.) was voluntarily reserved for flood management purposes. Due to the end user levies in general and the grid fees in particular, efforts were made to be exempt from these. German law states, that an exemption from grid usage fees for 10 years is made possible, when the capacity of a storage is increased by 5%. By abandoning the reserved volume for flood management and using it for energy storage purposes, the Schluchsee group was able to be freed from grid usage fees for 10 years, thus increasing the profitability of the power plants. Nevertheless, the Schluchseewerk AG wanted to guarantee flood management in the downstream area anyway.

So, an existing water balance forecast model for the Schluchsee catchment area was analysed and improved in 2019. As there is no storage volume being reserved for flood management anymore, it was necessary for the Schluchseewerk AG to be able to decompress previous to a flood. The decompression time depends on the availability of the turbines and the actual water-level of the Schluchsee. A study has figured out, that a forecast time of up to 50h (in the worst case scenario of only one turbine being available) is necessary to lower the water level and guarantee an adequate flood safety.

It was necessary to predict floods. Taking into account the calculated hydrological predictions for the inflow of the Schluchsee, the availability of the machine units and the water-level of the Schluchsee, it can be decided, whether or not and to what extent a drawdown via the turbines is necessary. The "Flood-Prediction-Central" of the state of Baden-Württemberg has a prediction model for the upper rhine (Hochrhein) area on the basis of the program "LARSIM", which includes the catchment area of the power plants from the Schluchseewerk AG.

For a significant improvement of the hydrological reproduction, the existing model was enhanced with more detailed data from the Schluchseewerk AG. The new model was tested with measured and predicted meteorological data. A simulation was conducted with HQ100 to show the performance of the new operational model of the Schluchsee lake.

The simulations have shown that the new model meets the requirements to conduct all the necessary steps before an actual flood incident.

6.1. Conclusion

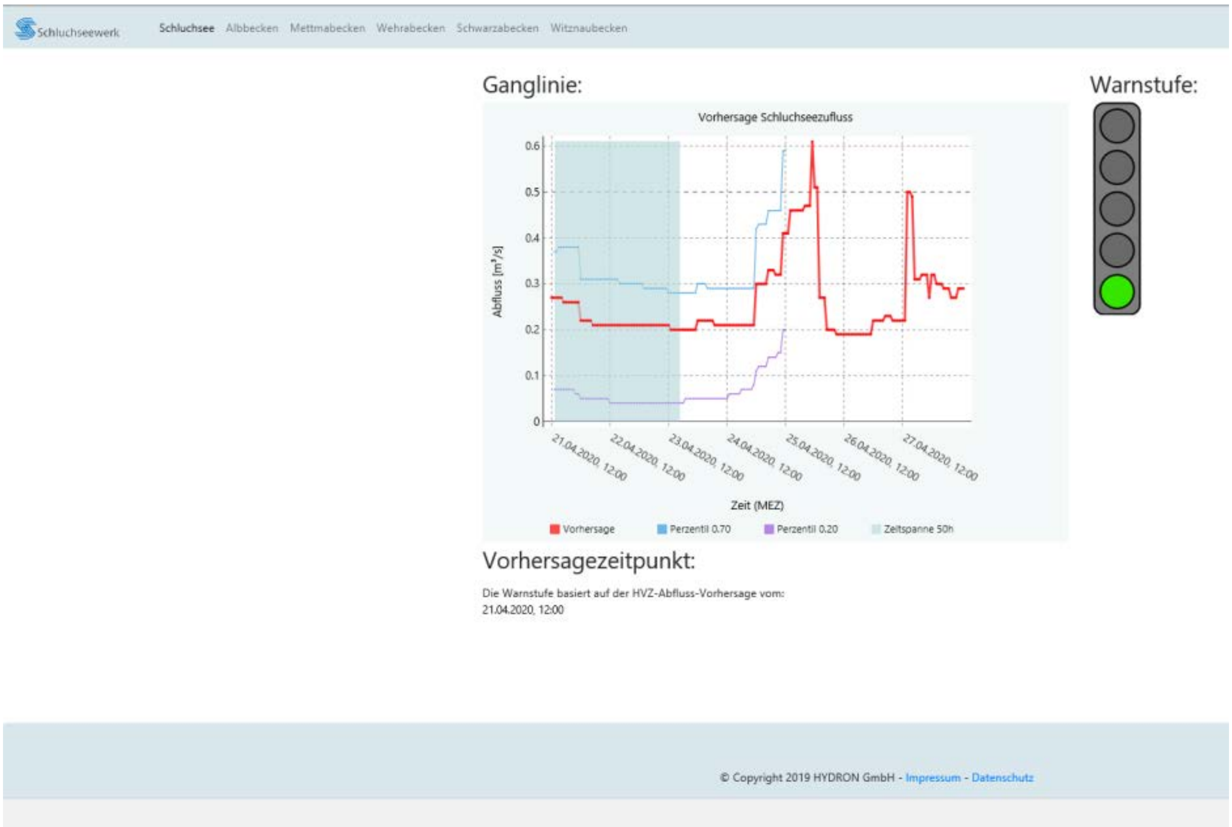

Figure 21

This example shows that it is possible to change the traditional system of reserving storage capacity to manage floods in the Schluchsee catchment area without scarifying flood management safety. It was possible to use the reserved capacity for energy storage purposes and enhance the economic efficiency of the Schluchsee power plant group. This was achieved by improving the governmental flood management system.

7. Nukabira Hydropower Plants flood control management services and climate change impact, Japan

By Murashige Hiroshi, Japan Electric Power Information Center

7.1. Introduction

In August 2016, 4 typhoons attacked Hokkaido Island in Japan continuously in short intervals and brough about a record flood disaster. Inflow to the reservoir of Nukabira hydropower plant owned by J Power in the Tokachi-gawa river systems exceeded over the design flood discharge of its spillway. However, Nukabira hydropower plant contributed to reduce damages downstream by releasing water from the reservoir until its water level became lower than its primary release water level to secure maximum volume of reservoir for flood. Although this reservoir operation was thanked by local people, further contribution was also requested. Under such situation, J Power decided to improve dam operation rule, considering of both damage alleviation and power supply responsibility. As the purpose of Nukabira reservoir is only power supply, contribution to local people downstream is limited. But J Power improved dam operation to reduce damage downstream by using climate prediction information. This paper introduces evaluation of its validity.

7.2. Assessment of Flood and Draught Services

In general, reservoir for hydropower is operated to keep water level high to increase head for power generation. On the other hand, reservoir providing flood control is operated to keep water level low to secure volume for flood inflow. Therefore, in case of reservoir for power supply, water level is kept high normally, but needs to be lowered if flood is predicted to reach the reservoir. However, it takes time to lower reservoir levels, and therefore reliable climate prediction information needs to be available.

In this assessment, Grid Point Value (GPV), as shown in Table 2 Grid Point Value ("GPV") Forecast by Japan Meteorological Agency, information from the Japan Meteorological Agency was used. Also typhoon location information was applied, because there was the possibility of the typhoon passing through the west side of the dam catchment area.

Table 2 Grid Point Value ("GPV") Forecast by Japan Meteorological Agency

Model	Rainfall Forecast in short time	LFM	MAM	GSM	
Predicted Time	6 h	9 h	39 h	84 h	192h
Delivery Interval	30 m	1 h	3 h	6 h	24 h
Horizontal resolution	1 km	2 km	5 km	20 km	

The Tokachi River system is managed by the national government and has a length of 156 km, and catchment area of 9,010km2. There are 6 dams owned by J-Power, 3 dams owned by Hokkaido Electric Power Co. and Hokkaido & Ministry of Land, Infrastructure, Transport and Tourism ("MLITT" hereafter) respectively as shown in Figure 22. Nukabira Dam, studied in this paper, is located in the upper part of the Otohuke River, which is branch of the Tokachi river system. Table 3 Main Dam Specification of the

Tokachi River System. shows the dam main specifications of Nukabira Dam and Tokachi Dam & Satunaigawa Dam owned by Hokkaido and MLITT. Nukabira Dam has as large or larger volume as Tokachi Dam & Satunaigawa Dam. Figure 23 shows image of Nukabira Dam Reservoir Volume.

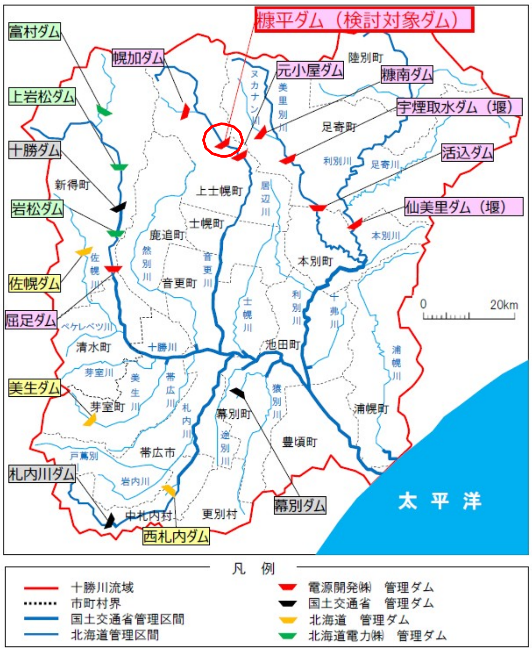

Figure 22 Dam Location in the Tokachi River System

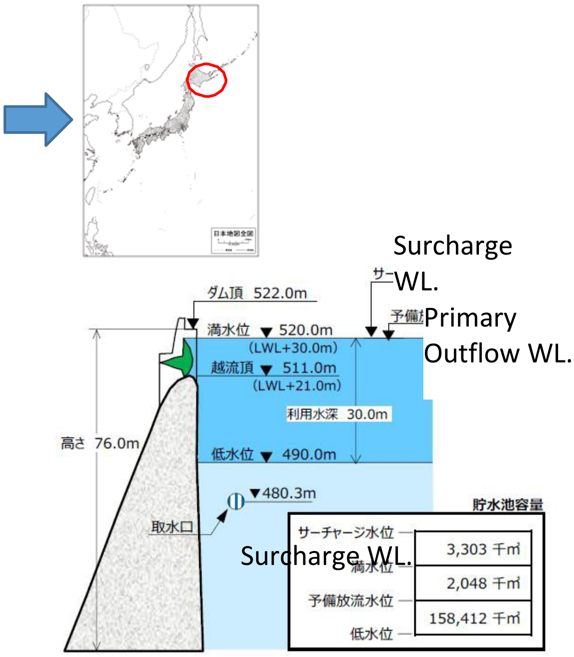

Figure 23 Nukabira Dam Reservoir Volume Distribution

Table 3 Main Dam Specification of the Tokachi River System

Dam Name	Height (m)	Dam Top Length (m)	Total Reservoir Volume (10^3 m^3)	Effective Reservoir Volume (10^3 m^3)
Nukabira	76.0	293.0	193,900	160,500
Tokachi	84.3	443.0	112,000	88,000 (80,000)*
Satsunaigawa	114.0	300.0	54,000	42,000 (25,000)*

*Values in brackets show flood control volume

7.3. Climate Change

An example of climate change is that four typhoons attacked Hokkaido Island in Japan continuously with short intervals and brought record flood disaster in August, 2016. This event was caused by rare pressure patterns, with extreme rainfalls whose total amounts exceeded 200mm. Average rainfall of the Nukabira Dam catchment area (analysed by Japan Meteorological Agency) for each typhoon is shown in Table 4 Average rainfall of the Nukabira Dam catchment area for each typhoon.

Table 4 Average rainfall of the Nukabira Dam catchment area for each typhoon

Typhoon No.	Nearest Distance from Core	Average Rainfall amount
7	103km (West)	173mm (8/15 00:00 to 8/18 06:00)
11	111km (East)	166mm (8/19 07:00 to 8/22 00:00)
9	53km (East)	104mm (8/22 01:00 to 8/23 09:00)
10	351km (West)	236mm (8/28 13:00 to 9/1 23:00)

Figure 24 shows that accumulative rainfall is much more than typhoons in other years. Figure 25 shows that inflow discharge is especially more than other years. Such phenomenon caused by the

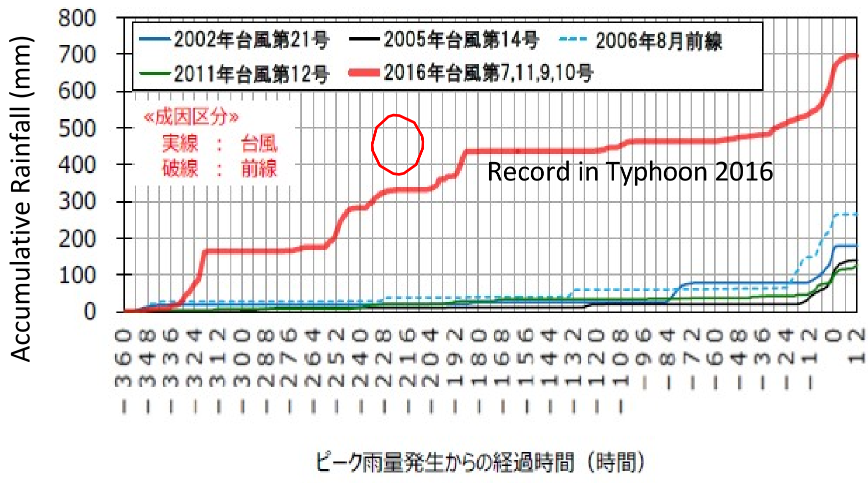

Figure 24 Past record of hourly Accumulative rainfall

rainfall by continued typhoon attacks such as Typhoon No.7, 11, 9 saturated the topsoil in the catchment, thereby causing rainfall to flow directly into the river system.

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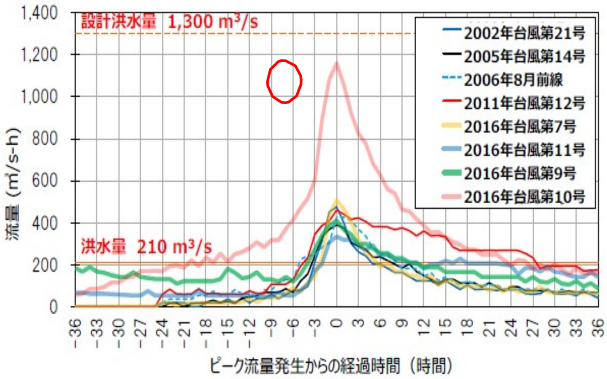

Figure 25 Past record of hourly Inflow to the reservoir

7.4. Conclusion

While the reservoir for the power supply dam does not provide flood control, it has a duty to maintain the conventional river function of the river. In the case of a dam with a large reservoir, "Late Gate Operation" (LGO) is followed to control outflow after a pre-determined time so that flood arrival time can be delayed. In the case of Nukabira Dam, the volume for LGO. is set as the volume between primary outflow water level and surcharge water level in Fig.-6. Expansion of LGO time effect is as shown in Figure 26, which can decrease outflow discharge, while outflow discharge is generally outflow whose inflow discharge is maximum. To accomplish this purpose, reservoir water level should be kept lower to absorb flood inflow discharge in the reservoir

LGO start time is determined by rainfall prediction information and typhoon location information. Comparison of predicted value of rainfall by "GPV" and rainfall record is as shown in Figure 27. GSM value fits with lead time of rainfall better, while MSM value fits with rainfall record better. Based on these findings, gate is to be operated in two stages, in which the first operation is based on GSM, and the second is based on MSM. Based on various analysis, LGO operation rule was defined as shown in Table 5 LGO rule.

Table 5 LGO rule

Water Level Lowering	Predicted Accumulative Rinfall in		Typhoon Location Forecast
First Stage	GSM (84hours) More than 100mm		
	or		
	More than 30mm	and	West side of Nukabira Dam Pass within

Second Stage	MSM (39hr) More than 100mm		
	or		
	More than 40mm	and	West side of Nukabira Dam Pass within

If LGO rule is adopted for operation on the flood in August, 2016, simulation result becomes as shown on Figure 28, where the maximum outflow can be decreased by 500m^3/s-h than under the present rule, and there still remains surplus storage for the water level to limit outflows.

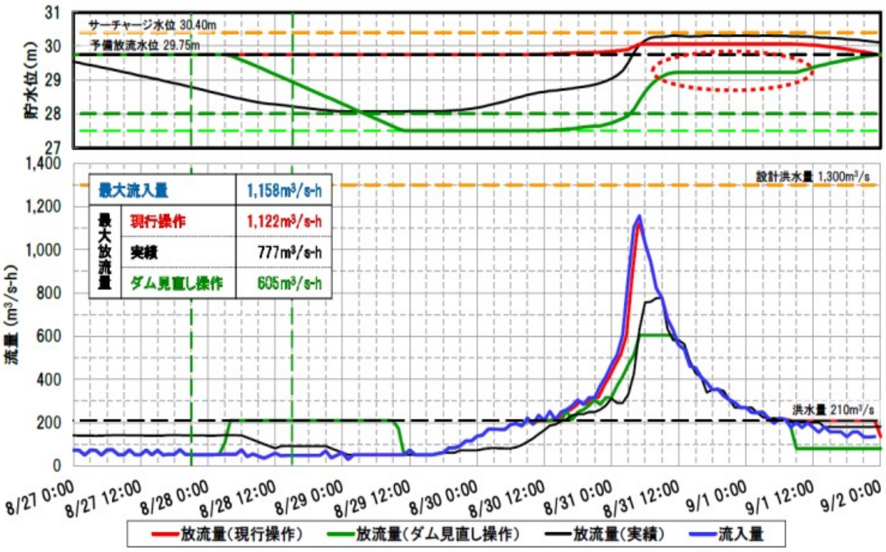

Figure 26 Outflow Discharge Decrease Effect in Hydro Graph. Present Operation, LGO rule, Actual Record, Inflow

8. Flood-forecasting and flood management in Skiensvassdraget, Norway

Ånund Killingtveit[1], Knut Alfredsen[1], Trond Rinde[2], Nikolai Østhus[3], Paul Christen Røhr[4]

[1] Department of Civil and Environmental Engineering, NTNU, 7491 Trondheim, Norway

[2] Norconsult AS, [3] Øst-Telemarken Brukseierforening (ØTB), [4] NVE

8.1. Introduction

Flooding is a serious threat to many communities along the lower reaches of the Skienselva watercourse, for example in Heddal, Notodden, Gvarv, Ulefoss and in Skien. The largest floods are usually caused by a combination of snowmelt and heavy rainfall. Observations since 1850 reveal that damaging floods have been gradually reduced during the last century, due to the construction of many large hydropower reservoirs. The reservoirs have a limited capacity, however, and large floods cannot always be completely controlled by the existing reservoirs, so that considerable flooding may still occur. One strategy may be to pre-release water before the flood-peak occurs, in order to keep a free buffer in the reservoir and thereby reduce the risk of flood spill at peak flow and reduce flooding in downstream areas. This operation requires good forecasts for rainfall and inflow, in order to avoid releasing too little or too much water and the risk of lost power generation. If hydropower reservoirs are used to reduce flooding, constraints on reservoir operation may lead to less optimal use of water for hydropower generation, reduced power generation and economic losses. In order to help decision makers balance risks and benefits during such events, a flood warning system, Telemark flood forecasting model (FMTV), has been developed for the most flood-prone part of the watercourse. FMTV integrates several data sources and computer models into one system to help optimize the operation of upstream reservoirs, prepare flood forecasts for downstream areas, taking into account the hydraulics of lakes, rivers and reservoirs and operational characteristics for gates and hydropower plants. Results from different models operated by separate organizations must be integrated in near real-time, in order to issue forecasts and prepare plans for actions both for reservoir operation, issuing flood warnings and possibly planning rescue and evacuation operations.

8.2. Topography, climate and hydrology

The Skienselva watercourse is located in the southern part of Norway, Figure 1 It has a total catchment area of 10772 km^2 and is located almost entirely within the county of Telemark. It is also often referred to as the Telemark watercourse, "Telemarkvassdraget" and it is partitioned in 5 sub-catchments. The catchment is dominated by mountains, with a median elevation is 920 masl, and 70% is over 650 masl. The runoff regimes is nival, with low flow during a long winter, and high flow during spring and summer, dominated by snowmelt. The natural flow regime has been changed dramatically by the regulation in large hydropower reservoirs. Storage during spring and release from these during winter has changed the annual flow regime completely.

Figure 27 Sub-catchments in the Skienselva watercourse (”Skiensvassdraget”)

8.3. The hydropower system

Hydropower development started early in this region. Already in 1885, the first hydropower plant was installed at Laugstøl Brug in Skien. New and much larger hydropower plants were built for industrial power use at Notodden and Rjukan. Steady water supply was crucial and the first regulation dams were constructed at Tinnsjø and Møsvatn from 1901 to 1906. By 1920, three of the world’s largest hydropower plants (at that time) were found in the East-Telemark watercourse: Svelgfos (28 MW ,1907), Vemork (108 MW, 1911) and Såheim (120 MW, 1915). Later came Frøystul (45 MW, 1926), Mår (200 MW, 1948) and several other power plants. Today, there are 11 plants >10 MW in Tinnvassdraget, totalling 896 MW and with an annual generation of 4759 GWh.

Most of the hydropower development in the rest of the Skienselva catchment came after Second World War and up through the 1970’s. Most important is Tokke/Vinjevassdraget where the largest plants are: Tokke (480 MW, 1961), Songa (140 MW, 1964) and Vinje (375 MW, 1965). Today there are 10 powerplants > 10 MW with a total capacity of 1210 MW and an annual generation of 5179 GWh. Hjartdøla (150 MW, 1958) in Hjartdal/Tuddalvassdraget, Sundsbarm (118 MW, 1970) in Bø/Seljordvassdraget and Skotfoss (23 MW, 1953) and Klosterfoss (10 MW, 1969) below Norsjø are the remaining large hydropower plants.

8.3.1. Reservoirs

Some small reservoirs were constructed already before 1900, mainly for easier the timber transport and for canal boats, but it was the development of hydropower from 1900 onwards that created an increasing need for storage in reservoirs. Initially, the lakes Tinnsjøen and Møsvatn were most important. One can identify two important construction periods, 1905-1920 with an increase of 1116 Mill.m^3 and 1955-1970 with an increase of 2400 Mill. m^3. The first period was during the pioneering development of hydropower and fertilizer industry at Notodden and Rjukan, the second was dominated by the huge Tokke-Vinje development. This increase in reservoir storage was of course most important for hydropower generation, but also had a significant impact on reducing floods.

8.4. Floods and the impact from hydropower reservoirs

The four large sub-catchments (Figure 29) all converge into lake Norsjø, which is hydraulically linked (by sub-critical flow) to lake Heddalsvatn. The elevation difference is small, and high inflow to Norsjø, for example from subcatchment Tokke-Vinje may give a backwater effect in Lake Heddalsvann and increased flooding at Notodden and Heddal, even if the local inflow to Heddalsvann is not very high. Norsjø-Heddalsvann may be controlled to some degree by the power plant and flood-control gates at the outlet at Skotfoss, but at high inflows the impact is small. Outflow from Norsjø goes to Hjellevatn in the middle of Skien. Rising water levels in any of these three may threaten agricultural and inhabited areas.

The most flood-prone areas are found close to the three downstream lakes Heddalsvatn, Norsjø and Hjellvatn. Before 1900 there were frequently very high water levels and severe damage in Skien and around Nordsjø, for example in 1860, 1872, 1879 and 1892With increasing capacity in hydropower reservoirs such events became less frequent, though not completely absent.

The flood in 1927 was the largest in historic times, possibly a 500 year event, but it would probably have been even more devastating without the reservoirs in Møsvann and Mår which held back much of the flood and reduced the flood further downstream. Even if the reservoir capacity then was less than a third of the current capacity, extreme flood levels gradually became less frequent in the years from 1910 up to the 1950’s. From 1955 and up to 1970 many large reservoirs were created, in particular in the West-Telemark catchment as part of the large Tokke-Vinje hydropower scheme. The impact on flood levels in Norsjø is consistent: the annual maximum flood water levels in Norsjø are typically now more than one meter lower than before 1900. In a study by NVE (Petterson, 2001) a flood-frequency analysis was carried out for Norsjø and Hjellvatn as part of the establishmet of flood-zone maps for this region. Figure 30 provides a summary of the findings, flood-frequency diagrams based on observations from 4 different periods during the years from 1850 to 2015

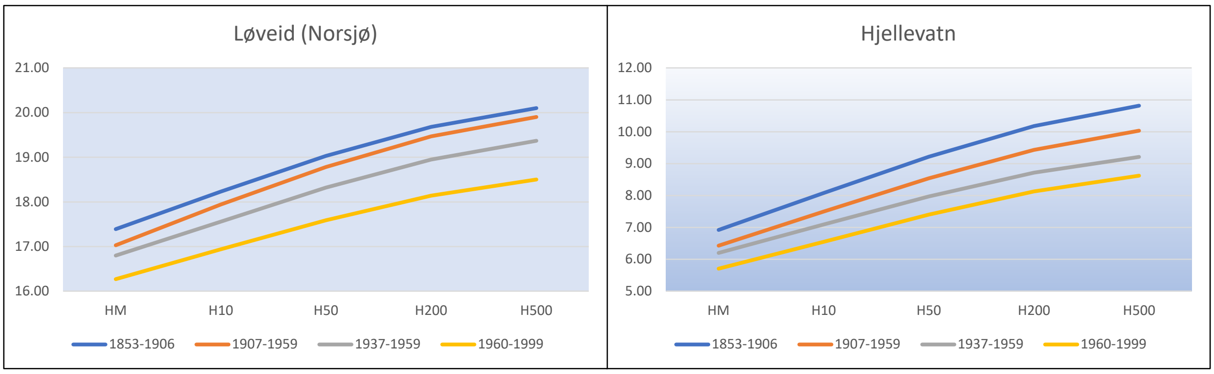

Figure 28 Flood-frequency diagrams for annual maximum water levels in Norsjø and Hjellevann for four different periods: 1853-1906, 1907-1959, 1937-1959, 1959-2000

The graphs show water levels (m) for: Average flood (HM), 10-year (H10), 50 year flood (H50), 200 year flood (H200) and 500-year flood (H500). One can clearly see that flood levels have decreased as reservoir capacity has been increased (Figure 31).

In Nordsjø the 10-year flood has been reduced from 18.23 m to 16.94 m – a reduction of 1.29 m. The 500-year flood is reduced by 1.6 m. For Hjellevann in Skien the reduction is even more, 1.53 m for a 10-year flood up to 2.20 m for a 500 year flood.

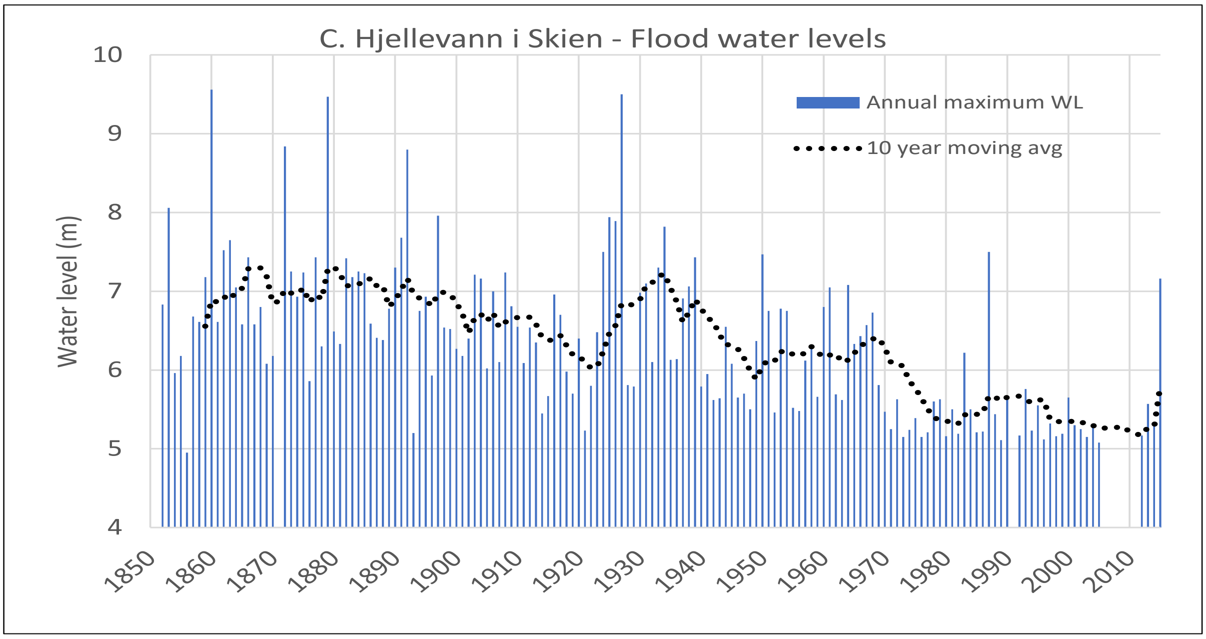

Figure 29 Annual maximum flood levels in Hjellevann in Skien

8.5. Flood management in Skienselva

The examples given show that the hydropower system in Telemark with its large reservoirs have had a significant impact on the flood regime and reduced flood water levels by typically 1-2 metres along the watercourse from Notodden to Skien. The new flood regime, though much lower than in the natural state, quickly becomes the new norm in the public view, with increasing pressure on land areas close to the river, which were previously not used. Since floods will continue to occur and probably create damage, there will easily be a risk of criticism – "Why did you not manage to avoid this flood?".

The operation of this very complex hydropower system is performed by 5 different and independent organizations, one for each of the 5 main sub-catchments (Figure 29). To coordinate reservoir operation during floods and other critical events, a special "Beredskapsgruppe" (Emergency preparedness group) has been set up, consisting of representatives from the 5 power plant owners and with the CEO at "Øst-Telemark Brukseierforening", Nicolai Østhus as leader. This group coordinates the flood management by preparing forecasts, evaluating operation strategies for power plants and reservoirs, calculating risks and finally deciding on what is the optimal operation. An important task is also to coordinate communication with other organizations like police, road authorities, fire-and rescue service, municipalities and NVE.

In order to be able to make timely forecasts and quantify consequences of different possible operational scenarios, a model system was designed, developed, implemented and tested by the authors of this paper. This model is called "FMTV - Flommodell for Telemarkvassdraget. The first version was installed in 2003 and has been in operation since. New functions and improvements were added through the following years, based on experience during many challenging flood events, as in 2015 when the tropical storm "Petra" brought record amounts of precipitation and created a large flow event, the second highest since 1950 in Hjellevann.

8.6. Summary and conclusions

Skiensvassdraget is a complex river system, both regarding topography, hydrology and hydraulic connectivity. Water is a vital source of energy from the large hydropower system, with an annual generation of almost 10 TWh, but it can also be a threat due to large floods. The many large hydropower reservoirs are important for securing a stable power generation, but has also been important for reducing floods. Today flood levels in the most flood-prone areas have typically been reduced by 1-2 m. In a study of the economic benefits of avoided flood damage by hydropower reservoirs, it was estimated that in the whole Skiensvassdraget the discounted value could be in the order of 200 million USD (Multiconsult, 2018).

Still, it may sometimes be difficult to achieve optimal results for both goals at the same time. For power generation, it is best to keep reservoirs as full as possible, for flood reduction it is the opposite. But keeping a buffer for flood control may, besides reducing floods downstream, also reduce flood spill from the reservoir and thereby increase generation. Managing reservoir operation often means balancing two seemingly contradictory goals under the uncertainty of future weather and hydrology. Accurate prediction of rainfall, snowmelt, runoff and changes in reservoir contents is vital for making good decisions, and for balancing benefit versus cost. In order to fully understand the consequences of the planned operation, it is useful to run computer simulations to study the effect on both flood and hydropower generation.

A flood warning model for the Skienselva river system has been developed and used for flood management simulations and has proved to be a useful tool. The model combines data from various distributed sources to provide a basis both for model control and updating and for the future prognosis. The experiences from operational use of the model shows challenges in synchronizing data sources and getting a seamless transfer of data, but also the potential of computing with distributed data sources.

Today, we have much better possibility to handle flood events than before, due to:

- Improved monitoring of reservoirs and access to hydrological and meteorological data
- Better meteorological forecasts for precipitation and temperature up to 10 days ahead
- Access to a model for simulating expected flow and water levels in rivers and reservoirs with reference to the FMTV model system
- Improved coordination between the four different power companies and ØTB
- Improved coordination with NVE and other public authorities
- Higher awareness of flood risk and the need to reduce flooding amongst operating personnel

8.7. References

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9. Schaffhausen, Switzerland

By Klaus Jorde, KJ Consult

The „Rheinkraftwerk Schaffhausen" in Switzerland is a run-of-river hydropower plant on the river Rhine with a capacity of 26 MW generated by 2 Kaplan Turbines and an annual generation of 173 GWh. The rated discharge is 500 m^3/s. The mean annual flow of the Rhine is 370 m^3/s and the effective head of the power plant is around 7 m, depending on the discharge. The upstream water level is kept constant whereas the tailwater level is fluctuating with the discharge. The backwater of the power plant reaches about 10 km upstream just below the outflow of Lake Konstanz (Bodensee). This natural unregulated lake has a surface area of 536 km^2 and a volume of 48 km^3. The volume of the lake exceeds the annual runoff of the Rhine river volume more than four times and serves as a natural flood retention reservoir. Flood flows are therefore rather small and reached a maximum of 1200 m^3/s in 1999 and the spillways are designed for a discharge of 1250 m^3/s.

Before the power station was built in the 1960s, an old dam, the so called Moser-Dam existed. It was built on to of a natural bedrock outcrop creating rapids. Before the Rheinkraftwerk Schaffhausen was built the lower part of the city of Schaffhausen, upstream of the natural rock outcrop and the Moder-Dam, particularly the "Fischerhäusern" quarter, was flooded regularly, basically every year. This threat has been banned completely ever since the new power plant was built and commissioned in 1964.

The power plant was built on a 4 m thick foundation slab and the upper part of the natural outcrop was blasted away before the new foundation was poured. The gated spillways have a much higher conveyance capacity as compared to the old river bed with its natural rock outcrop had at the same water level elevation.

Figure 30 https://de.wikipedia.org/wiki/Kraftwerk_Schaffhausen, a view of the Rheinkraftwerk Schaffhausen looking from downstream.

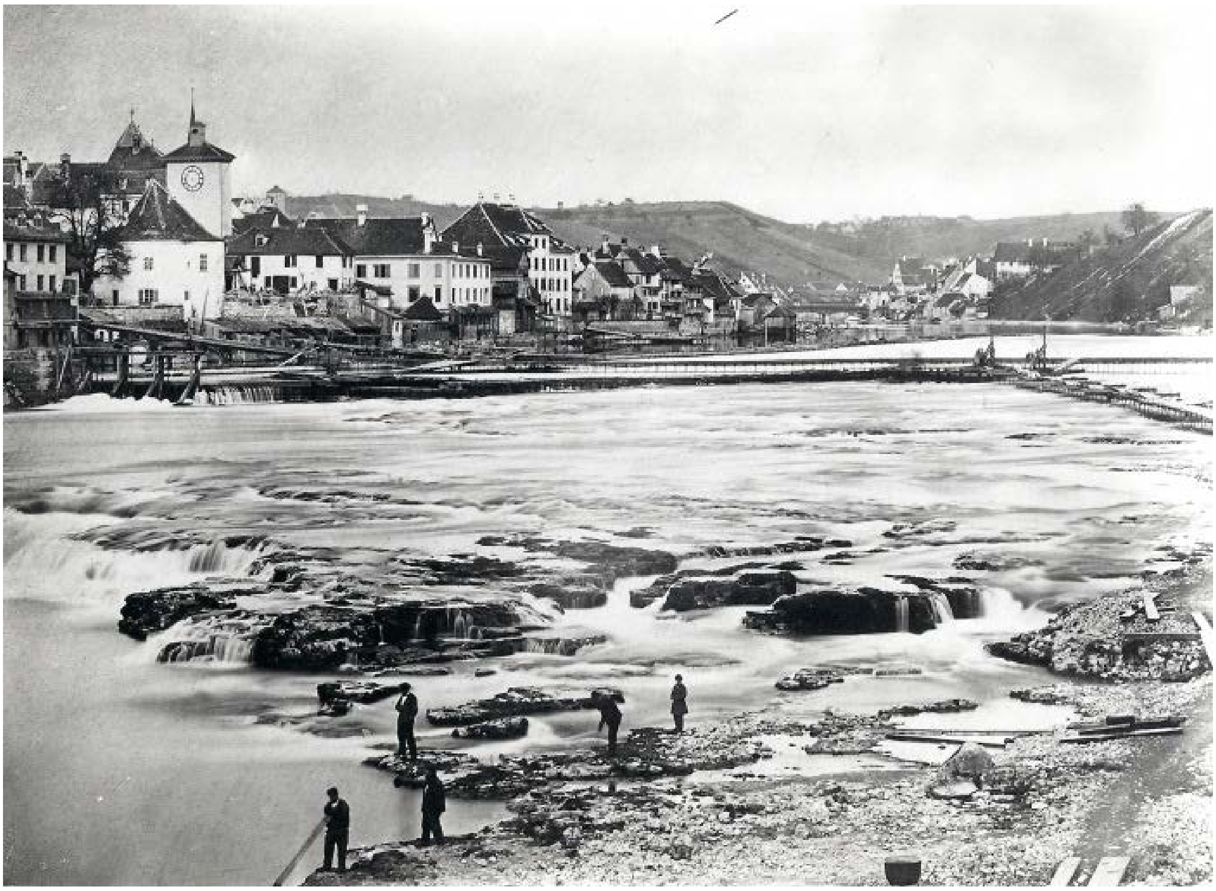


Figure 31 http://www.schaffhausen-foto-archiv.ch/moserdamm.html a historic picture of the old Moser-Dam and the natural rock outcrops on which it was built.

In 2011 the owner of the power plant conducted a study on the possibility of raising the level of the impoundment upstream of the weir by 20 to 30 cm in order to increase the annual power generation by approximately 5%. The project is opposed for environmental concerns and because some adaptive measures would be necessary along the banks to protect buildings and basements (which were regularly flooded before the power plant was there).

10. Minerve System, Upper Rhone Valley, Switzerland

By Anton Schleiss, EPFL

10.1. Overview of the MINERVE system

MINERVE[10] flood forecast system was developed since 2002 to reduce the flood risk in the Upper Rhone River basin in the Cantons of Vaud and Valais in Switzerland. This system aims to optimize flood management by making, when available storage volumes in the hydropower reservoirs are not high enough for flood routing, pre-releases based on weather forecasts taking advantage of the numerous existing high head power schemes and reservoirs.

The authors were both on the development team that led the research to establish this system. Professor Schleiss has been responsible for the research development team since 2002. Dr Garcia has been involved in the project since 2005 first in the framework of his PhD thesis and then from 2011, as the head of the operational team at CREALP, created the same year.

10.2. The basin of the Upper Rhone River

The Upper Rhone River basin (Fig. 1) is located in the Swiss Alps, upstream from Lake Geneva. It covers a surface of 5’524 km^2, including 658 km^2 of glaciers, and is characterized by high mountains with elevations varying from 372 to 4’634 m a.s.l. (meters above sea level). The total length of the Rhone River, from its source at the Rhone Glacier over 2’200 m a.s.l. to the Lake of Geneva at 372 m a.s.l., is around 165 km. The average year discharge between January 1st 1980 and January 1st 2014 at Porte du Scex, outlet of the basin, was 189 m^3/s, and the highest discharge 1’358 m^3/s, measured on October 15th, 2000.

Many hydropower schemes with large reservoirs are located in the watershed, strongly influencing the hydrological regime of the river network. The reservoirs have a total storage capacity of 1’195 Mio m^3 and a total equipped discharge of more than 500 m^3/s in all power plants. The main function of the reservoirs in the Rhone River basin is for hydropower generation. At the end of the summer, when the reservoirs are almost full and the flood risk is highest, they are also used for flood control purposes within the MINERVE flood control system.

[10] MINERVE is the acronym for « Modélisation des Intempéries de Nature Extrême dans le Rhône Valaisan et de leurs Effets », i.e. Modelling of extreme rainstorm events in the Rhone River and their effects

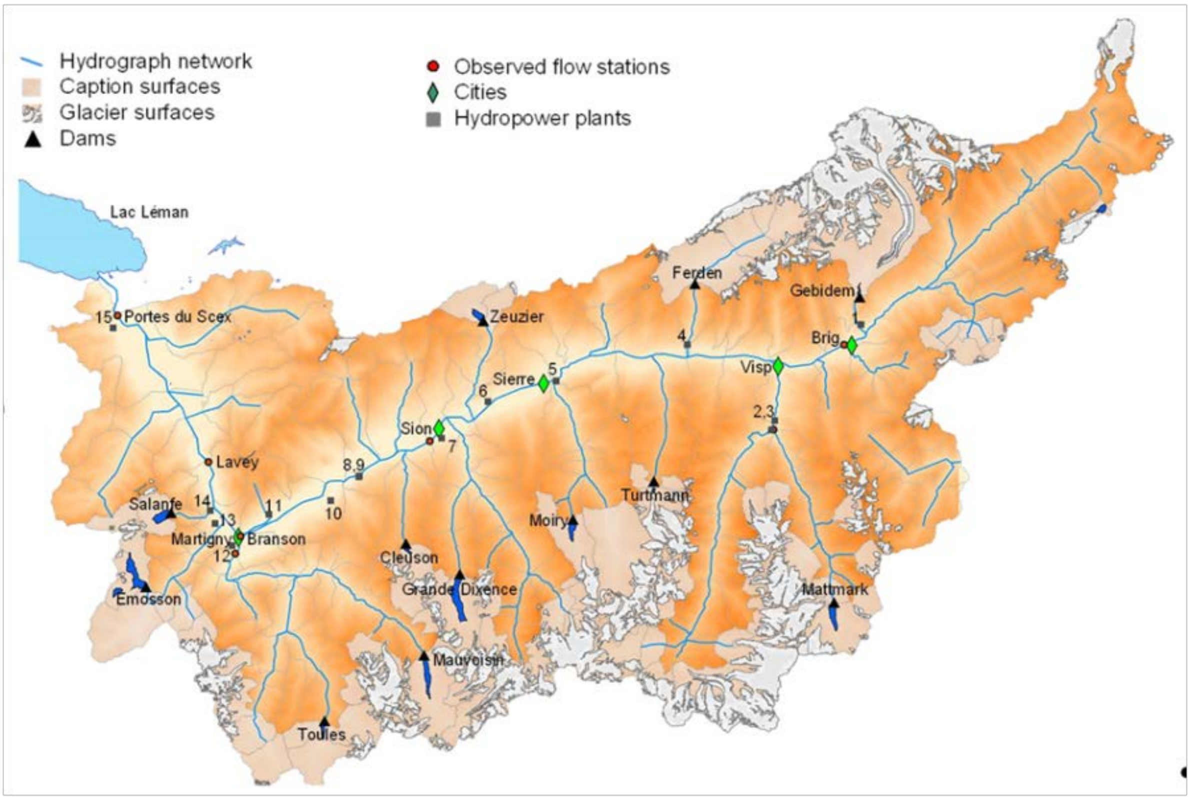


Figure 32 The Rhone River basin in Switzerland upstream from the lake of Geneva

10.3. Hydrological forecasts

The MINERVE system is able to provide hydrological forecasts all over the Upper Rhone catchment area based on meteorological forecasts.

The system makes use of the deterministic meteorological forecast COSMO-7, which is driven by the global model ECMWF (European Centre for Medium-Range Weather Forecasts) and covers most of Western and Central Europe. Deterministic COSMO-2 forecast is also used. It is driven by COSMO-7 (for the initial and boundary conditions) and covers, with a finer resolution, the Alpine region with Switzerland at the center. Both offer the benefit of short range forecasting (one to up to three days).

Furthermore, the probabilistic forecast COSMO-LEPS (Limited-area Ensemble Prediction System) is used with 16 members of high resolution for central and Southern Europe. Initial boundary conditions are representative members of the ECMWF ensemble. The purpose of COSMO-LEPS is to improve the early and medium-range predictability of extreme and localized weather events, particularly when orographic and mesoscale-related processes play a crucial role.

The characteristics of the MeteoSwiss meteorological forecasts are presented in Table 6. COSMO-7 is operational for the MINERVE project since 2006, COSMO-LEPS since 2008 and COSMO-2 since 2009

Table 6 Characteristics of the different COSMO models of MeteoSwiss

	COSMO-LEPS	COSMO-7	COSMO-2
Forecast type	Probabilistic (16 members)	Deterministic	Deterministic
Boundary conditions	ECMWF	ECMWF	COSMO-7
Spatial resolution	7 x7 km	6.6 x6.6 km	2.2 x2.2 km
Vertical levels	40	60	60
Lead time	132 h	72 h	24 h
Temporal resolution	3 h	1 h	1 h
Update	24 h	12 h	3 h

These forecasts provide a high resolution, required in the Alps because of the high topographic gradients ranging typically from 400 to 4'000 m a.s.l. The MINERVE hydrological model of the catchment area follows a semi-distributed approach. The basin is split into 239 sub-catchments which are further sub-divided into 500 m elevation bands, for a total of 1380 bands. For each elevation band, precipitation, temperature and potential evapotranspiration are calculated from the numerical meteorological data (observed or predicted) to calculate related processes accurately, such as saturation, evaporation, snow and glaciers melt or runoff. Hydrological forecasts are then established at any main point of the basin (e.g., Figure 35).

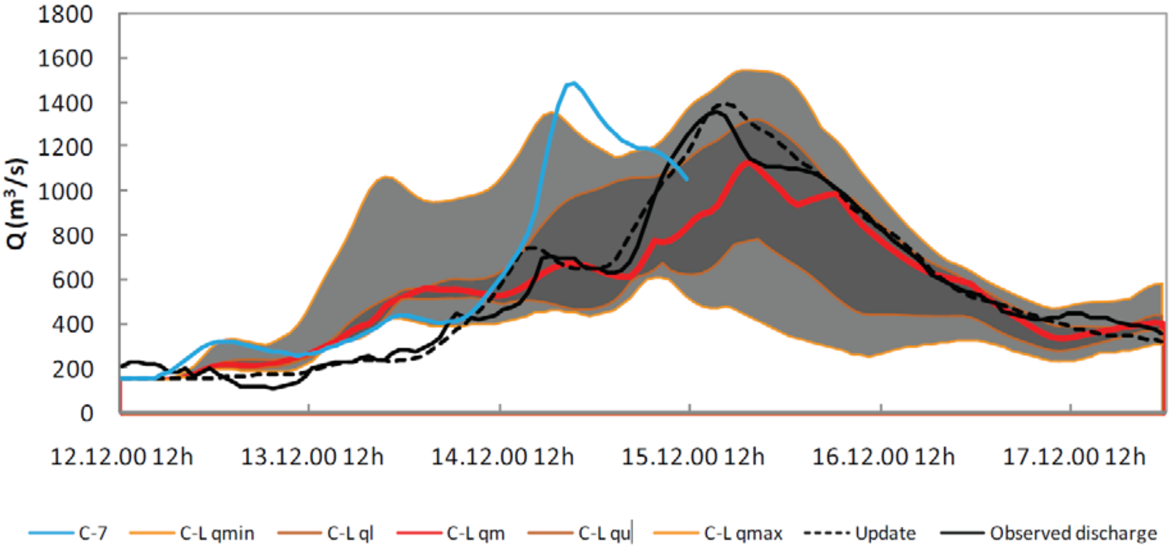


Figure 33. Hydrographs at Porte du Scex obtained by deterministic and probabilistic hydrographs. C-7 represents COSMO-7 and C-L COSMO-LEPS represented by the median q_m, the upper q_u and lower quartile q_l as well as by the minimum q_{min} and maximum discharge q_{max}. Update symbolises the simulations with meteorological observations and the update of the initial conditions of the hydrological model.

10.4. Decision Support system

In order to manage the multi-reservoir system during floods in an optimal way and to limit or avoid flood damages, the decision support system (DSS) called MINDS (MINERVE Interactive Decision Support System) was developed for real-time decision making based on the hydrological forecasts. This tool defines preventive operation measures for the hydropower plants such as turbine and bottom outlet pre-releases able to provide optimal flood routing in the reservoir during the flood peak. The goal of

MINDS is then to retain the inflowing floods in reservoirs and to avoid spillway and turbine operations during the peak flow, taking into account all restrictions and current conditions of the river network. Such a reservoir management system can therefore significantly decrease flood damages in the catchment area.

This system is based on information about potential damages for scenarios corresponding to certain forecast members and on pre-defined discharge thresholds at check points as well as on potential costs according to preventive operation strategies. The large scope of this information requires a DSS able to identify and solve the problem globally.

Nevertheless, the flooding problem is also complex when using hydropower schemes for flood management because the possible loss of energy production must be avoided or compensated. Preventive operations for increasing storage capacity (before flood peaks) can lead to energy losses for operators and, consequently, to economic losses which should be considered in terms of producing a fully performing DSS.

The hydraulic simulation model, implemented in MINDS, includes 21 reservoirs and 24 hydropower plants. They are regrouped into 10 independent hydropower groups (i.e. without any interconnections), which can be independently managed.

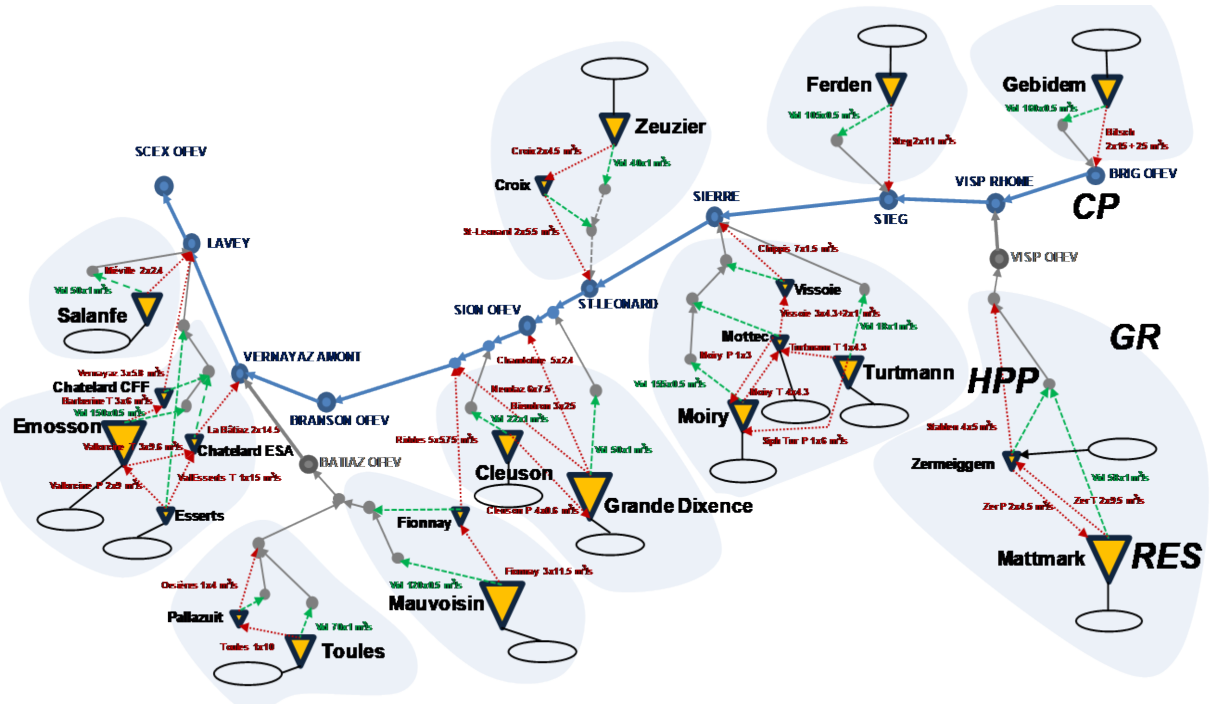


Figure 34 Functionality scheme of the complex hydraulic model with: inflows (ovals); reservoirs, RES (triangles); bottom outlets and spillways (square dotted lines); hydropower plants, HPP (round doted lines); main river network (solid lines); groups, GR (shading zones); and check points, CP (big circles).

The inputs of the model are computed hydrographs (from hydrological forecasts) at check points as well as the inflow and current water levels of the reservoirs. The constraints are installed capacity of turbines and pumps at the hydropower plants, the available volume in the reservoirs, the capacity of the bottom outlets, the reservoir spillway characteristics and the emergency rules. The hydraulic simulations take into account economic losses including the expected damages caused by the flood and the potential costs for the hydropower plants preventive operations.

The suggested preventive operations to the hydropower plants' operators are defined by the starting and ending time of the turbines, pumps and bottom outlet operations, respecting constraints of the river system.

Different objective functions are defined by multi-attribute decision making (MADM) approaches and can be chosen by the decision maker. The MADM methods calculate the loss function based on damages and costs of preventive operations taking into account the deterministic or the probabilistic forecast and the weight of each one of its members (i.e. particular forecast).

Once a check point at the outlet of a considered catchment area is selected by the decision maker, the objective function of the system is defined in order to minimize the combination of expected damages and energy losses upstream. The selected check point is usually identical to the outlet of the entire Rhone River catchment area, Porte-du-Scex. The optimization of the objective function gives then the optimal sequences of turbines, bottom outlets and pumps operations in the considered hydropower plants which minimize the global losses. Both, the expected damages and the energy losses are expressed as monetary values for comparison reasons. If no damage is expected in the catchment area, the system logically does not propose any preventive operation (pre-release).

Considering the energy production costs related to the preventive operations, they simultaneously result in a maximization of the use of the reservoir capacity over the optimization period. The reason is that preventive operations are only suggested if they reduce the expected damages. The preventive operations (i.e. the resolution of the objective function) are either optimized in a global way (all hydropower groups at the same time) by using the SCE-UA (Shuffled Complex evolution – University of Arizona) algorithm or independently group by group by using the Greedy algorithm. The purpose is to deal with the concept of risk and to transmit it to the end users.

When using COSMO-LEPS, the methodology avoids probabilistic evaluations and compares the set of expected damages before and after the optimization. The decision-maker has to be involved in operating and understanding this new probabilistic concept currently used in applied sciences.

10.5. Validation of the MINERVE System by simulation of the October 2000 flood.

A “real time” simulation was undertaken of the October 2000 flood to examine the benefits of flood forecasting using the MINERVE system. The results are presented in Figure 37. This Figure does not present all the steps of the hydro-meteorological forecasts from COSMO-LEPS and COSMO-7, but only the final hydrograph and the preventive operations achieved with them at the end of the period, with the aim of knowing the real consequences of the preventive operations proposed by COSMO-LEPS and COSMO-7. Therefore, three simulations with preventive operations are presented in the graphic:

- First, a simulation with preventive operations obtained from the perfect forecast (i.e. with observed precipitation and temperature),
- Second, a simulation with preventive operations obtained from optimization with COSMO-LEPS during the entire event.
- Third, a simulation with preventive operations obtained from optimization with COSMO-7 during the entire event.

Even having hydrological forecasts from COSMO-2 available, this forecast does not leave much maneuver margin to make use of preventive operations. Thus, it was not used in MINDS.

The COSMO-LEPS (probabilistic) and COSMO-7 (deterministic) forecasts provided comparable results. The results were slightly better for the probabilistic forecasts. Furthermore, the results of this simulation exercise demonstrated that knowledge about the range of hydrological forecasts provided by COSMO-LEPS facilitates the decision-making tasks (pre-release strategies) as well the risk assessment (expected flood damages and energy generation losses).

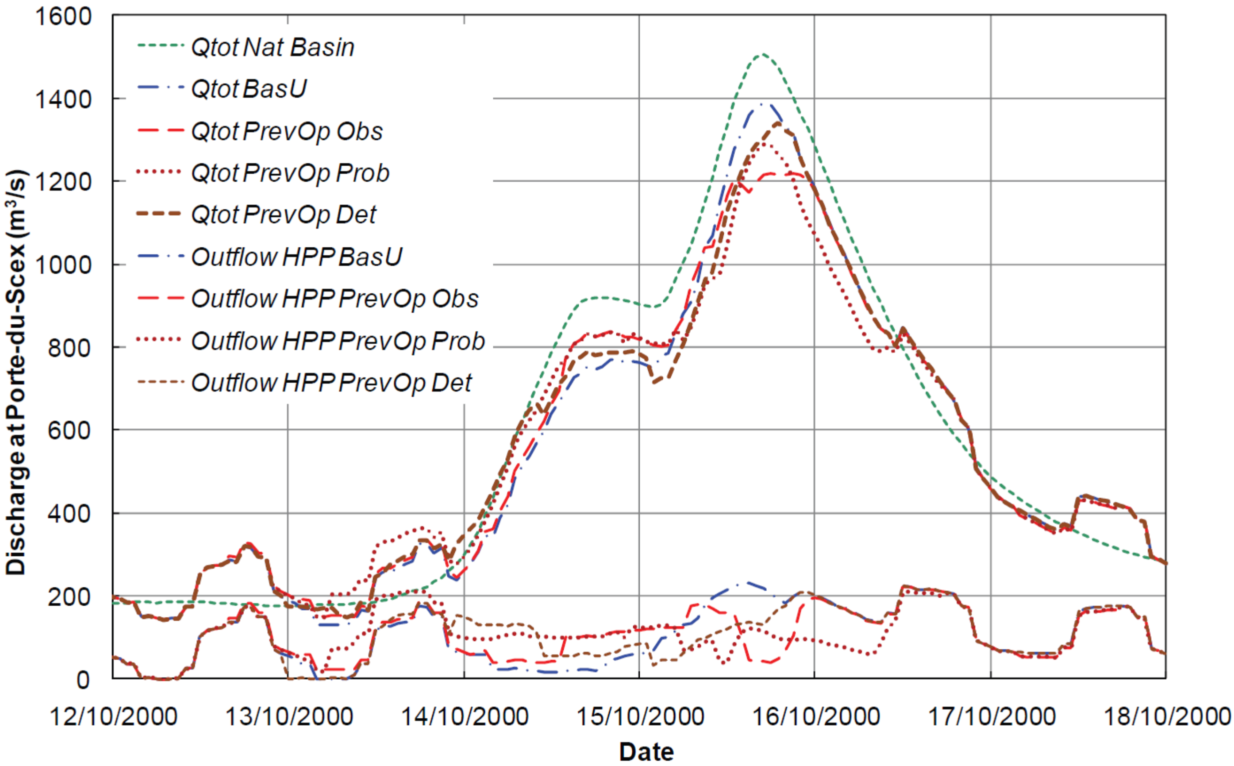


Figure 35 Hydrographs with optimization using hydrological forecasts of the October 2000 flood (starting on October 11, 2000 at 12 h with COSMO-LEPS and on October 12, 2000 at 00 h with COSMO-7). at the outlet of the basin, Porte-du-Scex. “Qtot Nat Basin” corresponds to the hydrograph from the natural basin, “Qtot BasU” to the hydrograph of the equipped basin simulated with Business as Usual operations, “Qtot PrevOp Obs” to the hydrograph from the optimization with a perfect forecast, “Qtot PrevOp Prob” to the hydrograph from the optimization with COSMO-LEPS and “Qtot PrevOp Det” to the hydrograph from the optimization with COSMO-7. “Outflow HPP BasU” represents the summation of the outflows from all hydropower plants calculated with Business as Usual operations, “Outflow HPP PrevOp Obs” the outflows from the optimization with a perfect forecast, “Outflow HPP PrevOp Prob” the outflows from the optimization with COSMO-LEPS and “Outflow HPP PrevOp Det” the outflows from the optimization with COSMO-7. “Inflow HPP” represents the total inflows to the reservoirs of the system.

When optimizing the flood with meteorological forecasts (COSMO-LEPS and COSMO-7), the preventive operations could be updated (with last available meteorological measurement and real reservoir levels) every time a new forecast was provided.

In a general way, the increase of the forecast period (e.g. even up to 10 days if the circumstances warrant it) could be also of worthwhile interest to provide better foresight of the whole flood event. In fact, only hydrological forecasts including the whole flood event can provide optimal results. In contrast, if only observed rainfall or shorter-range forecasts are relied on for decision making, this could lead to increased discharges at the time of the flood peak which produces sub-optimal results. Since in such cases the entire duration of the flood event is not fully taken into account, the proposed solutions can underestimate the pre-releases due to aggregated potential high inflows produced in the later part of the flood which have not been taken into account as an input of the system.

10.6. The operational system

The objective of the operational system implemented in the Canton of Valais is to provide hydro-meteorological information to improve flood management in the Upper Rhone River basin. To achieve this task, a cluster for flood forecasting and management was created at the Research Center on Alpine Environment (CREALP) in 2011. This multidisciplinary group is operating a real-time flood forecast system that provides hydrological forecasts at the main control points of the Rhone River and its tributaries. Based on the hydrological forecasts, automatic warnings, associated with four different thresholds at each control point, and preventive release strategies are provided to a governmental taskforce. Finally, and also based on these forecasts, the taskforce can require preventive operations by police order to hydropower schemes owners to reduce as much as possible the potential flood damages.

The implemented real-time flood forecasting system (Figure 38) is composed of: a database for hydro-meteorological data storage and real-time data transfer; a server for automatic hydrological simulation (hindcasting with observed meteorological values and forecasting with meteorological forecasts); and a website for hydro-meteorological data information, where observations and forecasts are presented through graphics and tables.

The database stores all hydro-meteorological information that it receives from the different providers. Afterwards, meteorological (precipitation and temperature observations and forecasts) and hydrological (discharge measurements) data are sent to the server dedicated to hydrological calculations.

The hydrological outputs (discharge and water level forecasts downstream at main control points) are sent to the database to be stored. Then, data are transmitted and published on a secure website which can be accessed by the governmental taskforce. This website has been created with the objective of displaying all useful information for managing floods, such as warning levels, hydrological forecasts at main control points of the Rhone River and its tributaries, precipitation forecasts over the whole basin, snow cover state and reservoirs water levels, among other information.

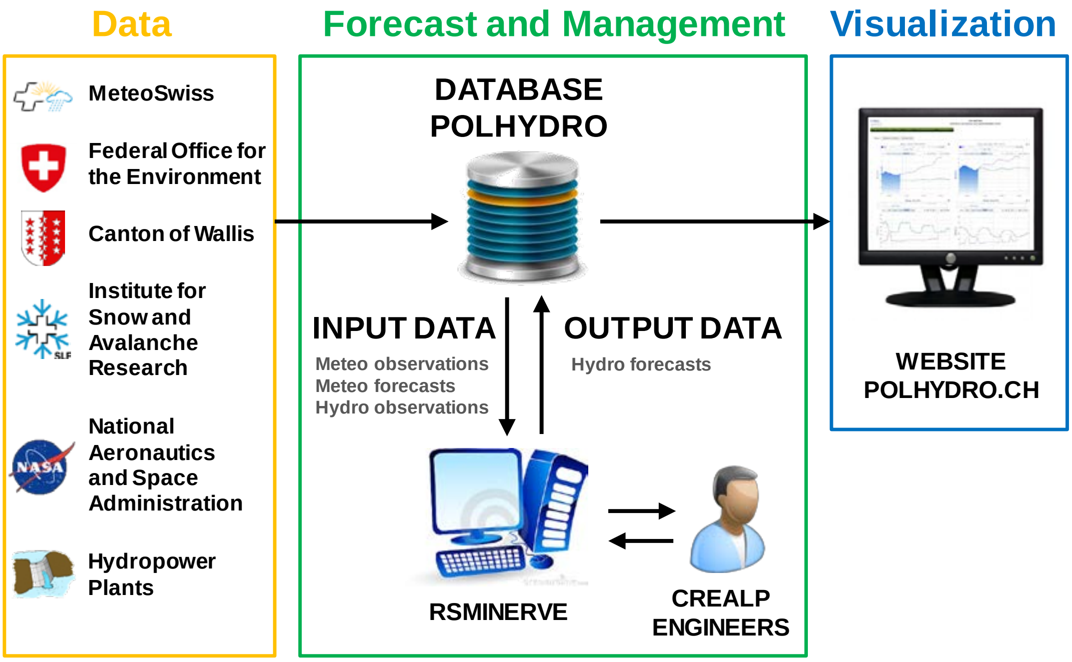


Figure 36 MINERVE operational system

10.7. Application of the MINERVE system

The system was applied for the first time in September 2006. After a meteorological warning from MeteoSwiss, the system provided hydrological forecasts for next 3 days, predicting high peak flows downstream in the basin. Current levels in reservoirs were analyzed and hydropower scheme owners were informed about the flood forecast. Finally, after several meetings of the taskforce, no preventive operations were demanded since the situation did not require it.

From then, the system provided flood warnings at different times, especially in November 2011, July 2012 and July 2013. The possibility of proposing preventive operations in July 2013 was also studied, but because the margin was sufficient, they would not be finally required.

11. Atatürk HEPP&Dam, Southeastern Anatolia Project (GAP), Turkey

Turkey Southeastern Anatolia Project (Gap) Flood Control, Drought Management Services And Climate Change Impacts

By Furkan Yardimici, Elektrik Üretim A.Ş

11.1. Introduction

In the period of 2003-2018; totally 156 billion TL investment was made in Turkey. Invesment to the total of 8,031 facilities, including 563 dams, 547 HEPPs, 303 ponds, 1,332 irrigation facilities, 207 consolidation, 236 drinking water facilities, 17 waste water facilities, 4,718 flood protection facilities, 44 animal drinking water ponds have been put into service. The irrigated area, which was 4.8 million hectares in 2002, is targeted to be increased to 6.64 million hectares by 2019 and to 6.84 million hectares by 2023. And also serious efforts are being made to fight with water floods. Within the scope of irrigation projects, Southeastern Anatolia Project (GAP), Eastern Anatolia Project (DAP) and Konya Plain Project (KOP) are continuing.

The Southeastern Anatolia Project (GAP) is one of the largest scale and costliest project of the Republic of Turkey. The project area covers 9 provinces (Adıyaman, Batman, Diyarbakır, Gaziantep, Kilis, Mardin, Siirt, Şanlıurfa and Şırnak) located in the Euphrates-Tigris Basin and upper Mesopotamia plains. These GAP provinces constitute, on average, 10.7% of Turkey in both geographical and population terms.

The objectives of the GAP include improving the level of income and life quality of the local population by utilizing the region's resources. The lands in the region generally include severe erosion, stoniness, drought problems. GAP was considered as a programme geared to developing water and land resources of the region and it was planned to launch 22 dams, 19 hydraulic power plants and irrigation investments covering 1.7 million hectares of land in the Euphrates-Tigris Basin. Within the scope of GAP, 13 Hydroelectric Power Plants (HEPP) and 18 dams have been completed so far. 53% of irrigation projects were put into operation according to the 1,060 thousand ha area, which is the Action Plan target.

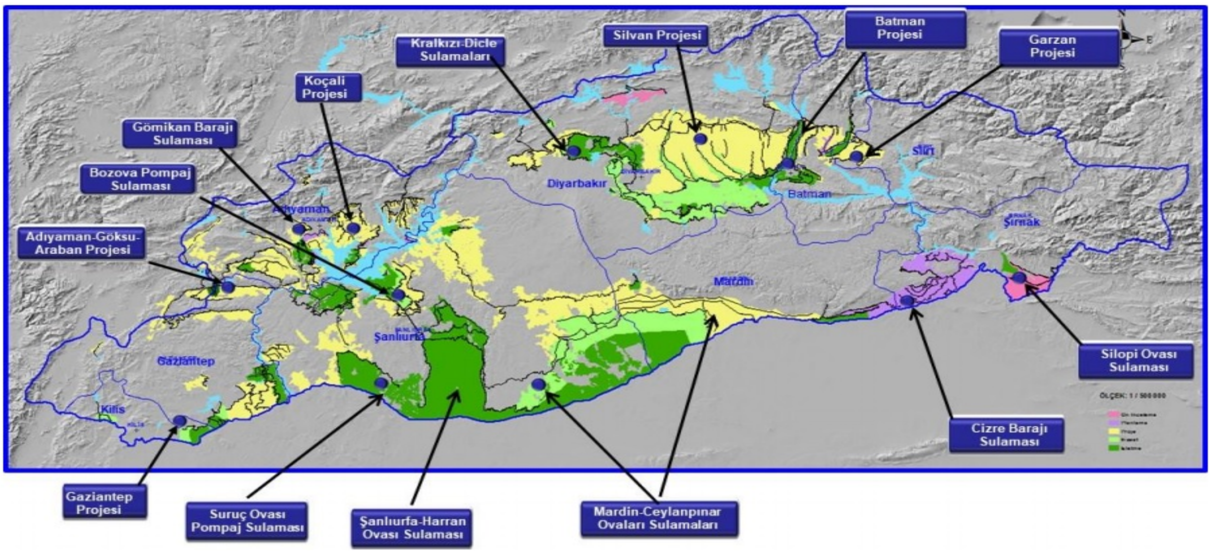


Figure 37 Euphrates-Tigris Basin

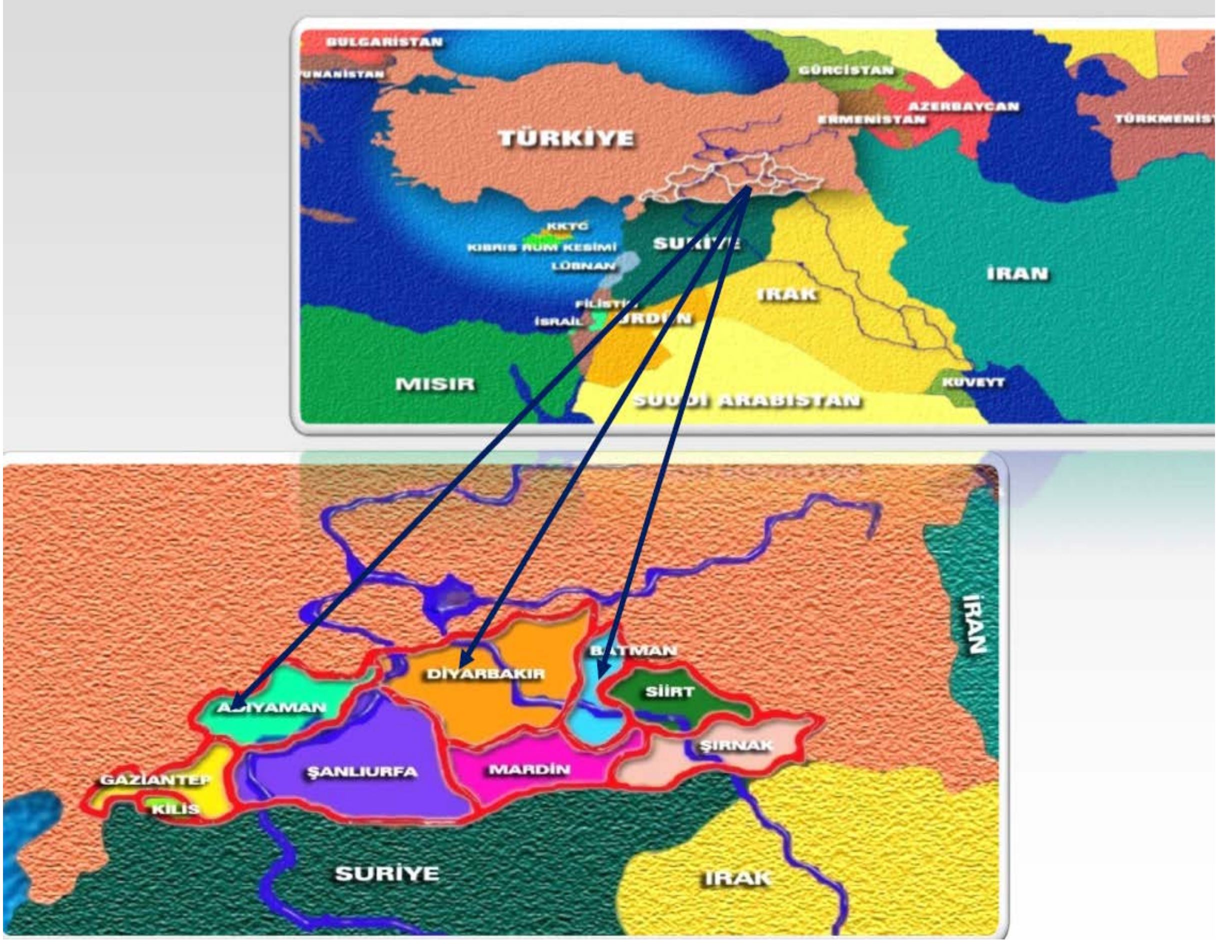


Figure 38 GAP Region

11.2. Assessment of Flood and Drought Services

The locomotive sector of the Southeastern Anatolia Region is agriculture. About 3.2 million ha of the 7.5 million ha area in the region is suitable for agricultural activities. Irrigation is one of the most important infrastructure investments of GAP. The gross area of approximately 2.1 million ha has irrigation potential. With the the project and high agricultural and industrial potential, it is expected that the economic product will increase 4.5 times and provide employment for 3.8 million people in total. With the completion of irrigation in the Region, a great increase is expected especially in the production of fresh vegetables, fruits and industrial plants (cotton, corn, soy).

Considering vegetation production before and after irrigation in the Region, only wheat, barley and lentils were planted before irrigation. With the start of irrigation, there has been a significant increase in the cultivation areas of cotton and other irrigated farming products. It is expected that irrigated farming will cause an increase of **3-7 times** income compared to dry farming and **2-4 times** direct employment increase depending on the season.

Figure 39

Table 7 Country Shares of Some GAP Region Products (1995--2016)

Name Of The Product	1995 GAP Region / Turkey (Production) %	2016 GAP Region / Turkey (Production) %
Corn	2,1	25
Helianthus (Sunflowers)	0,5	1,0
Garlic	28,7	37,3
Cotton	50,9	55
Tomato	3	6,5
Cucumber	3,2	5,8
Almond (*Prunus Dulcis*)	7,6	21,4
Pistachio	87	92
Red lentils	97	96,7

In the present case,today, the GAP region meets more than half of Turkey's cotton production (55%). Also, 93,6% of red lentils, 96,98% of pistachio and 35,3% of durum wheat are covered from GAP Region. With the irrigation in the region, a great increase has seen especially in the production of fresh vegetables, fruits and industrial plants. With the start of irrigation, in parallel with the fall of barley, lentil, chickpea, cultivation areas grown in dry areas, there was a significant increase in the cultivation areas of cotton.

Table 8 Areas Started to Irrigation by Years (2002-2018)

Years	Irrigation Area (ha)	Irrigation Area Started to Operation During the Year (ha)
2002	198.854	4.758
2003	206.954	8.100
2004	224.604	17.650
2005	245.613	21.009
2006	261.835	16.222
2007	272.697	10.862
2008	287.295	14.598
2009	300.397	13.102
2010	308.535	8.138
2011	370.418	61.883
2012	377.672	7.254
2013	411.508	33.836
2014	424.710	13.202
2015	474.528	49.818
2016	502.154	27.626
2017	547.333	45.179
2018	558.507	12.569

As an example; Atatürk HEPP&Dam is one of the biggest project in the Southeastern Anatolia Project (GAP). Atatürk HEPP&Dam within the GAP Project is located on the Euphrates River between Adıyaman and Şanlıurfa provinces and is for energy and irrigation purposes. The average annual water flow is 26 billion m3. The total water storage volume is 48.7 billion m3. In each group; There are 8 turbine generators with a power of 300 megawatts. Two of these 8 units were put into service in 1992. With the Şanlıurfa, Harran, Mardin, Ceylanpınar, Siverek-Hilvan plains, 1.43 million acres of land will become irrigated.


Figure 40

Before the GAP, Euphrates and Tigris floods were severe and occur at a bad time in terms of agricultural production in the basin. Floods that occur between April and June which is very late for summer crops and very early for stern crops. In addition, the heavy rain and floods occurring in the region negatively affected the region in terms of social, environmental and economic aspects. As a result of these floods, many people died and hundreds of people were affected economically and socially. The number and severity of floods decreased significantly in the region after the constructions of dams and sets.

Figure 41

11.3. Climate Change

According to the reference period 1971-2000; the period with an excess of soil moisture has shrunk significantly from the April-May to the March due to the large reduction of precipitation in the climate projections and a small increase in potential/real evaporation-sweating. Figure 44 shows the trend projected with global climate change for the period 2015-39, 2040-69 and 2070-99. The average monthly total precipitation (blue line) and the change of evaporation-sweating (red line) during this period.

In other words, irrigation water will now start in March, not in the 5th month of May, and will typically reach its highest level in July. The length of the period with excess soil moisture and this significant decrease in precipitation will also significantly reduce the feeding of groundwater.

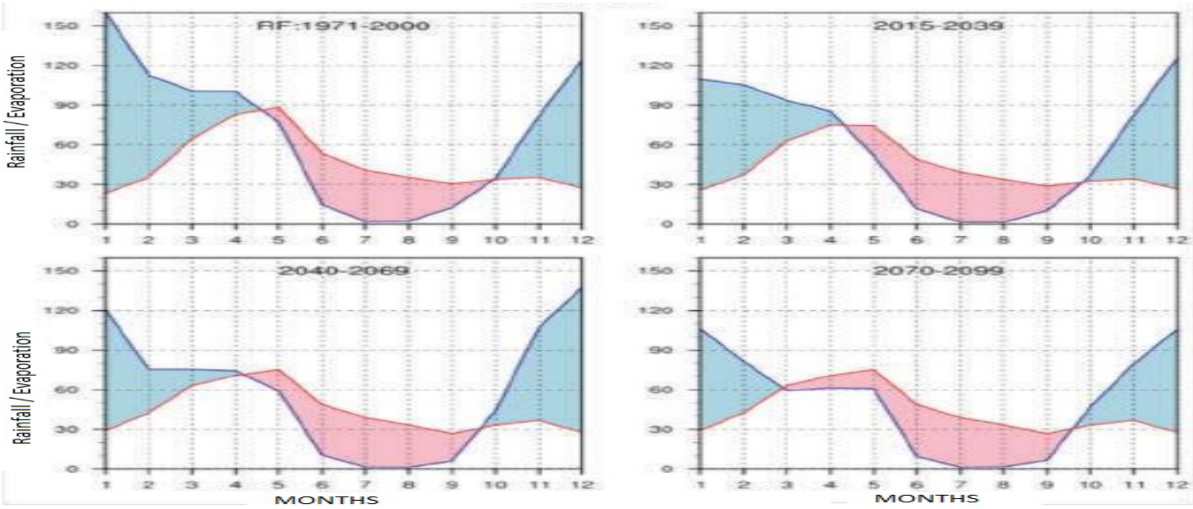


Figure 42

11.4. Conclusions

Undoubtedly, GAP has significantly contributed to the economic, social and cultural development of the region. In today's world, where global climate changes and drought feel more intense day by day, the economic contribution of GAP to the region and country economy, especially in the agriculture and energy sector, is an undeniable fact. With the completion of the GAP irrigation projects, it is aimed to open 1.7 million hectares of land for irrigation, which is vital importance considering the agricultural nature of the region. The projects carried out for the development of the regional industry, the support of the entrepreneurial class, and the development of transportation and infrastructure are of great importance.

With many flood protection facilities built within the scope of the GAP, many residential areas in the region were protected from floods, ensuring the life and property security of the citizens. After the construction of dams and water canals, there has not been a significant flood excepts small ones.

As a result, the Southeastern Anatolia Project (GAP) has significiantly contributed to region, and still continue to do. Damages of agricultere areas due to floods are almost not seen anymore, and because of prevalent irrigations, the farmlands became much more efficient.

11.5. References

http://www.gap.gov.tr/ GAP Master Plan, GAP General Presentations, GAP Action Plans, GAP Latest Status Reports, GAP Agricultural Research Projects, DSI 2018 Annual Report, Report of Climate Change and Agriculture Sustainability In Turkey

12. Dibang multipurpose Project, Lower Dibang valley, India

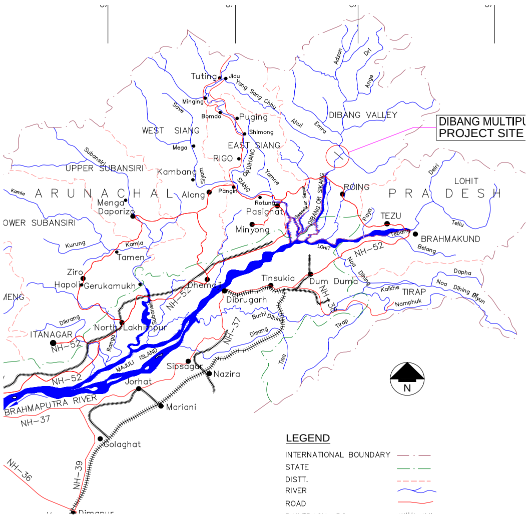
Dibang multipurpose project

Abhay Kumar Singh[1], Deepak Saigal[2]

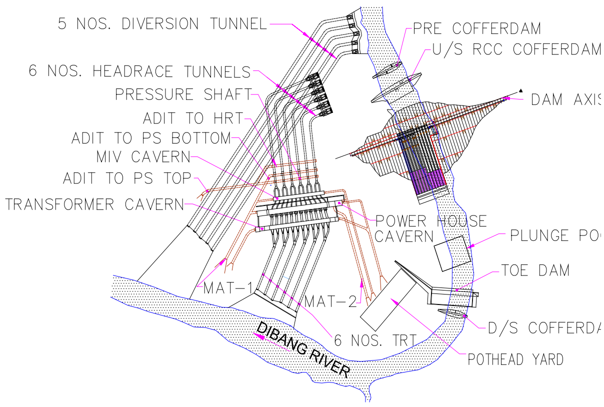
[1] CMD, NHPC Ltd, Faridabad, India, [2] GM, NHPC Ltd, Faridabad India

12.1. Introduction

Dibang Multi-purpose Project (MPP) is a hydropower cum flood moderation scheme proposed on the Dibang River in Lower Dibang Valley District of Arunachal Pradesh. The Dam site is located about 1.5 km upstream of the confluence of Ashu Pani and Dibang rivers and about 43 km from Roing District Headquarter. In Dibang MPP, a flood of 12756 m^3/s shall be reduced to 3000 m3/s due to proposed Flood Moderation. The Project is being developed by NHPC LTD (a Govt. of India Enterprise) on an ownership basis. The area has an average annual rainfall of 4,357 mm with a catchment area 11,276 km^2 and the probable maximum flood /observed maximum flood has been as 26,230/14,000 m^3/s.



LOCATION MAP



PROJECT LAYOUT

Google Image

Figure 43 Location map and project layout

A 278 m high concrete RCC dam is under development to generate hydropower in an underground power house using 12 no of Francis turbine of 240 MW capacity each and shall generate about 11,223 GWh annually. The diversion tunnel is designed for 8,680 m^3/s discharge. The dam will impound a reservoir covering 35.64 km^2 with a gross storage of 3,510 Million cubic meter (MCM).

12.1.1. FLOOD LOSSES IN ASSAM

Estimated annual damages due to floods in the state of Assam ranges from 300 to 1500 Million USD. Dibang. Project is chosen as potential flood storage site in Dibang basin and has been proposed in the event of occurrence of a 100 year return period flood wave preceded and succeeded by a 25-year flood wave at dam site. Release from the reservoir will be restricted to 3,000 m^3/s. Flood storage required for moderation of train of flood waves is computed as 1260 Million cubic meter. (MCM)

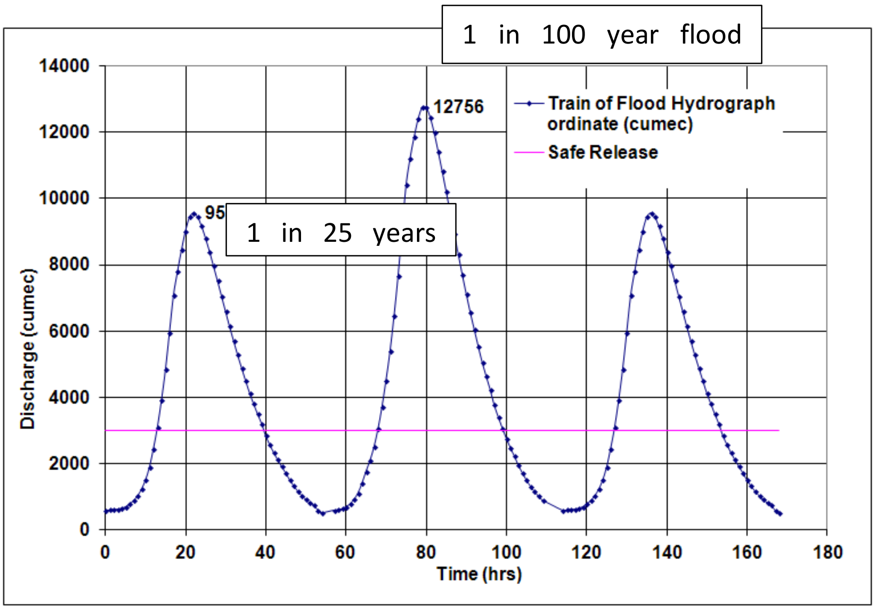


Figure 44

The reservoir rule curve is developed considering the (a)flood storage in first 10-daily of June to second 10-daily of August would be adequate to absorb the train of flood waves of 100-year flood preceded and succeeded by 25 year flood, (b) third 10-daily of August would be used to increase the reservoir level to absorb 100 year Flood, (c) all 10-dailies of September would be adequate to absorb 100 year flood and (d) first 10-daily of October would be used to increase the reservoir level.

Table 9

Months (Monsoon)	Reservoir Level at end of period (m)	Remarks
May-III to Aug-II	490.2	25+100+25 yr Flood can pass
Aug-III to Sept-III	512.6	100 yr Flood can pass
Oct-I	530.3	FRL

12.2. Effect of flood moderation on downstream of dam

Flood routing study has been carried out downstream of dam as far as the confluence with the River Lohit for 1 in 100 year return period flood (12 756 m^3/s) and 3 000 m^3/s (release after flood moderation) discharge to assess the impact of flood moderation d/s of dam. It is estimated that relief in water level is of order of 3 to 6 m in first 20 km and 1 to 2 m beyond 20 km d/s of dam for 1 in 100 year flood, which is quite significant considering the fact that Dibang is quite a wide river in these reaches. At just upstream of confluence with Lohit (60 km downstream of dam) near Dibru-Saikhowa national park, for 100 year return period flood, relief is 0.76 m in water level. About 45% of reduction in top width /area is estimated due to flood moderation in the stretch between dam and confluence with Lohit. After flood moderation the flood plain width will get reduced from average 6 km to about 3.3 km. Thus there will be land reclamation of about 2.7 km bank width in a reach of about 40 km till its confluence with Lohit river (108 km^2).

12.3. Allocation of cost and Benefits

The cost apportioned towards flood moderation has been calculated adopting following two methods as per Indian Standard no 7560-1974 and about 750 Million USD has been considered as cost towards Flood Moderation and is expected to be supported by Government of India as an under revised hydropower policy 2019. Flood apportioned component cost of the Project is very small in comparison to yearly flood losses enumerated above put together with land reclaimed and by preventing further agriculture land erosion.

On commissioning of Dibang Multipurpose Project, the energy and peaking problems would be considerably improved in Eastern & Northern Regions. The project is envisaged to bring Infrastructure in the Project vicinity (roads, bridges, educational facilities, medical facilities, fuelling stations etc.), tourism in the area, economic development by creating demand centre and promoting local market growth and employment generation through work contracts.

Revised concurrence to Dibang Multipurpose Project (2880 MW) accorded by Central Electricity Authority (CEA) on 18.09.2017. Investment approval for incurring expenditure on pre-investment activities were accorded in 2019 and now investment of the project is in advance stage of sanction for starting the construction of main project work.

13. Tehri Dam as flood moderator, India

R. K. Vishnoi, Director (Technical) THDC India Limited, Rishikesh, India

13.1. Introduction

13.1.1. The Ganges River System

The Ganges river system comprises of two major rivers, namely Alaknanda and Bhagirathi in upper Himalayan region. These two rivers have their confluence at Deoprayag, downstream of which the combined river is named Ganga River which has tremendous cultural and religious sanctity in India and thus both these arms also have their importance from religious and socio-cultural viewpoint.

13.1.2. Hydropower Projects in Ganges Valley

Apart from the above, a number of hydropower projects are either in operation or under construction/ planning on river Alaknanda and Bhagirathi. Tehri Hydropower Project (1000 MW) and Koteshwar (400 MW) are the major operative projects on river Bhagirathi whereas Tehri (Stage – II), a Pumped Storage Project of 1000 MW capacity is under construction. The location may and general layout of the Tehri project is shown as Figure 47 and Figure 48.

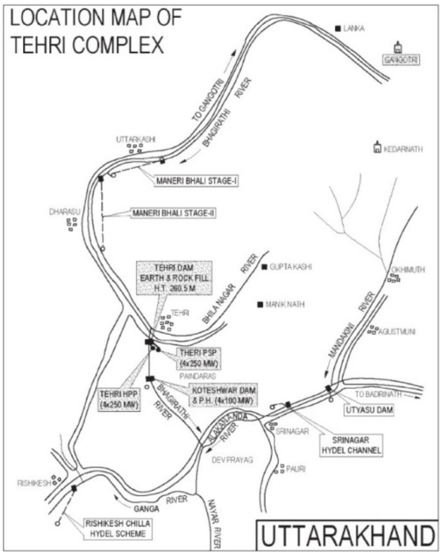


Figure 45 Location of Tehri Project

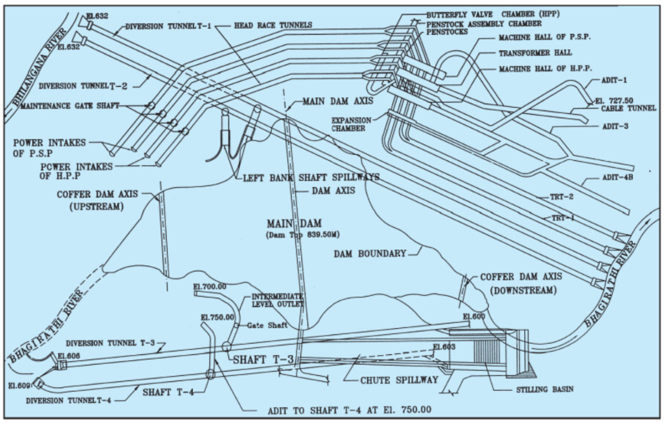


Figure 46 Layout of Tehri project

Tehri Hydro Power Project comprises of India's tallest rock and earth dam for generation of 1,000 MW clean hydroelectric energy is a multipurpose project and provides the benefits of drinking water, irrigation, flood control, tourism and other economic activities and is located on river Bhagirathi, immediately downstream of its confluence with river Bhilangana. The reservoir created by the 260.5 m high earth and rockfill dam thus extends on the River Bhagirathi as well as the River Bhilangana and has a total catchment area of 7,511 km^2 up to the dam site, out of which 2,328 km^2 is snow bound and remaining 5183 km^2 is rain-fed. The rain-fed catchment area is characterized by steep overland slopes, dense vegetation cover and vast drainage network. The average annual rainfall in the catchment is of the order of 1200 mm, however, the temporal distribution of rainfall is heavily skewed and nearly 80%

of the annual rainfall takes place in the 100 days of monsoon (June to September). Mean annual run-off of river Bhagirathi at Tehri Dam site has been estimated to be in the vicinity of 8.0 Billion m^3(BCM).

13.2. Tehri Dam

The gross storage capacity of Tehri dam reservoir is 3,540 Million m^3 (MCM) at full reservoir level (FRL) of 830.00m. Out of this, live storage above MDDL of 740 m is 2,615 MCM, renewed on annual basis. The reservoir extends to a length of nearly 44 km on river Bhagirathi and 25 km on river Bhilangana. The surface area of the reservoir is nearly 44 km^2 at FRL, whereas the surface area corresponding to Minimum Draw Down Level (MDDL) is 18km^2.

Figure 47 A View of Tehri Dam

13.2.1. Spillway Arrangement

The spillway arrangement has been designed for Probable Maximum Flood (PMF) of 15,540 m^3/s with an Ogee crest chute spillway for discharge capacity of 5,475 m^3/s and 4 diversion tunnels, 12.00 m diameter each converted into shaft spillways by way of connecting them to the reservoir surface by vertical shafts of 12 m diameter. The spillway system is thus capable of discharging nearly 13,000 m^3/s, as the peak outflow of PMF routed through the reservoir. The spillway operation strategy envisages the PMF striking at reservoir level 830.00 m to be safely managed with reservoir level not rising beyond Maximum water level (MWL) of 835.00 m.

Figure 48 Spillways: Clockwise from top Chute (1 & 2), Left Bank Shaft & Right Bank Shaft Spillways

13.2.2. Reservoir Operation

The water year considered for the purpose is from June 21st (at the onset of the monsoon) to June 20th of the next year implies that at the end of a water year, the reservoir depletes to the MDDL. The reservoir operation principle is that during the monsoon period, the reservoir is filled up to FRL. During the annual reservoir filling, the power house is operated at 20% of the capacity, i.e. 1000 MW generation is allowed for 4.8 hrs a day. The remaining inflow is utilized for the purpose of storage. Once the FRL is attained, the actual river inflow is utilized for power generation and the reservoir is maintained at (or around) the FRL during the monsoon period. In case the river inflow is more than the generation capacity, the balance is released through the spillways. The release from the reservoir is governed by the irrigation requirements of the command area and is optimized at the same time fulfilling the peaking power requirements. Koteshwar reservoir, immediately downstream of the main reservoir serves as balancing reservoir and releases uniform flows into the river. The shocks in the river flow due to peaking operation of Tehri Reservoir are thus absorbed by Koteshwar reservoir.

13.3. Flood management by Tehri reservoir

The philosophy of reservoir operation is based on irrigation and power generation requirements. As such flood control is not explicitly considered for Tehri reservoir operation. The flood control aspect is in-built in the functioning of Tehri reservoir and any flood is absorbed in the reservoir till the reservoir water level reaches EL 815.00 m. Once the reservoir reaches the spillway crest level, the flood can be significantly moderated, making use of nearly 575 MCM storage between spillway crest level (EL 815 m) and FRL (El 830 m). Even if, the flood is expected to impinge the reservoir at the FRL, the elaborate inflow forecasting system of the project in the entire catchment, allows sufficient warning time so as to commence spillway operation before actual impingement of the flood. Thus temporary storage capacity is created, which may be used for flood moderation as it negotiates the reservoir.

13.4. Uttarakhand Flood of june 2013

13.4.1. Precipitation in June 2013

One of the severest floods experienced by the Garhwal region in the Himalayan state of Uttarakhand occurred in June 2013 caused due to a combination of several factors. There were multiple incidents of cloud burst coupled with land-slides and blockage of water bodies followed by their breaches giving rise to flash floods. Furthermore, the month of June is traditionally a period of heavy tourist traffic in that area and presence of large number of tourists gave rise to the catastrophe. As a rough estimate of the intensity of rainfall, it may be considered that the nominal rainfall in the month of June is 200 to 300 mm for Uttarakhand state, whereas the rainfall during the period of one week only ranged from, 248 to 565 mm from June 13th to 19th, 2013 in some districts of Uttarakhand. There was huge variation in temporal as well as spatial distribution of this rainfall. Since this happened in the month of June, which is typically the month of low expectancy of heavy rainfall, the response mechanism was not prepared for such a calamity and no pre-emptive actions were in place.

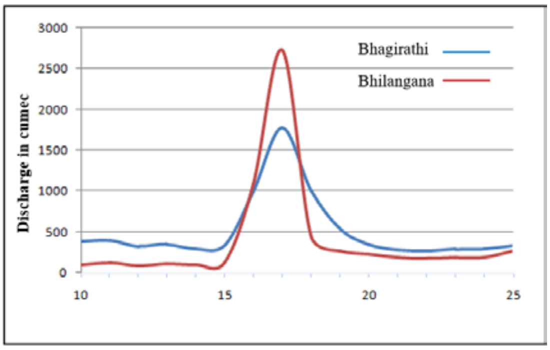
13.4.2. Chorabari Lake Breach

The devastation associated with the June 2013 flood is because of another event which is that of the breach of a natural lake. There is a place of worship named Kedarnath temple and Nearly 3 km upstream of this temple, a natural water body named Chorabari Lake is located at the feet of Chorabari Glacier. The depth of water in the lake remains of the order of 1.2 to 1.5 m covered by fresh snow. During the period of 2013 event, there was a rainfall of nearly 350 mm within 24 hrs (June 16, 2013) over and around this lake including Kedarnath town. This heavy rainfall not only accumulated a large quantity of precipitation water in the lake but also caused a large mass of glacial snow/ ice to slide down into the lake. With heavy rainfall on the surface of snow, the rate of snowmelt expedited and nearly 400 MCM accumulated in the lake. The moraine barrier could not resist the load of water and the lake burst on the morning of June 17th 2013 causing huge mass of debris, mud and slush in a flash and destroyed nearly everything on its way, except the temple structure. Due to the rainfall of the previous day, river Mandakini and other streams in the region were already running at high flood levels. The additional surge due to this flash flood deteriorated the flow regime and the damage occurred to all surrounding habitats apart from road network, bridges and other infrastructure of immense importance for rescue and relief operations. The severity of calamity increased because of hindrance to rescue operations and therefore overall toll was high. More than 5000 people were estimated to be dead or missing during this furious 2013 flood.

13.5. Role of Tehri dam project

13.5.1. Initial and Boundary Conditions

The period of occurrence of June 2013 flood, coincided with the period of Tehri reservoir being near the MDDL of El 740.00 m. On June 10th, 2013, the reservoir level was recorded at El 746.80 m. The spillway crest at El 815.00 m was 68.20 m higher and reservoir was capable as well as mandated to hold the total volume of river inflow. The inflow hydrographs at the upstream ends of the reservoir on the Bhagirathi and Bhilangana branches are shown in Figure 51. It is interesting to note that based on the catchment area drained by Bhagirathi and Bhilangana, the inflow of Bhilangana is usually much less than that of river Bhagirathi. However, on June 16th and 17th, the inflow of river Bhilangana exceeded that of Bhagirathi.



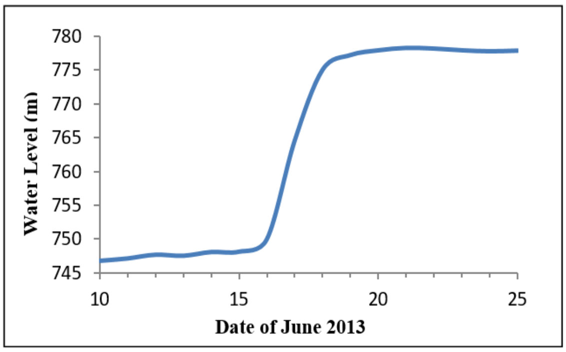
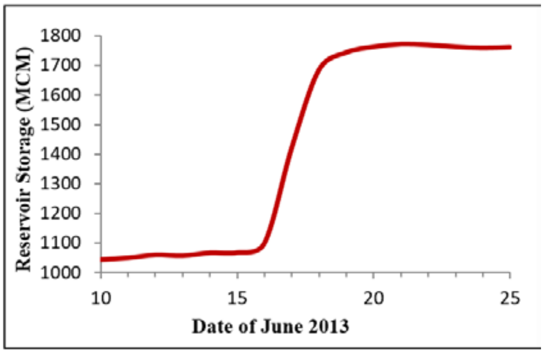


Figure 49 Inflow Hydrographs of Bhagirathi & Alaknanda Figure 50 Stage Graph of June 2013 at Tehri Dam



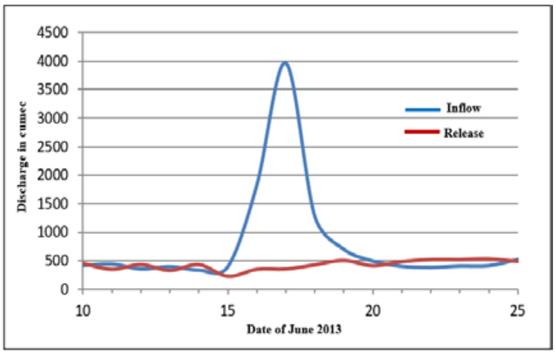


Figure 51 Storage Graphs of June 2013 at Tehri Dam **Figure 52 Inflow & Release Graph at Tehri Dam in June 2013**

13.5.2. The Role of Tehri Reservoir

The rise of reservoir water level and volume of water accumulated during the fortnight from June 10th to 25th, 2013 is shown in Figure 52 and Figure 53. It is seen from the figure that during 4 days from June 15 to 19, 2013, net accumulation in Tehri reservoir is 676 MCM which causes water level to rise by more than 29 m over the same span of time. Maximum one-day storage is noted on June 17th which is 323.10 MCM causing the reservoir to rise by 14.6 m in one day. The effect of Tehri reservoir on the flood is shown in Figure 54. As expected, the flood having a peak of nearly 4 090 cms is completely absorbed in the reservoir.

13.6. Analysis of flood downstream of Devprayag

The peak assessed at Devprayag was of the order of 9250 m^3/s on June 17th in which the contribution of Bhagirathi was of the order of 350 m^3/s only which is insignificant compared to Alaknanda contribution. On the other hand, the linear routing of flood hydrograph of Bhagirathi, incorporating the contribution of overland flow and assuming no reservoir at Tehri and Koteshwar yields a peak flood of approximately 4850 m^3/s at Devprayag on June 17th. The flood routing analysis is based on approximations, still it gives an indication that the flood peak in Bhagirathi (without Tehri Dam) and Alaknanda would have coincided at Devprayag as both the peaks occurred on the same day. In the actual flood analysis, the flood peaks are not linearly added because of dynamic characteristics of the two streams and the effect of junction, however it can safely be presumed that the peak flow at Devprayag would have increased by 30 to 40% apart from increase in the time period of peak being maintained.

The major towns such as Rishikesh and Haridwar including elaborate setup of irrigation head-works are located downstream of Devprayag, makes the role of Tehri Dam immensely important during the 2013 flood. Needless to mention that Rishikesh was at the threshold of getting large scale inundation, when the flood started receding. There were damages as well flooding of low lying areas of Rishikesh and nearby areas but major population of the town was saved by a narrow margin. Considering additional Bhagirathi flood in the absence of Tehri Dam, a scary situation emerges for Rishikesh. Whereas, this brings about the importance of Tehri Reservoir in safely managing the 2013 floods, another hypothetical situation of a major storage being available on Alaknanda yields the result of much easier and safer situation in the downstream stretches.

13.7. What if had Tehri Dam not BEEN there!

The flood in Bhilangana, if not contained by Tehri reservoir, had the potential of causing tremendous damage along its flow path apart from increasing the fury of the flood of river Alaknanda, downstream of its confluence. As per flood routing, the estimated rise in the flood peak would have been 50% of what actually occurred. Tehri reservoir thus made immense contribution as a flood moderator during the June 2013 event. This incident reinforces the concept of at least one storage reservoir on every major river.