INTEGRATED OPTIMAL OPERATION OF CASCADE HYDROPOWER STATIONS AND RESERVOIRS

Technical Bulletin

COMMITTEE ON INTEGRATED OPERATION OF HYDROPOWER STATIONS AND RESERVOIRS
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COMMITTEE ON INTEGRATED OPERATION OF HYDROPOWER STATIONS AND RESERVOIRS

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FOREWORD

Water energy is renewable, economic and environmentally friendly. Hydropower generation is to generate electric power by using the energy of water in a natural river system. The first time when human beings used water energy to generate electricity took place around 1880. In the first decade of hydropower development, generally the installed capacity was very small. For example, Sweden's first hydropower station, built in 1882, had only an installed capacity of 3 hp; and Japan's first hydropower station, built in 1889, also had only an installed capacity of 65 hp. In the second decade of hydropower development, the installed capacity began to increase significantly. In 1892, a hydropower station was built in Niagara Falls, USA, with eleven 4 MW hydroelectric generating units. In 1895, on the lower Rhone River, in France, a hydropower station was built in Saint-Clair, with an installed capacity of 107 MW. In the following 20 years, the scale of hydropower stations kept increasing rapidly and the development of installed capacity was very fast. In the USA, on the Mississippi River, from 1913 to 1930, the installed capacity of hydropower stations went from 147 MW to 9,650 MW, meaning it was multiplied by a factor of 65.

However, in the first 40 years, the development and management of hydropower stations was isolated and single-objective. In the first 30 years of the 20th century, the trend for cascade development of a river system first appeared in Japan, and achieved better results. However, the concept of cascade development of rivers was not clear at that time. Then in 1933, the United States first proposed multi-objective cascade development of the Tennessee Valley and implemented it. At the same time, the Soviet Union completed the cascade development plan for the Volga River from 1931 to 1934 and put it into practice. The hydropower in developed countries has begun to move towards an era of stable development since the 1970s, while some developing countries in Latin America have reached the climax of hydropower development since the 1960s, and cascade development has progressed rapidly. Between 1958 and 1986, Brazil carried out a series of cascade development for the Parana River and its tributaries, and a total of 17 cascade hydropower stations were built, with a total storage capacity of 17.922 billion m^3 and a total installed capacity of 39,580 MW. In China, the total installed capacity of hydropower was only 360 MW in 1950. Since 1980s, hydropower has rapidly developed and 13 large hydropower bases have gradually formed in China, including the Jinsha River base, the Yalong River base, the Dadu River base, the Wujiang River base, the Yangtze River upstream base, the Yellow River downstream base, the Yellow River midstream base, the Xiangxi base, and the Nujiang River base. Optimal allocation of water resources has been implemented there, so rational development and utilization of water resources in China have been promoted in an orderly manner.

In order to further promote the development of cascade hydropower optimal operation technologies, the second term of the Committee on Integrated Operation of Hydropower Stations and Reservoirs (“the Committee” or “Committee K”) has begun its service in 2016. It will continue to study integrated optimal operation of cascade reservoirs and hydropower stations based on the technical bulletin of the first term.

The terms of reference for the current Committee involve:

- Safe operation and management of hydropower stations;
- Integrated operation of hydropower stations and multi-objective reservoirs;
- Optimal operation of reservoirs and hydropower stations for cascade developments;
- Publishing of guidelines for management, operation and maintenance of hydropower stations in order to provide a reference and basis for improving their safety, efficiency and management level.

This bulletin serves as a reference for the readers in hydropower and related fields. It gives an overview of the main benefits brought by cascade hydropower stations and typical case studies in the member countries. It was formed by reviewing all the proposals and typical cases provided by the committee members.

The sincere cooperation and enthusiastic participation of the 21 committee members, who shared their experience for the creation of this bulletin, are highly appreciated.

I hope that this bulletin would give the readers a holistic vision of the functions and operations of cascade hydropower stations and reservoirs.

CHEN Guoqing

Chairman

Committee on Integrated Operation of Hydropower Stations and Reservoirs

1. INTRODUCTION

In the development and management of rivers, in order to balance between disaster mitigation and utilization benefits, it is necessary to develop a series of reservoirs which are called cascade reservoirs on the river mainstreams and tributaries to work as a whole. To some extent, the cascade reservoirs can regulate the runoff together to meet needs of different authorities within the river basin.

There are two basic characteristics of cascade reservoirs. One is the commonality. The cascade reservoirs jointly regulate the runoff and serve for some comprehensive tasks (such as navigation, disaster mitigation and power generation). The other is interconnectedness. There are certain interactions in hydrology, hydrodynamic force and water conservancy among the cascade. For example, there is a certain similarity (usually called synchronicity) in hydrological regimes of the mainstreams and tributaries of a river basin, a continuity of upstream and downstream water yield and hydraulic factors (hydraulic interaction), as well as a mutual cooperative and compensation relationship formed by the same water conservancy objects.

1.1. Types of cascade reservoirs

According to relative location and hydraulic interaction of reservoirs in a river basin, the cascade reservoirs can be divided into three types: tandem, parallel and mixed reservoirs.

1.1.1. Tandem reservoirs

"Tandem reservoirs" refer to the reservoirs developed downstream of each other on one river, and there are direct hydraulic interactions between two adjacent reservoirs, such as reservoirs A, B and C as shown in Figure 1.1.

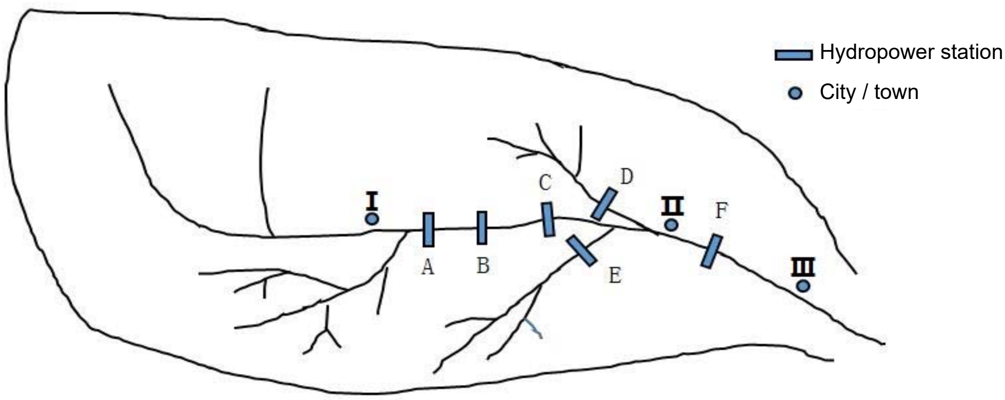


Fig. 1.1
Example of cascade reservoirs in a river basin

Globally, there are a number of typical cases of tandem reservoirs, such as the Tennessee mainstream cascade reservoirs (7 cascades in total) in the eastern United States, with a total storage capacity of 3.2 billion m^3 (Figure 1.2), and the Columbia River mainstream cascade reservoirs (14 cascades in total) developed together by the United States and Canada (Figure 1.3).

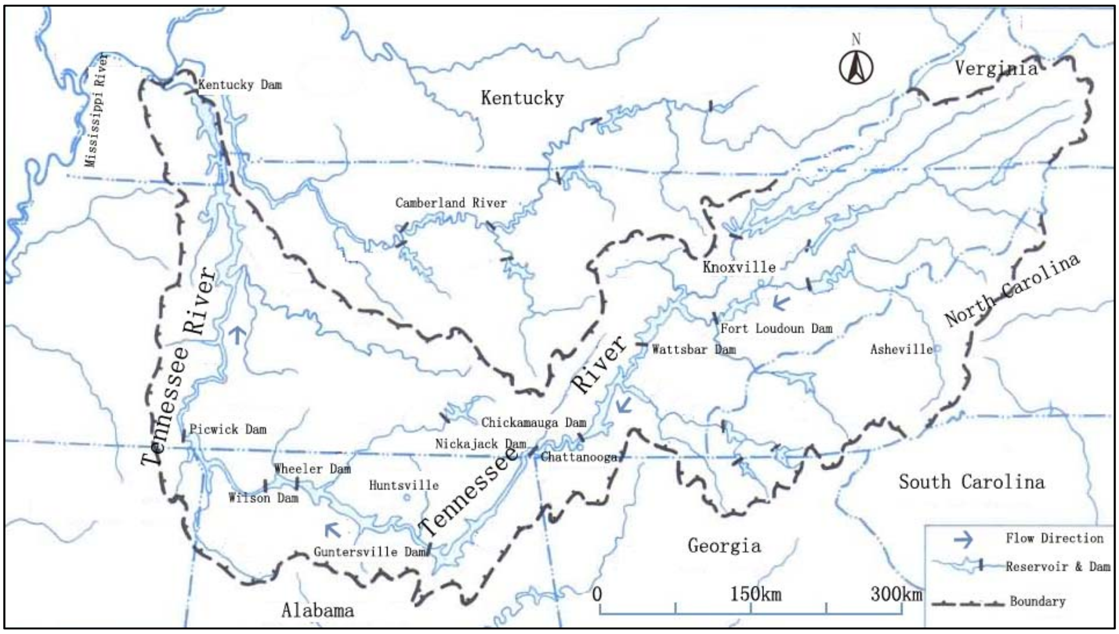


Fig. 1.2
Reservoirs in the Tennessee River basin

Fig. 1.3
Reservoirs and dams in the Columbia River basin

1.1.2. Parallel reservoirs

“Parallel reservoirs” refer to the reservoirs located on several adjacent mainstreams and tributaries of a river basin. They have separate catchment areas and have no direct hydraulic interactions between each other. But they may undertake common tasks of irrigation, disaster mitigation and power generation, etc. When they jointly serve the same task, they will have interactions in terms of water conservancy, such as reservoirs C, D and E as shown in Figure 1.1.

The Parana River, the second-largest river in South America, has a complex drainage system, numerous tributaries and a high degree of water energy resource exploitation. The total water resource reserves of its five major tributaries in Brazil (Paranaiba, Grand, Tiete, Paranapanema and Lguacu rivers) are up to 30 GW. On the five major tributaries, there are a dozen of large parallel reservoirs (including the ones have been built and under construction) and more medium-sized reservoirs. The reservoirs have great regulation performance and jointly undertake comprehensive operation tasks. The total installed capacity of the hydropower stations is over 4 GW. On the mainstream of the Yangtze River and one of its tributaries - Qingjiang River, China Three Gorges Corporation (CTG) owns nine giant hydropower stations (Baihetan, Wudongde, Xiluodu, Xiangjiaba, Three Gorges and Gezhouba on the Yangtze River, and Shuibuya, Geheyan and Gaobazhou on the Qingjiang River) at present (as shown in Figure 1.4). With a flood control capacity of nearly 28.7 billion m^3, these account for about 73% of the total flood control capacity (39.6 billion m^3) in the upper reaches of the Yangtze River.

Fig. 1.4
CTG’s hydropower stations

1.1.3. Mixed reservoirs

“Mixed reservoirs” are a group of reservoirs consisting of tandem and parallel reservoirs, such as reservoirs A, B, C, D, E and F as shown in Figure 1.1. Compared with a single reservoir, cascade reservoirs have a wider catchment area, more installed capacity and hydropower generation, as well as increased regulation storage capacity to play more important roles. It is usually difficult for a single reservoir to give full play to the benefit it should achieve. With integrated operation of cascade reservoirs, the overall comprehensive utilization benefits can be better improved.

The reservoirs in large river basins with comprehensive benefits are usually mixed reservoirs. For example, in the Yenisei River basin in Russia, a total of 30 cascade reservoirs have been built on the mainstream and tributaries, with a total storage capacity of over 440 billion m^3. And the total installed capacity of the cascade hydropower stations is up to 49 GW. The Yangtze River in China, which is the longest in Asia, has a complex drainage system, with main tributaries like the Yalong River, Dadu River, Wujiang River and Minjiang River. Currently, over 60 large mixed reservoirs have been built in the upper reaches of the Yangtze River, with a total storage capacity of about 160 billion m^3 and a total installed capacity up to 120 GW (including the ones that have been built and those under construction), and the scale of the installed capacity to be developed is about 65 GW.

1.2. Characteristics of cascade reservoirs

The working characteristics of cascade reservoirs are mainly manifested in four aspects:

1.2.1. Runoff and hydraulic interactions

Runoff and hydraulic interactions between cascade reservoirs will affect the inflow to downstream reservoirs and the head of upstream reservoirs. Cascade reservoirs have extremely close interconnections in operation control and selection of design parameters (such as normal water level, dead water level, installed capacity and spillway size).

1.2.2. Interactions in terms of water conservancy and economy

The water conservancy tasks in a region often cannot be completely solved by a single reservoir. For example, flood control requirements at the lower reaches of a river, the water demand for irrigation of large areas, and the power supply for large-capacity power grid. Usually, they should be jointly considered and can be better solved through integrated operation of cascade reservoirs in the same region, and it makes the cascade reservoirs have certain interactions in terms of water conservancy and economy.

1.2.3. Differences in storage capacity and ability of regulation

Reservoirs with large storage capacity and high ability of regulation can help the reservoirs with relatively poor regulation capacity to play the role which is called storage capacity compensation, and it can improve the water resources utilization efficiency of the cascades, and guarantee the water supply.

1.2.4. Differences in hydrological conditions

There may be differences in the characteristics of annual and inter-annual runoff changes of the rivers where cascade reservoirs are located. Through hydrological compensation among cascade reservoirs, the guaranteed rate of water supply and the firm output of hydropower stations could be improved.

1.3. Operation characteristics of cascade hydropower stations

Natural river basins contain tremendous energy, so reservoirs and hydropower stations can not only store water, but also take advantages of water energy to generate power. Compared with operation of a single hydropower station, the operation of cascade hydropower stations has the following characteristics:

1.3.1. Interactions in water volume for power generation

The water volume for power generation of the downstream hydropower stations mainly depends on the discharge from the upstream ones. Therefore, the power generation of the downstream hydropower stations is obviously affected by that of the upstream ones. In addition, based on accurate flood forecasting, integrated operation of cascade hydropower stations is implemented to properly lower the water level before the flood season, and the regulation capacity can be increased to retain minor floods. At the end of the flood season, the flood can be timely retained to increase the power generation in the dry season.

1.3.2. Interactions in water head for power generation

Among cascade hydropower stations, there are also interactions in terms of water head for power generation. If the water level of a downstream reservoir is too high, the tail water level of the upstream hydropower station will be raised, so that the water head for power generation of the upstream hydropower reservoir will be lower, resulting in a reduction of power generation efficiency. If the water level of a downstream reservoir is too low, the head for power generation of such reservoir may be lower, which will also lead to a decrease in power generation benefits.

1.3.3. Interactions in regulation of power gird

Cascade hydropower stations usually supply power to the same main power grid and usually undertake the frequency and peak regulation task of the grid system. Under integrated operation, power generation can be reasonably redistributed to reduce the surplus water, and the peak regulation capacity can be increased to improve the operation safety and stability of the power grid.

1.3.4. Changeable operation mode

Due to the influence of hydrological condition variation, the river discharge and water level constantly change, so the reservoir operation mode of hydropower stations is changeable. The operation mode of each hydropower station affects others in the cascade, which makes the operation of cascade hydropower stations more complicated. Integrated irrigation, flood control, water impoundment & drawdown, sediment discharge and other water regulation are conducted for cascade hydropower stations in the river basin. The order of water impoundment and discharge in a cascade is related to the overall comprehensive benefits in the river basin.

2. INTEGRATED OPERATION OBJECTS OF CASCADE HYDROPOWER STATIONS

Integrated operation of cascade hydropower stations: unified and coordinated operation of cascade reservoirs, hydropower stations and related engineering facilities in a basin which have interactions with each other. Optimal operation is used to meet the multi-objective demand of stakeholders for water resources utilization. According to the operation objects, integrated operation of cascade hydropower stations can be divided into two aspects: disaster mitigation operation and operation for utilization benefits.

The basic task of disaster mitigation operation is to control flood and drought by making a rational arrangement of the reservoirs' capacity on the premise of ensuring the dams' safety, as well as giving full play to the comprehensive utilization benefits of cascade reservoirs. Generally, it includes water replenishment during the dry season and other emergency operation. For example, extreme drought hit South Korea in 2015. Pre-reserved water in 9 reservoirs was used to meet water demand. In 2014, to mitigate a saltwater intrusion at the estuary of the Yangtze River, outflow from the Three Gorges reservoir was increased to replenish water at the downstream, which contributed to an improvement of the situation.

Operation for utilization benefits generally includes power generation operation, irrigation regulation and the operation to meet the requirements of industries, urban water supply and navigation, etc. Its main task is to redistribute the natural water flow by utilizing the reservoir's water storage and regulating capacity, to meet the water requirements of the stakeholders and the power system.

Object of cascade hydropower stations' integrated operation: to fully realize the integrated operation in hydrological, storage capacity and power compensation in a river basin by using a mathematical optimization method which takes into full account the close hydraulic and electric connections between the upper and lower cascades. By optimizing the system and coordinating across regions and industries, cascade hydropower stations can give full play to their huge regulating capacity and cascade compensation ability, and thus, improve the utilization efficiency of hydropower resources, the quality of hydropower output, and also enhance the safe operation capacity of the power grid, such as peak shaving, frequency modulation and accident reserve. Disaster mitigation and utilization benefits should be taken into account as a whole, to guarantee the supply of water used for daily life, production and ecological requirements, while minimizing the flood threat in the river basin, improving the navigation conditions, maintaining the river's health, protecting the ecological environment, and promoting the sustainable and coordinated development of the river basin.

2.1. Realizing scientific disaster mitigation

Integrated operation of cascade hydropower stations in a basin can facilitate flood control during the flood season. According to the hydrological characteristics, rainfalls in a basin are different in terms of spatial and temporal distribution. We can give full play to the advantages of reservoir regulation and improve the flood control capacity of the whole basin through reduction and stagger of flood peaks. In addition, flood forecasting in a basin can not only provide cascade hydropower stations with reliable information for flood control, but can also help the flood control headquarters to make rapid decisions on dispatch schemes for flood control. In the United States, the Tennessee Valley Authority has built 54 reservoirs. Among them, 35 reservoirs with a total flood control capacity of about 14.5 billion m^3 have been built on the Tennessee River. A unified and effective reservoir flood control system has been formed. The standard of flood control in the river basin has reached one hundred-year, and the benefit of flood control and disaster reduction in the whole basin is about 140 million US dollars per year. In China, 51,200 reservoirs have been built in the Yangtze River basin, and the total flood control capacity of the major flood control reservoirs reaches 62.7 billion m^3. They undertake the task of flood control for the middle and lower reaches of the Yangtze River. In 2016, through the scientific operation of more than 30 large reservoirs in the upper and middle reaches of the Yangtze River, a total volume of 22.7 billion m^3 flood which would cause 525,000 hectares of cultivated land to be flooded and 380 thousand people to suffer, has been saved and reduced effectively (see Figure 2-1). As a result, the flood control pressure on the middle and lower reaches of the Yangtze River was effectively reduced.

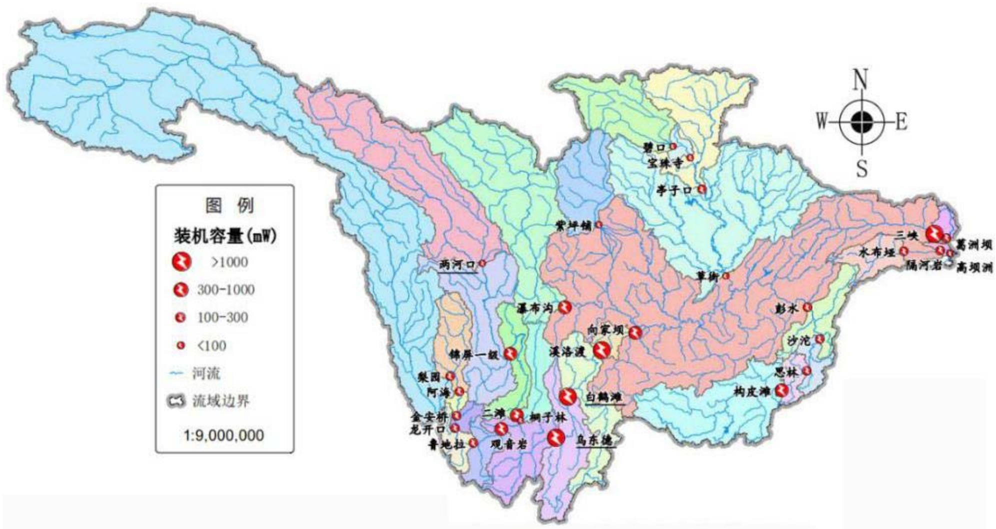


Fig. 2-1

Giant hydropower stations (reservoirs) on the upstream of the Yangtze River

2.2. Maximizing the benefits of comprehensive utilization of water resources

2.2.1. Object of maximizing power generation benefits

There are close hydraulic and electric interactions among cascade hydropower stations. The power generation benefits of each hydropower station are greatly affected by the upstream and downstream ones. Hydropower stations on the upstream directly restrict the inflow and productive head of the downstream stations, while the tailwater of the downstream stations also affects the productive head of the upstream ones. When the cascade hydropower stations operate separately, not only will the hydropower utilization efficiency be lower, but also, it may cause a large amount of surplus water. Therefore, through the integrated operation of cascade hydropower stations, the operation mode of reservoirs and generating units is further optimized, and from the view of maximizing the water energy utilization ratio in the whole basin, the load is rationally distributed among the cascade, and the power generation and economic benefits can be optimized.

In Cameroon, integrated optimal operation of cascade reservoirs and hydropower stations of the Sanaga River has generated remarkable economic benefits since the impounding of Lom Pangar. In 2018, optimal operation was implemented for the four reservoirs on the Sanaga River, ensuring that all these reservoirs were full. The cumulative volume of water in the four reservoirs has made it possible to guarantee a minimum flow of 1,062 m^3/s upstream at the hydroelectric plants of Song Loulou and Edea during the low water period of 2018. In addition, the volume of the four reservoirs made it possible to guarantee an average available capacity of 594 MW for the Song Loulou and Edéa hydroelectric plants, i.e. an energy of around 3,250 GWh. All four reservoirs have enabled the electricity company to save about forty (40) billion CFA francs in the supply of fuel in thermal power stations.

In the Dadu River basin, in China, the integrated optimal operation of cascade hydropower stations has generated remarkable economic benefits. Through integrated operation, the average annual output of the cascade is increased from 105.3 TWh to 112.3 TWh, increasing it by 6.6%; the firm output is increased from 4,790 MW to 10,830 MW, increasing it by 126%, and the output in the dry season is increased from 19.5 TWh to 41.3 TWh, increasing it by 112%. The integrated optimal operation of the cascade hydropower stations in the Dadu River basin can increase the power generation by 7 TWh a year, which is equivalent to burning about 2.1 million tons of standard coal, and can reduce the pollution emissions.

2.2.2. Object of efficient utilization of the water resources

Integrated optimal operation of cascade hydropower stations in a basin can better bring the functions of the leading reservoirs with stronger regulation capacity into play, and improve the utilization efficiency of water resources under the unified consideration of flood control and power generation. With regards to water supply, the ability of cascades to resist drought and replenish water can be greatly improved by increasing discharge in the dry season. With regards to navigation, the condition of channels and the safety of ships are improved significantly; therefore the standardization and scale of ships are promoted, also the transportation costs are reduced. With respect to ecology, it can bring into play the ecological benefits of sediment regulation, ecological dispatching, drought emergency dispatching, and establish the ecological dispatching pattern of the whole basin, to promote the coordinated development of people, water and reservoirs.

In the Yalong River, in China, the Jinping-1 reservoir has a storage capacity of 7.765 billion m^3 and a regulating capacity of 4.91 billion m^3 under the normal water level, with its storage coefficient being 13%. As the leading reservoir on the main stream, it has remarkable compensation benefits. Through integrated regulation, the average flow in the dry season at the dam site can be increased from 367 m^3/s to 678 m^3/ s, increasing it by 85%.

The main development object of the European Danube is navigation. To improve navigation conditions on the Danube, international agreements on free navigation of the Danube were signed in Belgrade. Since then, the canal project of the whole river started, and hydropower has been developed along with navigation improvements. A 45-cascade water conservancy project for navigation and power generation was planned to be built, with a total water head of 401 m, a total installed capacity of 7,865 MW and an annual generating capacity of 43.8 TWh. Up to now, 38 projects have been built with a total installed capacity being 5,023 MW, an annual generating capacity being 98.38 TWh, and the utilization ratio of water energy being 65%. Originally, the slope was very steep and the water flow was very fast in some sections of the river, or the water was very shallow and the river had many curves, neither is conducive to navigation. At present, the navigation conditions have been greatly improved through engineering measures and integrated operation of hydropower stations.

The Tennessee Valley Authority of the United States has carried out a comprehensive review and study on operation plans of the water conservancy and hydropower projects managed by them, and established an evaluation system with minimum flow and dissolved oxygen standards in the downstream as indicators. Additionally, optimized adjustment on the operation modes of 20 water conservancy and hydropower projects under their control was carried out, which effectively improved the aquatic ecological environment in the Tennessee basin.

3. KEY TECHNOLOGIES

3.1. Water and rainfall regime telemetry technology

The networking channel of the water and rainfall regime telemetry system applies multi-channel redundancy and mutual reserve mode. The system uses advanced modern communication technologies, such as communication satellite systems, public switched telephone network (PSTN), mobile communication systems (GSM, GPRS, CDMA, etc.), shortwave channels (VHF), and synchronous digital hierarchy (SDH). Each remote telemetry station of the system uses two separate communication channels, these two channels are backups of each other, and either can be assigned as the primary channel. The primary channel is designed to communicate in both directions, and the station can both upload data and accept commands via the primary channel. Thanks to that configuration, the system can acquire all water and rainfall regime telemetry data within a short time (including water, rainfall, flow, temperature, wind speed, wind direction, and working condition data), and transfer all these data to the telemetry system data center.

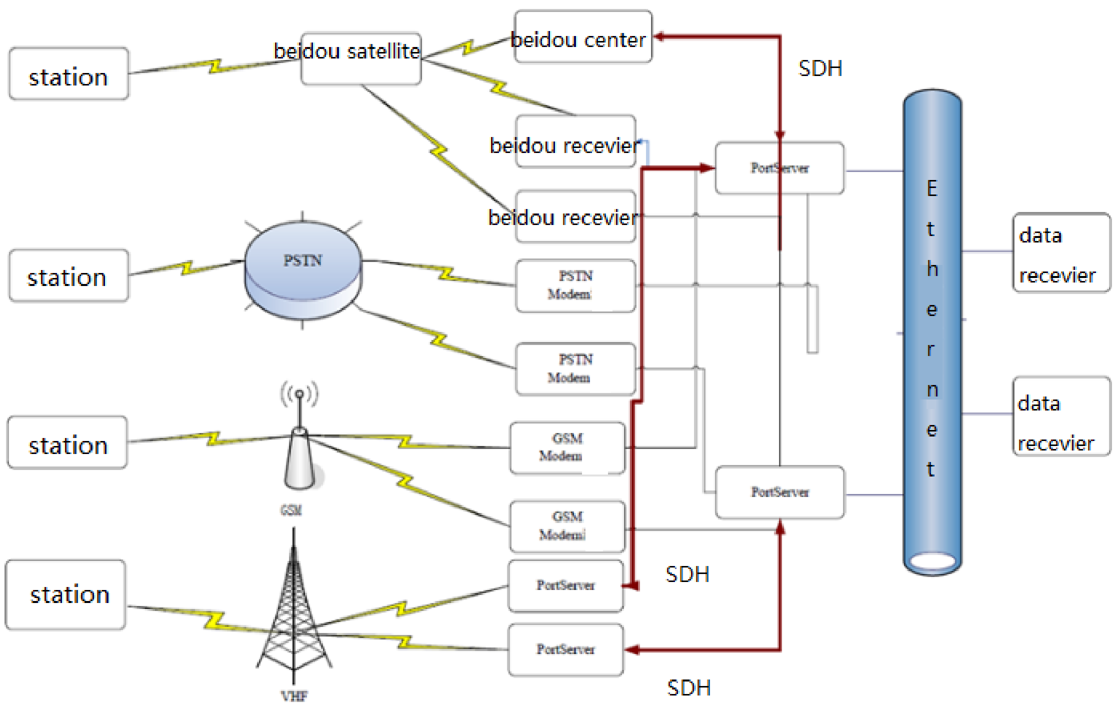


Fig. 3.1
Topographic map of the telemetry system’s communication network

The United States Geological Survey (USGS) is the agency that takes charge of the arrangement of basic hydrological network, the acquisition of hydrological elements at the hydrometric stations, as well as the distribution, storage and management of data. The density of the hydrological network in the United States is about 18 stations/10,000 km². As of today, the nation has 10,240 hydrological stations, and 2,048 river/reservoir/lake level stations. The means of hydrological data transmission include telephone network, satellite, shortwave radio, ultrashort wave radio and computer network. The continuously running hydrometric stations can send real-time data to the hydrological database of USGS and end users. The first instance of using satellites in hydrological data transmission dates back to the early 1980s. Satellite communication has the benefits of high reliability, and good support for telemetry, remote control and automation; therefore more and more hydrometric stations are using a satellite communication network. Currently, more than 60% of all hydrological stations are using satellite communication as the default method and other methods as backup in hydrological data transmission. The real-time hydrological data acquired by instruments (water level gauge, rain gauge, etc.) are first automatically uploaded to the Data Collection Platform (DCP) of hydrometric stations, then the DCP forwards the data to the two Geostationary Operational Environmental Satellites (GOES) of the National Oceanic and Atmospheric Administration over the Pacific Ocean or Brazil. The geostationary satellites then transmit the hydrological data to the commercial satellites, which then send the data to the USGS and other end users. The automatic acquisition and transmission equipment installed in the hydrological stations can continuously acquire and automatically transmit river levels and the changes of other hydrological elements. These automatic instruments are equipped with solar cells or storage batteries. Under extreme conditions such as flash floods or rainstorms, if both the telephone communication and power supply fail, the acquisition and transmission of hydrological elements can still go on.

In China, to understand the water and rainfall regime on the upstream of the Yangtze River, we have established the Three Gorges water and rainfall regime telemetry system, which is the largest and most versatile system in the Chinese hydropower industry. The system consists of over 600 stations that cover 540,000 km² of areas in Yunnan, Sichuan, Guizhou, Hubei and Chongqing on the upstream of the Yangtze River basin. The real-time water and rainfall regime of over 1,000 stations and the operation information of over 20 reservoirs on the upstream of the Yangtze River are accessible from the reservoir information sharing platform. In the last decade, the system has maintained stable operation, with technical index satisfaction rate and availability rate constantly kept at over 99% and 98% respectively.

3.2. Weather forecasting technology

Weather forecasting is transforming from qualitative and descriptive forecasting to numerical and gridded forecasting. The elements of weather forecasting include rain or shine, temperature, precipitation, humidity, speed and direction of wind. Among all these elements, precipitation is the most important factor that influences reservoir operation and regulation; therefore, the weather forecasting for operation of reservoirs is primarily focused on precipitation forecasting, especially the total precipitation and its spatial-temporal distribution in the catchment area controlled by the reservoir.

3.2.1. Types of precipitation forecasting in a river basin

The types of precipitation forecasting in a river basin are classified in the basis of the length of the forecast period:

- Short-time imminent quantitative precipitation forecasting: it means the forecasting for the next 0~6h.
- Short- and mid-term precipitation forecasting: it means the forecasting for the next 1~7d (or 3~10d) and is focused on the forecasting of the precipitation process.
- Extended-period precipitation trend forecasting: it means the forecasting for the next 11~30d and is focused on two aspects: (1) precipitation process forecasting, which mainly includes the number of precipitation processes in the forecast period, time of each precipitation process, precipitation intensity, and location of precipitation center; (2) precipitation trend forecasting, which mainly includes total precipitation and its distribution in the forecast period.

3.2.2. Key technologies and methods of weather forecasting

Precipitation forecasting in river basins is rising with the development of scientific hydrology. Accurate hydrometeorological forecasting in river basins is the key to make rational use of water resources and give full play to the comprehensive benefits of flood control, power generation and navigation of reservoirs. Precipitation forecasting in a river basin is mainly focused on the precipitation trend of catchment controlled by reservoirs. After decades of development, a series of seamless in-basin forecasting techniques have been developed with time scales ranging from short-term approaches to short-to-medium-term, extended periods, monthly, critical periods (seasons), and years.

3.2.2.1. Short-time imminent quantitative precipitation forecasting technology

Short-time imminent quantitative precipitation forecasting (QPF) is a technology of forecasting precipitation for the next 1~6h using radar, satellite and terrestrial precipitation station data. In 1954, Ligda proposed the radar echo extrapolation approach for short-time imminent precipitation forecast. In the next two decades, with the growth of computing capacity, many researchers proposed other extrapolation methods. In 1980, the first imminent forecasting systems saw the light of day. A prominent example is the Nimrod system of the United Kingdom Meteorological Office. The system combines radar echo extrapolation with numerical precipitation forecasting products. This method extends the forecasting period and represents a mainstream solution for short-time imminent QPF. Then with the increasing spatial-temporal resolution of numerical models, radar observation-based short-term forecasting is more closely integrated with traditional numerical forecasts. The radar echo assimilation approach is replaced by mode output field, which can reveal the nascence, development and movement of a convective precipitation system in short-time imminent forecasting.

3.2.2.2. Short- and medium-term precipitation forecasting methods

The forecast methods for short and medium term precipitation include the synoptic method, the forecast model and the dynamic-statistical method. Generally speaking, the key is to accurately judge the circulation in different stages of atmospheric movement and the evolution trend of the weather. With the development of computer science, weather forecast has gradually changed from subjective forecast to numerical forecast. For example, the Norwegian meteorological institute (DNMI) issued the quantitative forecast model LAM, which is applicable to the characteristics of Norwegian meteorology. The forecast time is 36h, and then the European meteorological center (ECMWF) global forecast model is used to make the 6-day qualitative forecast. Based on the results of the global forecast system (GFS), the Iranian meteorological organization developed the regional numerical weather prediction system (RFS) in 2005, which uses radar precipitation data to revise the model results. The Brazilian Hydroelectric Company's forecasts come mainly from two models: the 10-day short-to-medium forecast, which is based on the data from the GEFS Global Ensemble Forecast System developed by the National Oceanic and Atmospheric Administration (NOAA), and the Eta regional model, which is mainly used for short-time imminent weather forecasting.

However, the combined use of the numerical prediction method, dynamic statistics method and synoptic method can effectively improve the quality of medium-term forecast. For example, the commonly used "ingredient method" and "MOS prediction method" can improve the prediction skills of precipitation intensity and location compared with the simple numerical prediction.

The development of ensemble model forecasting is another important way to improve the precision level of forecasting. Previous studies have shown that even low-resolution ensemble models can show higher prediction skills than single high-resolution models. Compared with the deterministic model, the main advantage of ensemble prediction is that it can provide probability prediction, which will help users make more scientific decisions according to their own cost/loss ratio. Since 1992, the ensemble forecasting system (EPS) of the National Center for Environmental Forecasting (NCEP) and the European Center for Medium-Range Weather Forecasting (ECMWF) has been put into operation for the first time. After several years of operation and continuous development, the ensemble forecasting system is quite mature. At present, the one-month ensemble forecasting system of Japan Meteorological Agency and the seasonal ensemble forecasting system of Canadian Meteorological Center (including 10-day medium-range forecast) have also been put into operation. Since 1996, the National Meteorological Center of China has carried out the experimental operation and application of ensemble forecasting.

At present, short- and medium-term precipitation forecasting is gradually becoming more refined and intelligent. For example, the Ottawa Watershed Management Decision Support System (ODSS) in Canada interpolates the global numerical model to a resolution grid of 1 degree, and calculates the average of the whole basin based on the interpolation results. Norway and Switzerland have applied the results of the European Centre for Medium-Range Weather Forecasting (ECMWF) global model to precipitation prediction. In 2006, the resolution of the prediction results of Iran's RFS model in Karun and Dez river basins was improved, providing 15 km*15 km grid prediction every 3 hours. In China, along the channel segment between the downstream of the Jinsha River and the Three Gorges area, an intelligent grid forecasting system for power station controlled watershed is currently being developed. The precipitation forecast of the river basin control system will change from a traditional zoning forecast to a lattice forecast. Precipitation forecast will change from an 11-zone forecast every 24 hours to a 2.5 km*2.5 km grid forecast every 3 hours. The time and space precision of the forecast will be improved obviously, so that users can obtain location-based meticulous meteorological service at anytime and anywhere. This will effectively improve the accuracy of meteorological monitoring and forecasting in the Yangtze river basin and play a key supporting role in improving the forecasting accuracy of hydrological forecasting and prolonging the forecast period.

3.2.2.3. Extended-period precipitation trend forecasting method

There are two approaches for extended-period forecasting. The first approach is to directly extend the integral length of mode product to obtain extended-period forecast, and to explain the mode product with dynamics mode. Typical examples include the DERF (dynamic extended range forecast) of China Meteorology Administration’s National Climate Centre, the CFS (climate forecast system) of American National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-Range Weather Forecasting (ECMWF). These systems apply the output of mode product directly, or compare the annual average output of mode product with actual observation results, make adjustments, and use the corrected outputs; or establish a relationship between mode atmospheric circulation and actual observations, and use atmospheric circulation classification to obtain extended-period forecast.

The other approach is physical variable analysis and statistics, using atmospheric low frequency signals to obtain its cycle, oscillation amplitude and etc., and then extrapolating these low frequency signals to obtain an extended-period forecast. The representative methods include low frequency weather map, low frequency cycle extrapolation, previous climate characteristic similitude fluctuation extrapolation, and mid-low latitude low-frequency intra-seasonal oscillation similitude extrapolation.

3.3. Hydrological forecasting technology

Hydrological forecasting uses available information to conduct qualitative or quantitative hydrological forecasting in a certain period of the future. It is based on fundamental hydrological rules and hydrological models. The forecasting method or forecasting solution is intended for actual needs. Hydrological forecasting technology is widely used in flood and drought control, reservoir operation and other fields.

3.3.1. Types of hydrological forecasting

The applications of hydrological forecasting are wide-ranging, including: (1) basin or regional flood and drought forecasting; (2) ice regime forecasting for rivers, reservoirs and lakes, etc; (3) snowmelt runoff forecasting of snow deposit and glaciers, such as reservoir hydrological forecasting in Norway and Switzerland; (4) temperature of the water, chemical composition of water or fluxes of suspended matters forecasting, like the Ariege cascade reservoir in France, and the Three Gorges cascade reservoir in China; and (5) inflow process and water stage prediction for all reservoir operation. Hydrological forecasting of reservoirs is generally classified into short- and long-term forecasting.

- Short-term hydrological forecasting: it refers to forecasting based on hydrological elements. The length of the forecasting period varies from a few hours to several days. Representative types include rainfall runoff forecasting and river flood forecasting. Countries have different rules for reservoir operation, so the definition of short-term hydrological forecasting is also different. For example, the short-term forecast of the Brazilian Interconnected Power System is the runoff forecast within one week, and the short-term forecast in French Ariege cascade water resources management is the flood or drought forecast for the next 24 hours.

- Mid and long-term hydrological forecasting: it refers to hydrological forecasting with a forecast period longer than the maximum runoff confluence time of the basin. Representative types include ten-day, monthly and yearly runoff forecasting, and drought and flood trend forecasting. Main methods include cause analysis and mathematical statistics. The forecasting can be classified into mid-term forecasting (3~15d), long-term forecasting (15d~1 year) and extended-period forecasting (over 1 year) according to the length of the forecasting period. The length of the forecast period varies with the requirements of reservoir operation. For example, the longest forecast period for French Ariege cascade water resources management is a few weeks of 40 reservoirs inflow. However, most reservoirs need to formulate annual power generation plans or forecast future power generation trends. Therefore, it is necessary to predict the runoff for more than one year or predict the change trend of runoff in the next few years or decades. For example, long-term hydrological forecast periods range from one month to five years in Brazil, and in Malaysia, the runoff trend is predicted in the next few decades based on the simulation of different climatic background.

3.3.2. Key technologies and methods of hydrological forecasting

The hydrological forecasting methods can be roughly classified into parameter methods and non-parameter methods according to the hypothesis on concrete forms of data distribution. If the mathematical form of hypothetical general distribution is known, and there are only limited unknown real parameters, then the forecasting is parameter forecasting; otherwise it is non-parameter forecasting. The conventional conceptual model, distributed model and mathematical model are parameter models. The recently developed phase space forecasting method based on chaos theory and the non-parameter regression method based on conventional regression model both are non-parameter methods. The types of hydrological forecasting methods are as shown in Figure 3.2.

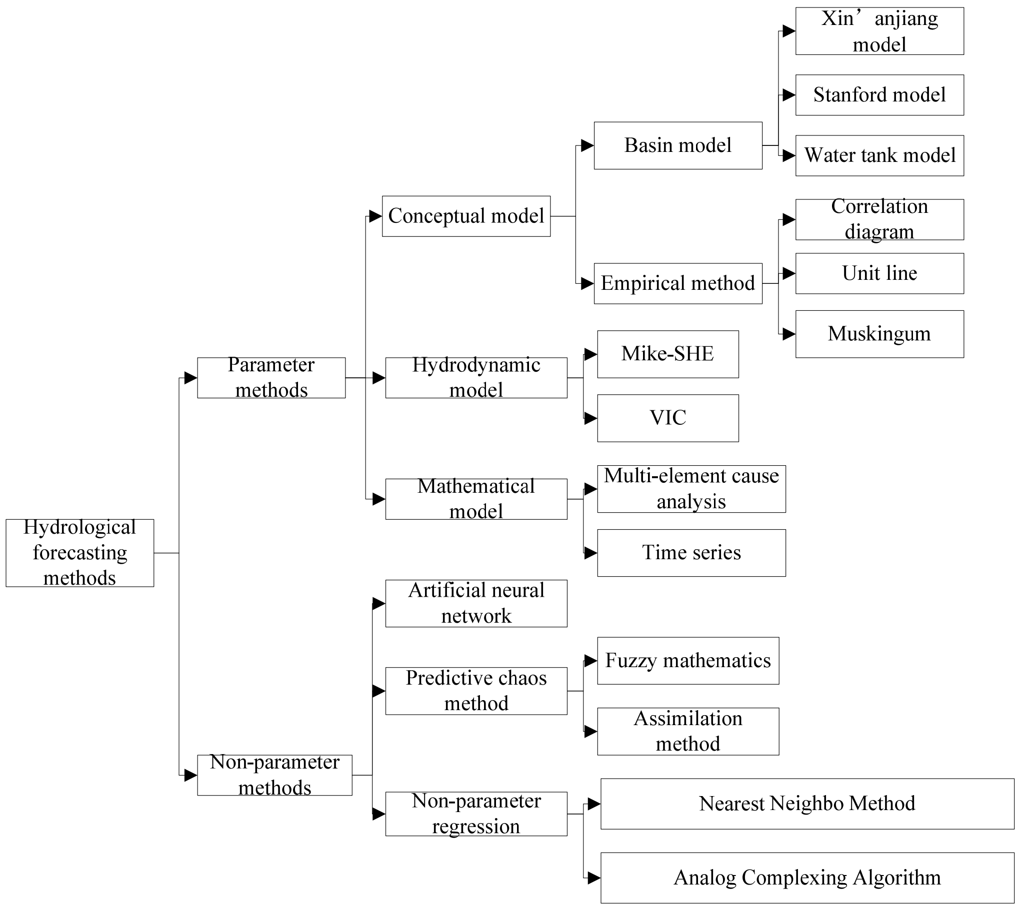


Fig. 3.2
Types of hydrological forecasting methods

- Practical hydrological forecasting schemes based on correlation diagrams

Common practical hydrological forecasting schemes based on correlation diagrams include: (1) rainfall runoff empirical correlation method (API model) that considers previous precipitation; (2) up and down-streams relevant stage-discharge method; (3) synthesized discharge method; (4) multi-element coaxial correlation method; and (5) precipitation runoff method. The advantages of correlation diagrams include: table form compilation is easy to use and can be corrected when necessary; the statistical correlation of actual measurements won't become abnormal or paradoxical. For example, in Cameroon's Southern Sanaga watershed, Excel and other tools are used to analyze the runoff law of the upstream lakes, so as to predict the reservoir inflow, and to revise the historical runoff data of the past three years. Meanwhile, the disadvantages include: the internal relationships between the impact factors are not considered, the changes of underlying surface and other conditions are not considered, and the reliability of extended correlation is not guaranteed.

- Basin hydrological model

This hydrological forecasting model is used to simulate the internal relationships of hydrological elements. It tries to reveal the mechanism and rules of hydrological phenomena. Therefore, it is much better than the practical hydrological forecasting scheme based on correlation diagrams.

1) Conventional ensemble conceptual hydrological model

The conventional ensemble conceptual hydrological model has certain physical significance, but the dynamics equation is not completely based on precipitation confluence process. The rainfall runoff process is simplified and many parameters are empirical ones that can't be directly acquired. The parameters are homogenized. Conventional hydrological forecasting models include the basin hydrological model (such as Xin'an Jiang model), the river course calculation hydrological and hydrodynamics model (such as the Muskingum river course calculation method, the dynamic wave flood evolutionary model), and other models based on basin characteristics. The Xin'an Jiang model was proposed by a team led by professor Zhao Renjun of Hohai University in 1973. It is a basin hydrological model suitable for humid and semi-humid regions, and a representative hydrological model of China. The model has been widely used and continuously refined in China. In 1980, it was first introduced to other nations. In the Ottawa basin of Canada, the HSAMI model is widely used for hydrological forecasting. It was developed at Hydro-Québec (Bisson and Roberge, 1983) and is a global conceptual model. So it is simpler but less demanding in terms of data entry and calculation time. HSAMI uses the following inputs: daily minimum and maximum temperatures, rainfall and snowfall.

2) Modern distributed hydro-physical model

The strong physical mechanism distributed hydrological model is based on physical principles and basin characteristics. It derives correlated mathematical equation sets that describe rainfall runoff generation, saturated and unsaturated flow-carrying motion, and sediment generation and transport process. It reflects the unevenness of parameters, namely the spatial-temporal change of parameters. Representative models include VIC, SHE, SWAT and HBV.

Distributed hydrological model are widely used in water resource management. For example, the SWAT model is used by the United States Department of Agriculture to manage water resources and predict environmental pollution. At present, it is gradually applied in reservoir operation. The Swedish Meteorological and Hydrological Institute has developed the HBV (Hydrokogiska Bryans advising for Vattenbalans) model for river flow forecasting and river pollutant dissemination monitoring. The model has been widely used in the Nordic countries for hydropower station runoff forecasting. In Norway, it is regarded as the most important rainfall runoff model for hydropower applications. Developed in the 1970s, mainly for the spread of river flow forecasting and river pollution, HBV is a half-distributed model, including meteorological interpolation, snow melting estimation and calculation of soil water. The Norwegian Hydrological Department has developed the guidelines for HBV model calibration based on a large number of model calibration experiences. Switzerland has developed a conceptual half-distributed model named RS 3.0. It is based on the GSM-SOCONT concept developed specifically for high mountainous catchment areas. The model is divided into glacier and glacier-free areas, and integrates reservoir and power generation structures. It has been successfully applied for several years.

- Mid- and long-term hydrological forecasting method

1) Hydrological statistics method

The hydrological statistics method uses mathematical and statistical tools to find the statistical relationship between forecast object and forecast factor from long series of historical hydrological data, or the statistical trend of hydrological elements, and establish forecasting model. For instance, in Norway, the medium and long-term forecast is usually related to the snowmelt runoff. This is one case of the impact of snowmelt on the medium and long-term forecast. The other case is long-term small flow unrelated to snowmelt. In this case, the initial groundwater condition will control the river flow. In view of the above two situations, the Norwegian forecasting department adopts the rainfall-runoff model or the regression model to calculate the medium and long-term forecast.

2) Cause analysis method

River runoff mainly originates from atmospheric precipitation and has a close relationship with atmospheric circulation. Modern researches indicate that some astronomical and geographic factors such as the earth's rotation speed, ocean temperature fluctuation, and solar activity have certain impacts on hydrological processes. After determining the relationships between these impact factors and the hydrological processes, the trend of hydrological elements can be forecasted quite a long time into the future. In sum, the cause analysis method uses previous atmospheric circulation, previous ocean temperature characteristics, relative cycle of sunspots, change of earth rotation speed, and planets and other factors to conduct qualitative forecasting of hydrological regime in the future.

3.4. Integrated optimal operation technology of cascade hydropower stations

Cascade hydropower stations can bring great benefits in flood control, power generation, agricultural irrigation, water supply, navigation, ecology conservancy, landscape beautification and other aspects. The operation of cascade hydropower stations must meet both water resource conservancy and power generation requirements. For water resource conservancy, the water resources must be wisely exploited to meet the requirements of human activities. For power generation, the cascade hydropower stations shall provide renewable clean energy and meet the energy demand of social and economic development. These two aspects are correlated and intertwined. The upstream and downstream reservoirs in cascade have close hydraulic relationship. The upstream reservoirs can retain and store the natural inflow. Especially, the big reservoirs with high regulation capacity can significantly adjust the inflow and stretch runoff distribution of downstream reservoirs in different periods of the year or even over several years, and change the runoff characteristics of the whole basin. Integrated optimal operation is based on operational research and reservoir operation theory. The essence of reservoir operation optimization is to find the optimal mathematical solution with restrictions: the interests and demands of water users at the upstream and the downstream of the basin shall be coordinated, and the overall benefits of the cascade reservoirs must be maximized. Integrated optimal operation technologies mainly include two aspects: conventional operation and optimal operation of cascade reservoirs.

3.4.1. Conventional operation of cascade reservoirs

The conventional operation explores the best reservoir operation plan with the runoff regulation and hydraulic energy calculation theories based on the historical reservoir runoff data, then the reservoir operation regulation is determined, and a conventional operation map or operation guideline is implemented in reservoir operation management.

3.4.2. Optimal operation of cascade reservoirs

The optimal operation of cascade reservoirs is based on operational research and reservoir operation theory. The essence of reservoir operation optimization is to find the optimal mathematical solution with restrictions. The multi-objective integrated optimal operation plan is calculated according to the short, mid and long-term hydrological forecasting results, with a computer as the tool of calculation and analysis. Compared with conventional operation method, the multi-objective optimal operation method takes into account reservoir inflow forecast, multiple reservoir operation objects and a variety of restrictions. With its high efficiency in water resources utilization, the multi-objective optimal operation technology has become the common method in reservoir operation. Generally, the optimal operation method is divided into single object optimal operation technology and multi-objective integrated optimal operation technology.

3.4.2.1 Single object optimal operation technology

Single object optimal operation technology is based on the single object optimal method, with which specific flood control or water conservancy benefits in a certain period can be achieved. There are multiple kinds of optimal objects in reservoir operation. For example, the maximum power generation, maximum flood retaining, unobstructed navigation at downstream of the dam, protection against flood at downstream during the flood season, etc. The classification of single object optimal operation technology and methods is as shown in Figure 3.3.

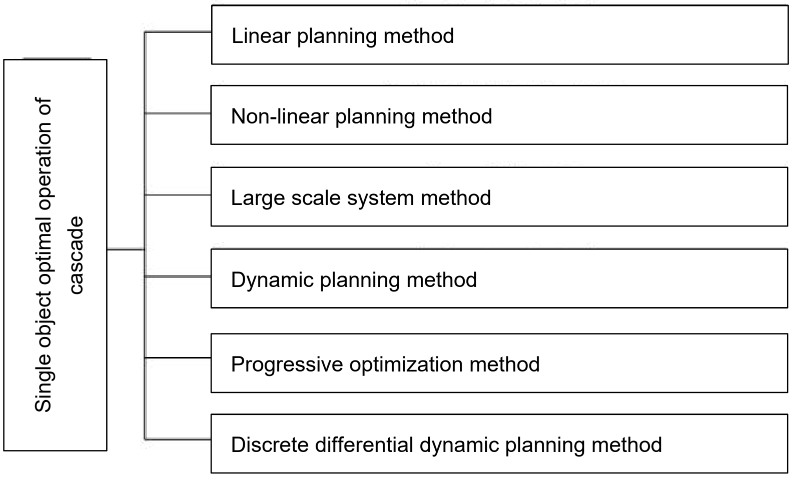


Fig. 3.3
Single object optimal operation technology and methods

3.4.2.2 Multi-objective integrated optimal operation technology

Power generation, flood control, navigation, ecology conservancy and other objects must be considered in the decision-making of cascade reservoirs' operation, that is to say, both economic benefits as well as social and environmental requirements should be weighted. Therefore, conventional single object optimization can't meet reservoir operation requirements in the new era, and a well-considered and better coordinated operation mode must be determined.

With the advancement of optimization theory, the theory put forward linear planning, integer planning, non-linear planning, dynamic planning and other algorithms. Some of these algorithms can be used to obtain a global optimal solution at the cost of a very long time, and some algorithms can be used to quickly find a solution, but the solution isn't the global optimization. All of these methods are rather complicated, and the question must be written in specific expression, so they are only used for small scale optimization and seldom used in large scale practice. Therefore, researchers redirected their attention to quick and near-optimal solutions. In 1950s, the researchers discarded conventional mathematical tools and created the bionic algorithm (BA). The bionic algorithm is used to simulate the structural pattern, evolutional rule, thought structure and foraging behavior of biotic population. It reflects a population coordination mechanism and involves swarm intelligence. Therefore, it belongs to swarm intelligence algorithms.

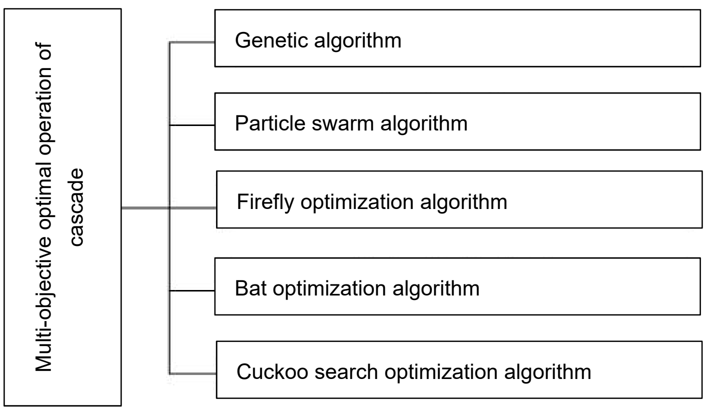


Fig. 3.4
Multi-objective optimal operation technology and methods

3.5. Decision-making support system

Because of the randomness of inflow, the fluidity and instantaneity of decision-making, the nonlinearity of the system, and the multi-objectives of management, the integrated operation of cascade reservoirs is a very complicated undertaking. There are crucial problems and technical challenges to be solved. The three functions below are designed to cope with these main technical problems.

3.5.1. Simulation of reservoirs and river channels

The use of a decision-making support system (DSS) in water resource management has a long history and a wide range of applications. It involves distribution of water resources in river basins, operation management of cascade reservoirs, etc. In recent years, human activities have changed the underlying surface conditions of the basin in the context of global climate change. For example, construction and impoundment of cascade reservoirs have changed the rivers' dynamic characteristics and hydrological process. So it is necessary to develop intelligent DSS to cope with the climate, environment and overall change conditions of the basin, and provide big data of dynamic changes needed for integrated optimal operation of cascade reservoirs and efficient utilization of water resources.

In China, an intelligent DSS has been established by CYPC this year to support cascade reservoirs forecasting and operation planning, and to provide technical support for decision-makers and regulatory agencies. The system can simulate the reservoir operation and river channel runoff characteristics in the upper reaches of the Yangtze River. The functions of reservoir simulation mainly include: collecting and processing the reservoirs' historical operation data, quantitatively analyzing the long/mid/short-term operation rules of each hydropower station, creating a generalized operation model on different time scale of a reservoir system, analyzing possible operation strategies of cascade reservoirs under different scenarios, and providing recommended operation plans for the decision-makers. The functions of river channel simulation include: analyzing the water flow pattern in the river channels, accurately simulating and predicting individual reservoir's flow profile change under the influences of other reservoirs, and analyzing the stage-discharge change process under severe changes in runoff and downstream water levels.

In Iran, as a part of the DSS, a river basin simulation module was developed by upgrading the Acres Reservoir Simulation Program (ARSP) for the big Karun basin. The Modular Simulator (MODSIM) engine developed jointly by the Colorado State University (CSU) and the Bureau of Reclamation's Pacific North West Region, was used. It runs stably to meet the needs of domestic and industrial water use, irrigation, flood control, and environmental requirements for reservoir water supply.

3.5.2. Integrated optimal operation of cascade reservoirs

As for intelligent optimal operation, a DSS is a useful platform to forecast cascade reservoirs changes and provide an optimized operation plan for hydropower stations. And in all, it can provide the decision-maker and regulatory authority with technical supports.

The DSS for the upper reaches of the Yangtze River in China has embedded with a powerful optimal operation module. Under the premise that the demands of comprehensive utilization of water resources such as flood control, navigation and ecological conservation as well as the demand of electricity market are considered in an overall way, the DSS can analyze the objective functions and constraints of the long-, medium- and short-term and real-time optimal operation of cascade reservoirs, and provide a variety of optimization algorithms quickly and effectively through hierarchical operation models and nested coupling models. Meanwhile, based on the general operation integration technology under rolling optimization, the following models are created: the long-, medium- and short-term optimal operation model for cascade reservoirs aiming at guiding production management, the real-time optimal running model of power stations and the conventional operation model adapting to production & operation demands. Through the coupling nesting technology for long-, medium- and short-term optimal operation model, the operation plans are constantly updated to optimize the operation mode of cascade reservoirs.

In Canada, for regulation planning of the Ottawa River system, a DSS has been established to simulate manual control of reservoir outflow. Five variables can be controlled in this way: outflow, elevation, storage capacity, change in elevation and change in storage. The HEC-Ressim model, which is embedded in the DSS, offers several methods of simulating reservoir operation. And routing is accomplished by an iterative solution of the storage continuity equation.

An operational DSS has been set up in the Saane River basin, in Switzerland. It is available on the web and is accessible to authorities and electricity producers. Basically, the DSS contains two different parts. The first one is a map interface of the Saane River basin with various hydrological and hydraulic elements. The user can click on these objects and quickly access information. The web technology is based on the Google Maps Application Programming Interface (API). The available information on the website includes measured and forecasted discharges, reservoir level evolution and optimal preventive operations to minimize the downstream peak. The second unit of the DSS is a GIS database named Expert Area. The catchment is divided into six large zones that are coherent from a geographical and hydrological point of view. These entities make it possible to synthesize the hydro-meteorological information and give a global vision of the basin.

3.5.3. Operation evaluation module

Operation evaluation module plays an important role in the DSS. The accuracy of forecasting model or forecaster, as well as the advantages and disadvantages of operation strategy can be evaluated through retrospective evaluation of flow forecasting process, operation strategy and running process, thus to improve the accuracy of flow forecasting and operation level of reservoirs in the basin.

In China, traditional forecasting and operation evaluation mainly adopts a single process to assess the operation performance of cascade reservoirs on the upstream of the Yangtze River. However, without systematic evaluation and closed loop feedback, it is impossible to improve operation level. Based on long series of data, the operation evaluation module of the DSS is used to evaluate the forecast results and cascade reservoirs' operation plans and running results. More specifically, the hydrological forecasting results of different forecast software or forecasters are evaluated by the module, based on long series of runoff data. Afterwards, improved methods and applications of forecasting software are proposed to improve the prediction accuracy. According to the ensemble forecast results, the module presents an adapted evaluation method, and gives the confidence level of forecasting results. The module is implemented after the evaluation of the operation plan, and then the evaluation and feedback are carried out again. Also, when the cascade reservoirs change, the module can quickly and scientifically assess the impact of these changes to make corresponding operation strategies.

In Iran, an economical DSS module was basically needed for evaluation of water resources planning scenarios from an economical point of view, in the big Karun basin. The module computes agriculture and hydropower benefits along with flood inundation damages based on crop income, power network characteristics, and floodplain properties. Then economic indexes such as cost/benefit ratio, net benefit, and internal rate of return are determined by investment & operational costs and the benefits of the projects for each scenario.

4. CONCLUSION

This research systematically summarizes the characteristics of integrated operation of typical cascade reservoirs and hydropower stations throughout the world, and some key technologies are also introduced. It can be summarized into the following four points:

(1) More and more reservoirs are built on a same river basin. Integrated operation may involve many developers and different nations. The operation activity is being transformed from single-reservoir operation to integrated operation of cascade reservoirs.

The internal connections and mutual complementation between cascade reservoirs make it possible to operate them according to the overall conditions of the river basin while taking all factors into consideration to fully develop and utilize water resources, and enhance water use efficiency. By coordinating points (reservoirs), lines (rivers) and planes (basins), the two main purposes of flood control and utilization benefits can be better achieved. Therefore, since the 1950s, with the planning and development of hydropower cascades being widely carried out throughout the world, integrated operation of cascade reservoirs has also been implemented by many countries with noticeable social and economic benefits.

(2) With the water demands increasing continuously, more and more factors are being considered in reservoir operation. Single-objective operation can no longer meet all the needs. We have now entered the age of integrated multi-objective cascade reservoir operation.

The operation and regulation of reservoirs plays important roles in many aspects, such as flood control, impoundment and power generation, agricultural irrigation, urban and rural water supply, navigation and transportation, aquaculture and ecological environment protection. In traditional reservoir operation, only one important function is emphasized, considering the major development objective as the basic one and other objectives as constraints. With more and more factors being considered for reservoir operation, traditional single-objective operation can no longer meet the requirements, which is why multi-objective optical operation of cascade reservoirs came into being. According to the requirements in multi-objective operation of cascade reservoirs, besides comprehensively considering the objectives such as flood control, water supply, power generation, irrigation, navigation and ecological dispatch, the social, economic and ecological protection benefits of reservoir operation must be rationally coordinated. Under the condition that the safety of flood control is ensured, the demands of entities for water quantity and quality must be coordinated as a whole to rationally regulate water resources and maximize the comprehensive benefits of cascade reservoirs.

(3) The application of new technologies provides a means for integrated operation of cascade reservoirs and makes multi-objective optimal operation feasible.

Integrated operation of cascade reservoirs is a complex process of management and decision making, which covers multiple aspects. During the real-time operation of cascade reservoirs, many countries encounter various problems, such as the reliability of data collection, uncertainty in meteorological and hydrological prediction, real-time and dynamic characteristics in the decision-making process, and the limitations of mathematical models and optimization techniques, which make decision making regarding reservoir operation unstructured. At present, the continuous progress of hydro meteorological forecasting, big data and IT application technologies have bred some new theories and key technologies related to integrated operation of cascade reservoirs, such as refined numerical weather forecasting, hydrological probability forecasting, and decision support technologies. Meanwhile, a series of operation tests have been carried out according to the research results as well as the characteristics of river basins and reservoirs.

(4) Smart operation of cascade reservoirs is indispensable, and the integrated operation of reservoirs and hydropower stations will be the main development trend.

With the continuous development of cascade hydropower stations in management based on the river basins, market rules and integration of multiple functions, a new type of smart operation of cascade hydropower stations has appeared which will become an irresistible trend in the future. At present, "Smart +" has witnessed relatively mature application in cities, transportation, medical treatment and other domains, but it still awaits more exploration in the operation of hydropower stations. In the future, under the guidance of human beings' intelligent mechanisms and based on the Internet / Internet of Things, big data, cloud computing, mobile communications, artificial intelligence, etc., smart operation will aim at safe, efficient and sustainable use of water resources in river basins, establishing a brand new operation method that features self-learning, self-control, self-adaptation and self-evolution capabilities, which can intelligently perceive, judge and analyze the huge amount of information in the water resources system, and conduct smart response, decision making and evaluation to guarantee the safety of the hydraulic complex, and social & economic benefits. This will definitely contribute to the efficient operation and intelligent development of hydropower in the future.

5. CASES

The following examples of six countries are related to the contents mentioned above, but each nation has its specific priority since their conditions are not the same. The cases of some countries, such as those of Canada and Iran include quite detailed description of a water resource management decision-making support system based on the typical river basin characteristics of each country. The cases of other countries provide a more detailed description of cascade reservoir operation. For example, the cases of China and Japan present the experiences in cascaded reservoir operation for flood control, power generation, navigation and ecological purposes. The case of Sweden presents a description of flood forecasting; while the case of Cameroon provides a detailed report on integrated optimal management of hydropower stations and cascade reservoirs.

5.1. Water management for integrated optimal operation of hydropower stations and reservoirs of the Sanaga River waterfall in Cameroon

5.1.1. Introduction

Cameroon is a resource rich country in term of hydropower, with a potential estimated at more than 20,000 MW. About 50% of this potential is located on the Sanaga River, the largest river in the country. The climate in the Sanaga catchment is shared between a tropical climate and an equatorial climate. The hydrologic regime of the Sanaga River is quite variable within the year, with flow rates going from 8,000 m^3/s during the wet season to less than 100 m^3/s in the dry season. The network of the Sanaga watershed is subdivided into five sub-basins according to the meteorological and hydrological conditions as well as artificial correction.

The optimal water management for the efficient operation of the Song Loulou and Edea hydropower stations can be divided into several categories: annual operation management of the river basin system, daily operation management for the next three months, weekly operation management and daily operation management for the next five days.

Integrated optimal operation of hydropower stations and reservoirs of the Sanaga river waterfall is nowadays based on the four upstream reservoirs, namely Bamendjin (1.8 billion m^3), Mape (3.3 billion m^3), Mbakaou (2.6 billion m^3), Lom Pangar (6 billion m^3) and the two hydropower stations at Song Loulou (384 MW) and Edéa (265 MW), which make up the interrelated Sanaga River hydropower system. These are, at present, the main power-generating capacity of Cameroon's Southern interconnected grid. The Edéa Hydropower Station was the first to be constructed. In the beginning, the units could operate all year at virtually full capacity, even in the dry season, essentially in run-of-river mode. Afterwards, with additional hydropower stations and due to insufficient natural flow in the Sanaga, four regulating reservoirs were progressively built in the upper reaches of the Sanaga system at Mbakaou (1967), Bamendjin (1974), Mapé (1988) and Lom Pangar (2016).

Lom Pangar reservoir, first step for the implementation of this strategy, has been regulating downstream water levels in the Sanaga River by storing 6 billion m^3 water during the wet season and releasing it during the dry season. The second step is the progressive development of cascade hydropower stations on the Sanaga River, downstream of the Lom Pangar, Mapé, Bamendjin, and/or Mbakaou reservoirs. Nowadays, due to climate change, the challenge is the best use of available water resources for integrated optimal operation of the hydropower stations on the Sanaga River.

This section therefore aims to presents the water management for integrated optimal operation of hydropower stations and reservoirs of the Sanaga River.

5.1.2. Types and characteristics of the Sanaga cascade

The cascade of the Sanaga River is a mixed type. It is now a group made up by the reservoirs of Bamendjin, Mapé, Mbakaou and Lom Pangar, and by the hydropower stations of Song Loulou and Edéa, in operation, and the Natchigal hydropower station under development (Fig. 5.1-1, left part). The Sanaga River has four main tributaries: the Lom, Djerem, Mbam and Noun rivers. The Sanaga hydropower potential includes these tributaries. Figure 5.1-1 (right part) below presents the national water system and hydropower potential of the Sanaga River.

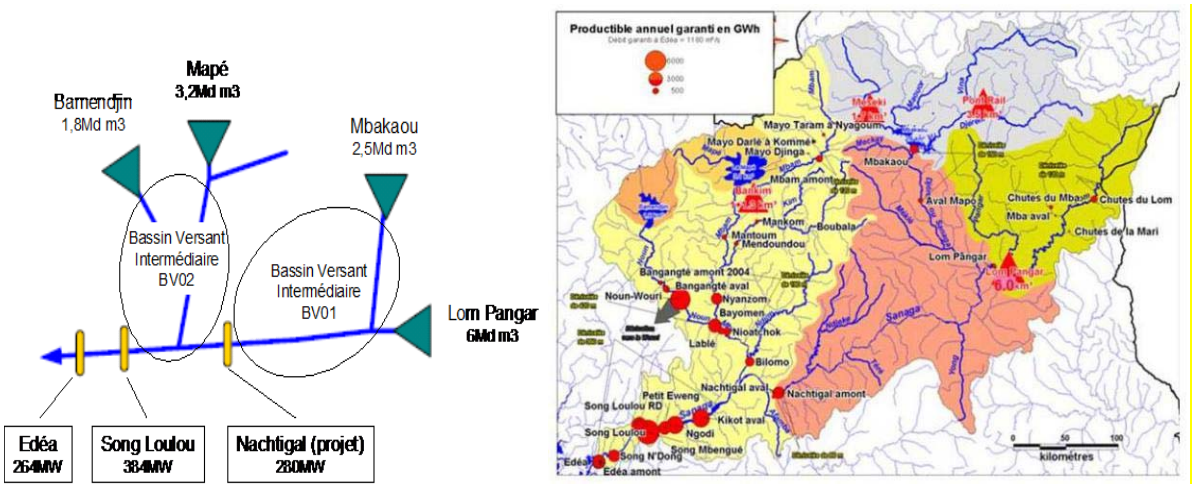


Fig. 5.1-1 Reservoirs and hydropower stations in the Sanaga River basin

5.1.3. Hydrologic regime of the Sanaga River, water resources reserves and uses

The Sanaga River flows for 918 km from its source on the Adamawa Plateau to its mouth in the Gulf of Guinea. The river drains a basin of approximately 130,000 km^2, which accounts for a quarter of Cameroon's land area. A tiny portion of the Sanaga basin is located in the Central African Republic, but the basin is considered a national basin. The hydrologic regime of the Sanaga River is quite variable within the year, with flow rates of seasonal fluctuations. The climate in the Sanaga catchment is shared between a tropical climate and an equatorial climate. The annual means of rainfalls are spatially heterogeneous over the watershed. The annual average of rainfall varies between 1,355 mm/year at Nachtigal (located in the midstream of the Sanaga, upstream of its confluence with the Mbam river) and 2,639 mm/year at Ngambe (located in the midstream of the Sanaga, downstream of its confluence with the Mbam river). The steep slope of the Sanaga River (1m/km), its high flow rates, the four existing regulating reservoirs of Mapé, Mbakaou, Bamendjin and Lom Pangar, explain the exceptional hydropower potential of this river. The Sanaga basin plays a critical role in Cameroon's economic development, and the river and its basin are used for multiple purposes. Although only a small part of the population of Cameroon lives in the basin, hydropower on the river produces 95% of the country's electricity. The river is the source of drinking water for several cities. Industrial water use is still limited, while local communities depend on the river water for agriculture, livestock, and fishing. Annual water use in the Sanaga basin for 2012 is estimated at 27.8 billion m^3. This is considerably lower than the volume of water flow at Edéa. However, water demand surpasses supply during part of the dry season when hydropower stations in the basin cannot function at full capacity due to insufficient water flow. Approximately 23% of the 266 billion m^3 of Cameroon's surface water resources are located in the Sanaga basin. The volume of water flow at Edéa (near the mouth of the river) is approximately 60.64 billion m^3 per year. Annual averages have significant seasonal variations between the dry season and the wet season. Water availability in the Sanaga Basin has varied over time including, for example, a relatively wet period from 1950 to 1970 and a relatively dry period in the 1980. The main non-consumptive water use in the Sanaga River is electricity generation. Its regular and strong flow rates during the wet season, and the existence of regulating reservoirs contribute to a high hydroelectric potential. The two hydropower stations at Edéa produce 95% of the electricity generated in Cameroon. The Lom Pangar hydropower station that has started operation in 2016 has increased the economic viability of cascade hydropower stations on the river – several of which are under study.

5.1.4. Water management activities

5.1.4.1. Data collection and decision support system

The best forecast and a good operation model are the key for optimal water management for integrated operation. The effectiveness of the actions is dependent on the control of hydro meteorological information from the entire watershed upstream of hydropower stations. The Sanaga watershed is subdivided into five sub-basins namely: i) the Mbakaou sub-watershed with an area of 20,400 km^2 and its maximum storage capacity being 2.6 billion m^3; ii) the Mapé sub-watershed with an area of 4,020 km^2 and its maximum storage capacity being 3.3 billion m^3; iii) the Bamendjin sub-watershed with an area of 2,190 km^2 and its maximum storage capacity being 1.8 billion m^3; iv) the Lom Pangar sub-watershed with an area of 19,700 km^2 and its maximum storage capacity being 6 billion m^3; v) the midstream and downstream sub-watershed of the Sanaga River, of which its storage capacity of the four reservoirs (14 billion m^3) are controlled by the Song Mbengue Hydropower Station.

The equipment of each power station consists of: generating units, sensors for data acquisition, a data storage and periodic transmission system, a METEOSAT transmitter, rainfall sensors, air temperature and humidity sensors, wind sensors (direction and speed), PLS level sensors, and power supply by 30 W solar panels, with buffer battery.

The equipment is completed by a portable PC connectable to the central units via infrared or RS232 to recover the data. The ground receiving station is a PC for data retrieval via the internet from the EUMETSAT website. The gauging equipment includes an oxygen measurement system, which measures the hydrological parameters of rivers through a Doppler velocimetry system located in the ecliptic zone.

Relevant data of the Sanaga River basin available on the network include meteorologic data (36 stations: temperature, humidity, wind & rainfall); and hydrologic data (18 stations: water level & flow rates). There is a real-time hydro meteorological data collection system which is reliable and efficient, without control protocol. A certain level of quality is nonetheless ensured by those in charge of hydrology who empirically control the data received. The data is stored on Excel for historical data, and in the receiving server system.

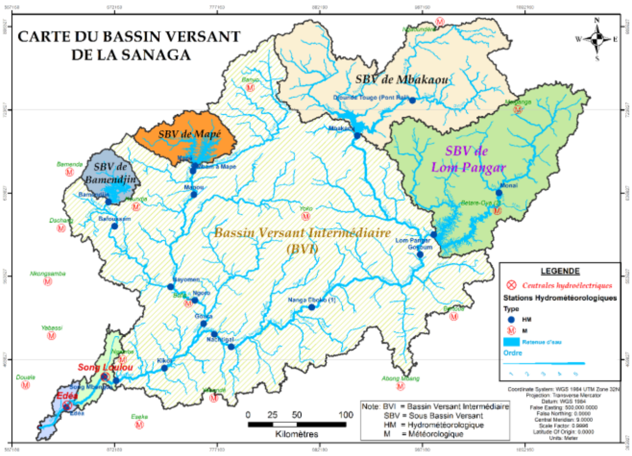


Fig. 5.1.2
Map of the watershed, hydro and weather stations of Sanaga

5.1.4.2. Forecasting and reservoir operation

The runoff law of the lakes at upstream is analyzed using an Excel-based tool, which allows the reservoir inflow to be predicted and corrected according to the historic runoff data observed during the last three years. The filling of the dams generally starts at the beginning of July and ends early in December. A filling report is revised at the end of November to refine the operation objectives which usually starts in the first week of December and ends around the last of June. The objectives of optimal water management for the efficient operation of the Song Loulou and Edéa hydropower stations are planned as well:

Long-term: preparation of an annual water management plan with a time step of 2 months based on the statistics of water demand. The objective is to compare this demand with the natural inputs in order to determine the water supply plan of each reservoir, and maintain a certain amount of water and avoid a large water gap in the dry season.

Mid to long-term: preparation of a monthly water management plan for the next quarter with a time step of one day on the basis of the annual management plan.

Mid-term: preparation of a fortnightly water management plan on the basis of the quarterly management plan.

Short-term: preparation of a five-day water management plan on a basis of the fortnightly management plan to ensure continuous optimal management for the current hydrological situations and effectively deal with any unforeseeable events (uncertainty of installed capacity and energy demand, etc.).

The operation plan defines the water supply priority: the water is first supplied by Mbakaou, followed by Lom Pangar. Mapé and Bamendjin serve as support for reservoir operation. This strategy can realize continuous water supply of each power station in the dry season, maximize the water storage capacity of each lake, and provide continuous water supply for the later period, so as to realize the optimal operation for up to 3 years.

5.1.5. Water resource management

Reservoir operation is performed in the forms of reservoir impoundment and regular operation.

5.1.5.1. Water impoundment in 2017

Reservoir impoundment begins in early July and ends in early December. The impoundment of each reservoir is carried out according to a pre-defined plan. The initial schedule for the Bamendjin and Mape dams is two impoundments every year.

Before impoundment in 2017, the remaining volume of all reservoirs was 2.794 billion m³ (May 2017). In the end of November 2017, the aggregate impoundment volume of the four reservoirs was 13.172 billion m³ (94% of total capacity). Details are as shown in Fig.5.1.-3.

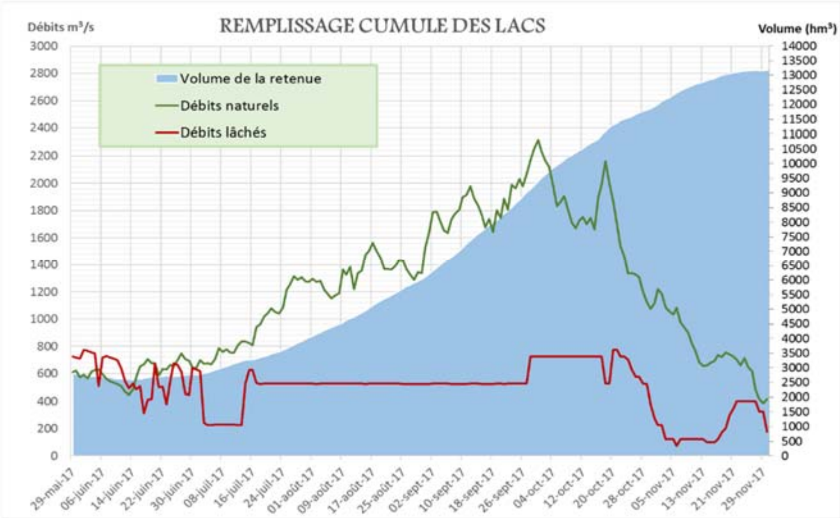


Fig. 5.1-3

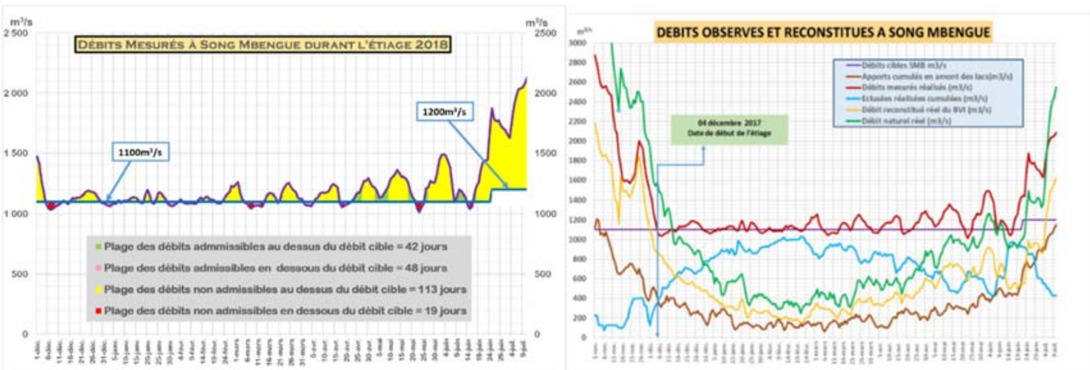
Reservoir impoundment process

5.1.5.2. Regular impoundment in 2018

When the inflow is lower than 600 m³/s, the outflow of the Sanaga River is used to replenish the downstream. The discharge volume of the reservoir is increased to realize the water replenishment target. If rainfall fails, the flow rate will continually decrease in an exponential manner.

In the integrated operation of the four reservoirs, the reservoirs are divided into two groups, namely group 1 and group 2. Group 1 is composed of the Lom Pangar and Mbakaou reservoirs, while group 2 is composed of the Bamendjin and Mapé reservoirs. Group 2 is the backup of group 1. To accomplish the impoundment plan 95% of the time during the whole year, the flow target of Song Mbengué in 2018 is set at 1,050 m³/s, and the total impoundment volume is set at 13.172 billion m³. Since BIV has good hydrological conditions, the target flow rate is increased to 1,100 m³/s when reservoir operation begins. Therefore, the active power of Edéa Hydropower Station is maintained at around 200 MW.

In this way, the operation target of the Sanaga River in 2018 is realized. In the dry season, the deviation is ±3%; in the wet season, the deviation is +10% and -3%. The target flow rate is marked in yellow. The deviation is mainly caused by the absence of a control model for the intermediate basin.



In the dry season of 2018, the measured flow rate of Song Mbengué is 700 m³/s, which can meet the water impoundment requirement 70% of the time. The average flow rate in this period is set at 1,192 m³/s, which is 8% higher than the target value.

The natural flow rate in dry season is different from that of the previous year. When the inflow is inadequate, the average hydrological trend is 45%. The observed minimum flow rate on February 21, 2018 is 248 m³/s.

5.1.5.3. Accumulative water volume and flow rate in the dry season of 2018

The dry season of 2018 ends on July 5. The accumulative water replenishment volume of Lom Pangar, Mbakaou, Mape and Bamendjin is 2.858 billion m³.

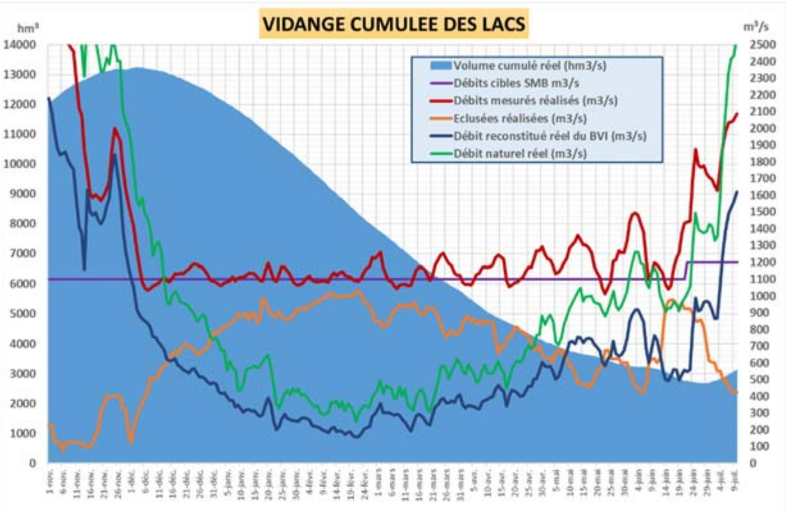


Fig. 5.1-4

Operation process and accumulative water replenishment volume of four power stations in the dry season of 2018

5.1.5.4. Comprehensive benefits of integrated operation of cascade reservoirs in the dry season

Lom Pangar, Bamendjin, Mapé and Mbakaou are a part of the reservoir operation plan. In the dry season of 2018, to meet water supply and power generation needs at the downstream, the four reservoirs were impounded to their full capacities on November 30, 2017. The minimum flow rates of Song Loulou Hydropower Station and Edea Hydropower Station in the dry season of 2018 (December 4, 2017 through July 5, 2018) were increased to 1,062 m³/s. The impoundment volume of the four reservoirs was enough to sustain the average available capacity of Song Loulou Hydropower Station and Edéa Hydropower Station at 594 MW (power generation volume is about 3,250 GWh and the contribution rate is about 32%). In this way, the electric power company saved about 4 billion francs of thermal coal.

5.1.6. Conclusion

The cascade of 2 hydropower stations and 4 reservoirs currently in operation on the Sanaga River have significantly improved the power generation and comprehensive utilization benefits thanks to the forecast-based operation mode. Factors influencing the change of hydrological elements are the observation of hydrological elements, data compilation, hydrology rules obtained from limited actual data analysis and forecast methods. On account of some errors, it is possible that the accuracy of the operation mode has been affected. The integrated optimal operation of cascade reservoirs and hydropower stations of the Sanaga River has generated remarkable economic benefits since the impounding of Lom Pangar.

To continuously improve water management on the Sanaga River, it is important to refine the forecasting system, to increase the density of the observation equipment network, and to develop a reliable model to control the behavior of the intermediate watershed.

5.2. Decision making support system for the regulation of the OTTAWA River basin

5.2.1. Introduction

Canada is blessed with plentiful water resources as it ranks fourth in the world for freshwater resources. Over the centuries, Canadian lakes and rivers have been used for various purposes including navigation and using the power of water for various industrial uses such as water mills that have been constructed since the 18th century. Waterpower for producing electricity started in Canada in the late 1800s with one of the first hydropower stations built being located at Chaudière Falls on the Ottawa River. While dams had been built early in the development of Canada, larger dams for the purpose of flood control and river regulation were constructed essentially starting in the early part of the 20th century. Over the course of the 20th century, further development of water resource infrastructures took place, which included construction of more dams for water management purposes as well as larger hydropower developments to provide electricity for an increasing population. The case study presented in this section is related to the Ottawa River Basin, in particular to the technical work undertaken by the Ottawa River Regulation Planning Board (ORRPB) to ensure the integrated management of the flow from large reservoirs within the basin for the purpose of minimizing the impact of floods and droughts.

5.2.2. Description of the OTTAWA River Basin

5.2.2.1. Hydrography

From its source east of the Dozois Reservoir to its confluence with the St Lawrence River, the Ottawa River has a length of more than 1,130 km. The Ottawa River constitutes the principal tributary of the St. Lawrence River and for most of its length forms the boundary between the provinces of Ontario and Quebec. Its basin has a total area of 146,300 km^2, 65 percent of which is in Quebec and 35 percent in Ontario. The topography of the basin consists predominantly of a lowland area and two mountainous formations: the Laurentians on the left bank and the Algonquin dome on the right bank. Mont-Tremblant has the highest altitude (967.5 metres) and the minimum altitude within the lowlands is of approximately 40 metres. The Ottawa River has a dense hydrographic network encompassing 19 tributaries of over 2,000 km^2 in area. The largest of the tributaries, both in terms of length and discharge volume, is the Gatineau River.

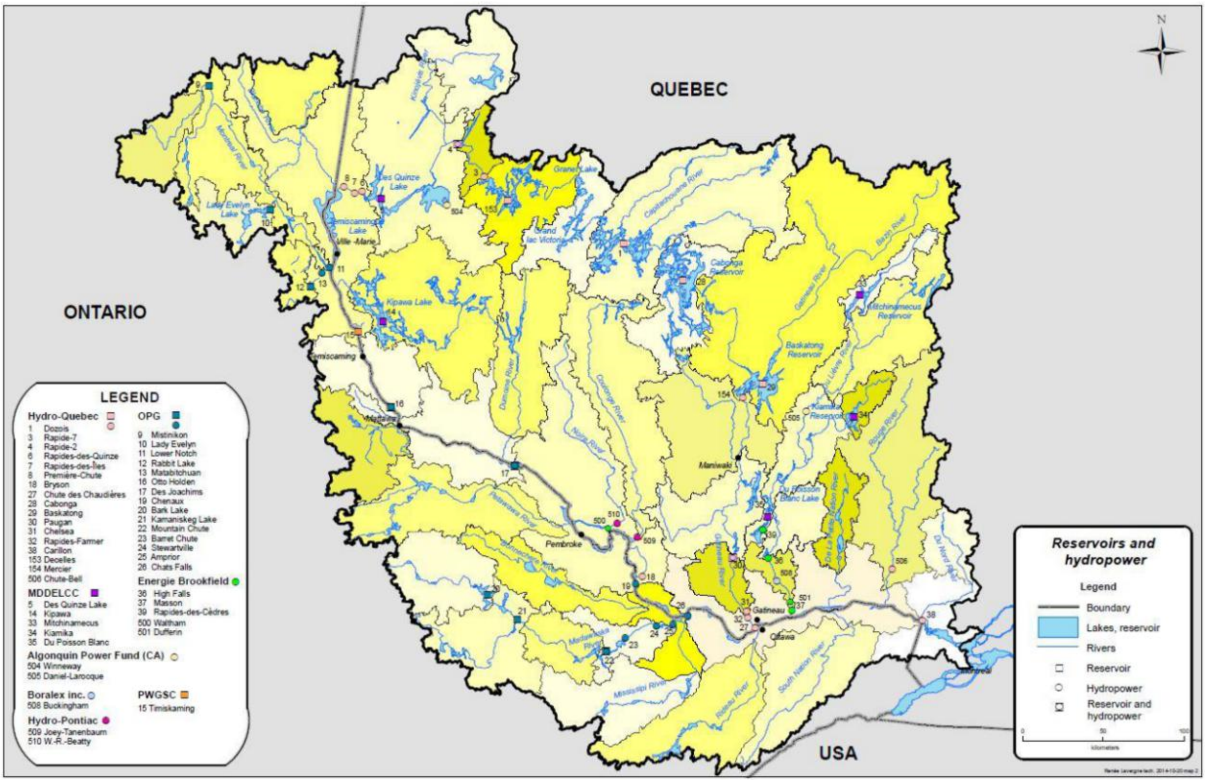


Fig. 5.2-1
Map illustrating the Ottawa River basin along with major sub-basins and hydropower stations.

5.2.2.2. Dams/reservoirs and hydropower stations

The idea of using large natural lakes to store water took hold in the early twentieth century in connection with the requirement for a more uniform flow for navigation and power developments on the lower reaches of the river. This led to the construction of the Quinze, Timiskaming and Kipawa reservoirs, between 1911 and 1914, by the federal government. At that time, the Chaudière structure was the only hydropower station on the river system. Currently, there are thirteen large reservoirs within the basin that each has usable capacities of more than 200 million cubic meters. These reservoirs, which combined have a total storage capacity of 12,115,000,000 m^3 (or 12,155 million m^3), are subject to integrated management under the ORRPB policies. Table 5.2-1 provides a list of these reservoirs along with their storage capacity, the year the reservoir was built, and the dam operator. Regulation of river flows is made possible by storing part of the river's natural runoff in these major reservoirs during spring and releasing it at other times during the year. In addition to these 13 main reservoirs, another 14 smaller reservoirs also provide limited storage. Given the small storage capacity of these other reservoirs, they are not included in the Decision-Making Support System that is discussed in this section.

Table 5.2-1
List of main reservoirs within the Ottawa River basin

River	Reservoir	Year Built	Reservoir Operator	Capacity (million m^3)
Ottawa	Dozois	1949	HQ	1,863
	Rapide 7	1941	HQ	371
	Quinze	1914	MELCC	1,308
	Timiskaming	1911	PSPC	1,217

	Des Joachims	1950	OPG	229
Montreal	Lady Evelyn	1925	OPG	308
Kipawa	Kipawa	1912	MELCC	673
Madawaska	Bark Lake	1942	OPG	374
Gatineau	Cabonga	1928	HQ	1,565
	Baskatong	1926	HQ	3,049
Lièvre	Mitchinamecus	1942	MELCC	554
	Kiamika	1954	MELCC	379
	Poisson Blanc	1930	MELCC	625

Notes:

HQ: Hydro-Québec

MELCC: Ministère de l'Environnement et de la Lutte contre les changements climatiques (Québec)

OPG: Ontario Power Generation

PSPC: Public Services and Procurement Canada

Hydropower stations have been constructed on the Ottawa River since the late 1800s. There are 43 hydropower stations located within the basin ranging in size from less than 1 MW to 753 MW with a total of over 4,200 MW (Canadian Hydropower Association, 2019). These hydropower stations represent a significant portion of the hydropower generation capacity for both Hydro-Québec and Ontario Power Generation. Other independent power producers also own and operate hydropower stations within the basin. However, given the limited size of their reservoirs, they do not have a significant impact on minimizing the impact of floods and droughts in the river downstream.

5.2.2.3. ORRPB Structure

The Ottawa River Regulation Planning Board and Ottawa River Regulating Committee were established with the objective of ensuring integrated management of the principal reservoirs. Following a devastating flood in 1974, particularly in the Montreal region, the federal and provincial governments began to take steps to attempt to reduce the amount of damages incurred. Another large flood occurred in 1976, apparently increasing the efforts.

These efforts culminated with the signing of a Canada-Quebec-Ontario Agreement Respecting Ottawa River Basin Regulation (the Agreement), which established the Ottawa River Regulation Planning Board, the Ottawa River Regulating Committee (ORRC) and the Ottawa River Regulation Secretariat (ORRS). Various organizations that form this Planning Board include federal and provincial agencies as well as power utility companies, namely Hydro-Québec and OPG.

The role of the ORRPB is to ensure the integrated management of flows from the reservoirs listed in the Agreement and to formulate policies and criteria for their management. The Regulating Committee is tasked with enacting and formulating appropriate regulation and operational practices and procedures to ensure that operation of the principal reservoirs is carried out in accordance with the regulation policies and criteria adopted by the Planning Board. Finally, the Secretariat’s role is to act as an executive arm of the Planning Board by collecting and analyzing data; reporting and forecasting on hydrological conditions in the Ottawa River basin; developing and operating mathematical models to carry out the mandate of the Board; and maintaining the ORRPB website (http://www.ottawariver.ca/).

5.2.3. Technologies for integrated operation of hydropower station and reservoirs

This section of the paper introduces the various aspects for integrated operation of hydropower stations and reservoirs. This includes various steps from data acquisition, to meteorological and hydrological modeling, and finally to the implementation of a Decision-Making Support System for optimal operation of the reservoirs.

5.2.3.1. Data acquisition

To run the various models used to assist in the management of the Ottawa River basin, a large amount of data is collected, verified, calculated and transmitted on an hourly, daily or weekly basis depending on the season. Knowledge of water levels, discharges and snow conditions is essential to assessing basin hydrological conditions and forecasting the hydrologic response of the tributaries and the main stem of the Ottawa River. The location of hydrometric stations is illustrated in Figure 5.2-2.

In addition, meteorological data, particularly temperature and precipitation, are collected on a daily basis for use in the natural inflow forecasting model. The meteorological data available is captured from 151 meteorological stations located both within the watershed and at locations just outside of the basin. Similarly, snow survey data is measured at 79 stations within the basin. In addition to these stations, another 38 snow stations located outside of the basin are also used as part of the data analysis to describe current snow conditions in the basin.

Among the data collected are the “declarations” by dam operators of their anticipated operation plan for each individual dam. These declarations of reservoir elevations or discharges represent the intent of the operators at each of the reservoirs and hydropower stations.

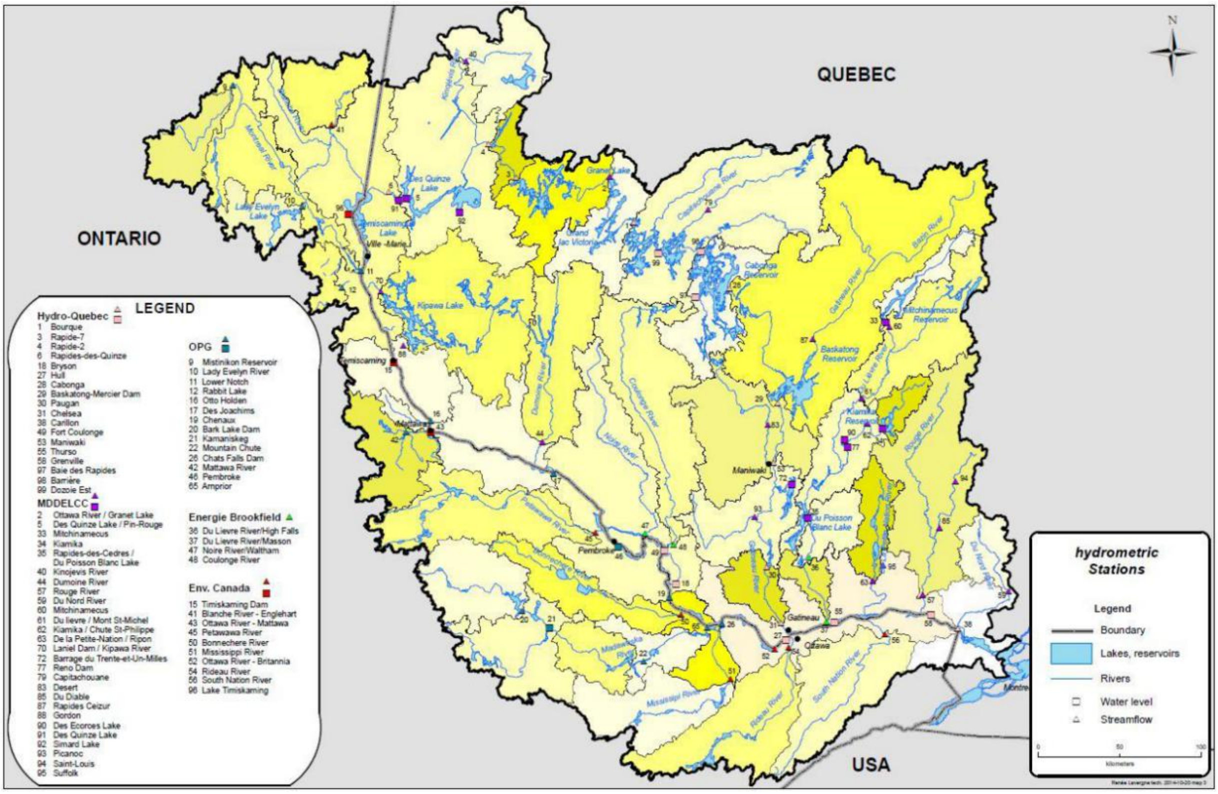


Fig. 5.2-2
Location of hydrometric stations within the Ottawa River basin

The first step is to acquire data through real-time observations. Depending on the type of data, the Hydro-Québec and ORRC jointly set up computerized systems to perform automatic data acquisition. The data are archived and transferred to the various tools that use them. There are four large categories of data:

a) Hydrological data include water levels, flows and water temperatures. Water levels in reservoirs are used to calculate storage, while levels in rivers are used to calculate flows through the use of rating curves. Flow data include turbine flows, spillage, and inflows. Water temperature data provide indirect information about the freeze-up and ice-melt conditions on the rivers and reservoirs.

b) Snow data include snowfall amount, snow density and snow water equivalent. The snow surveys and GMON data from all partners are centralized and interpolated to produce basin averages which are adjusted in the hydrological model.

c) Meteorological data include data collected using a wide variety of conventional sensors employed in the network of synoptic meteorological stations. Since these data are inputs to the hydrological model, the main data are air temperature and measured precipitation, but also include relative humidity, atmospheric pressure and solar radiation. Lastly, data on wind speed and direction can help explain variations in measurements of reservoir water levels. Other sources of information, for example radar imaging or Environment Canada’s Regional Deterministic Precipitation Analysis (RDPA), are also consulted without being formally collected, at least for now.

d) Electricity generation data, including the electricity (in MW) from the generating units in the plants, are used to calculate the turbine flows. This category also includes the data on floodgate openings, which are used to calculate spillage flows related to maneuvers at the facilities.

Data validation:

Once data acquisition is complete, the data must be validated. This step includes the following actions:

a) Detect missing data or outliers. When problems are discovered, the teams responsible for the equipment are contacted and repair and/or maintenance visits are planned. The validation team then follows up on those visits.

b) Correct missing data or outliers manually.

c) Define the physical state of precipitations and separate the total amounts measured as rain and as snow (two inputs of the HSAMI model).

d) Calculate the basin averages for the meteorological data and snow survey data, using the Kriging method of interpolation.

e) Calculate the inflows observed in the past few days by means of water balances or average measured flows.

Once the validation has been completed, the observed hydrological and meteorological data are ready to be used in the hydrological forecasting step. The only other inputs required in order to proceed with the forecast are the meteorological forecast scenarios.

5.2.3.2. Meteorological forecasting

The meteorological forecasting step is crucial because it is the source of a large part of the uncertainty inherent in any hydrological forecast. Every day, various model outputs are available to the meteorologist. Since each model “sees” the physical world in its own way, the forecast scenarios produced by different models are sometimes similar but may also sometimes be very different.

The current meteorological forecasting procedure is as follows:

a) Analysis of the current and past meteorological context. The meteorologist compares the output of the model with the observations from the previous day and the first six hours of the day.

b) Analysis of the future meteorological context. The meteorologist compares the output from the deterministic models—Canadian (GDPS and RDPS), American (GFS and NAM), and European (ECMWF)—as well as the North American Ensemble Forecast System (NAEFS).

c) Construction of meteorological scenarios. Based on the previous analysis, the weather grids will be modified to a resolution of 1° to obtain the most likely weather scenario for probability of exceedance. Three grids—total precipitation, minimum temperature and maximum temperature—are modified using the time-steps in the Canadian models, i.e., 6-hour time-steps for the first 48 hours and 12-hour time-steps for the following days. The type of precipitation is determined automatically based on a temperature threshold. Also during this step, depending on the level of certainty and the hydrological context, the meteorologist will decide on the forecast horizon, which can vary from 4 to 9 days.

d) Based on the grids, an interpolation is performed and the averages are calculated for all the watersheds. Lastly, to assess uncertainty, weather scenarios for 85% and 15% probability of exceedance are constructed.

5.2.3.3. Hydrological forecasting

HSAMI is the operational hydrological model used within the ORRC. It was developed at Hydro-Québec (Bisson and Roberge, 1978) and is a global conceptual model that was modernized about 15 years ago (Fortin, 1999). The term “conceptual” means that the physical processes within the model are approximated using empirical relationships rather than the laws of physics. The term “global” means that the watershed is represented as a single, homogeneous spatial entity. Thus, the spatial variability of the processes is not explicitly taken into consideration. For example, a global model does not differentiate between rain that falls in the upstream portion and the downstream portion of the watershed. A global conceptual model is simpler but less demanding in terms of data entry and calculation time.

HSAMI uses the following inputs: daily minimum and maximum temperatures, rainfall and snowfall. Figure 5.2-3 shows the interactions between the different processes within HSAMI. Precipitation falls either on the ground or into the reservoir. Then, depending on soil saturation and ground frost conditions, the water may accumulate on the ground as snowpack, infiltrate vertically into the sub-surface soil or flow horizontally via the surface runoff hydrograph. With vertical infiltration, the water recharges the aerated zone and the saturated zone, and is then routed through the intermediate hydrograph and the base hydrograph, respectively. At the same time, the evapotranspiration process removes water from the snow cover, the soil surface, the vegetation and the surface of the reservoir and returns it into the atmosphere in the form of water vapor. Lastly, the natural inflows are defined by the sum of the three discharge hydrographs (surface, intermediate, and base). In HSAMI, the physical processes and their interactions are governed by parameters which are set during calibration of the model. HSAMI contains 23 parameters: 2 for evapotranspiration, 6 for processes involving snow, 3 for surface runoff, 7 for vertical infiltration, and 5 for horizontal flow. The model has 23 parameters, which can form several thousands of combinations. Iteration process is used to find the optimal solution. The best solution is the parameter combination with maximum NASH–Sutcliffe efficiency.

Before it can be used in an operational setting, the model must be put through the calibration process, and the calibration must be done independently for each watershed. The purpose of the calibration is to ensure that the model reproduces the hydrological behavior of a watershed as accurately as possible based on past observed data. To perform the calibration, daily series of minimum and maximum temperatures, precipitation (rain and snow) and calculated or measured inflows taken over a common period are required.

Calibration is an important work that determines behavior of model in specific operation mode. Obviously, better is the calibration data, higher is the model performance. If a model is well calibrated, a forecaster can save a lot of trouble in inflow forecasting. A good calibration sets a sound basis for forecasting activities and saves a lot of forecasting time.

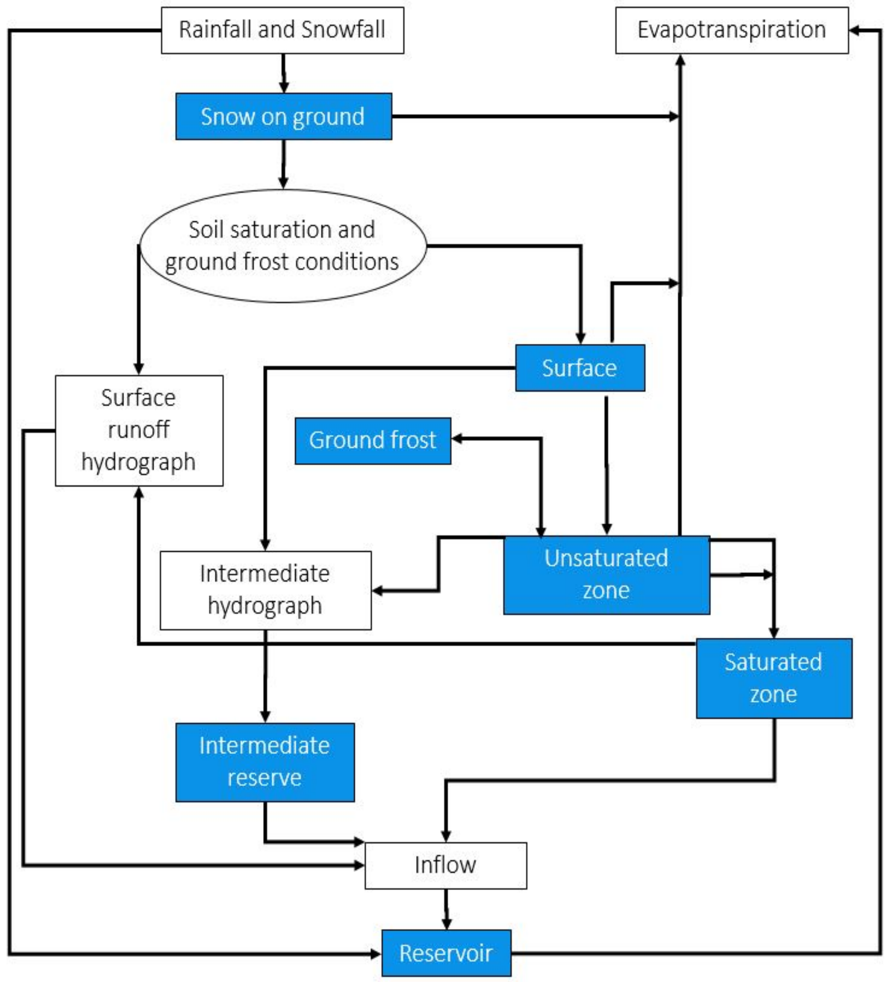


Fig. 5.2-3
The HSAMI conceptual model

5.2.3.4. Decision-making support system

This is a brief description of the HEC-ResSim model and its application in the operation planning of the Ottawa River system. For regulation planning of the Ottawa River system, the watershed model component of the HEC-ResSim model is omitted since the natural inflow forecasting model HSAMI, produced by Hydro-Quebec, is currently used. Output from the HSAMI forecasting model is fed into the HEC-ResSim model for use in the other two components, namely flow routing and reservoir operation. The model must be provided with a pre-specified operating plan (water levels or discharge declaration by operators) in order to route flows through storage reservoirs and eventually through river reaches. The HEC-ResSim model was developed by the U.S. Army Corps of Engineers and is the next generation of model replacing the SSARR model. As of January of 2016, the SSARR model had been used by the ORRC ever since the creation of the ORRPB in 1983.

a) The River System Model

This section gives a brief description of the parts of the HEC-ResSim model that are used for Ottawa River regulation, namely the channel and lake routing procedures and reservoir operation.

(1) System Configuration

A schematic representation of the HEC-ResSim model for the Ottawa River basin is shown in Figure 5.2-4. As shown in the figure, the Ottawa River basin is conceptualized as 46 watersheds that contribute runoff (or natural inflows) in specific locations along the physical river system. Starting in the headwater areas, natural inflows are routed and summed up along the physical river system, down to the basin outlet at the Carillon dam.

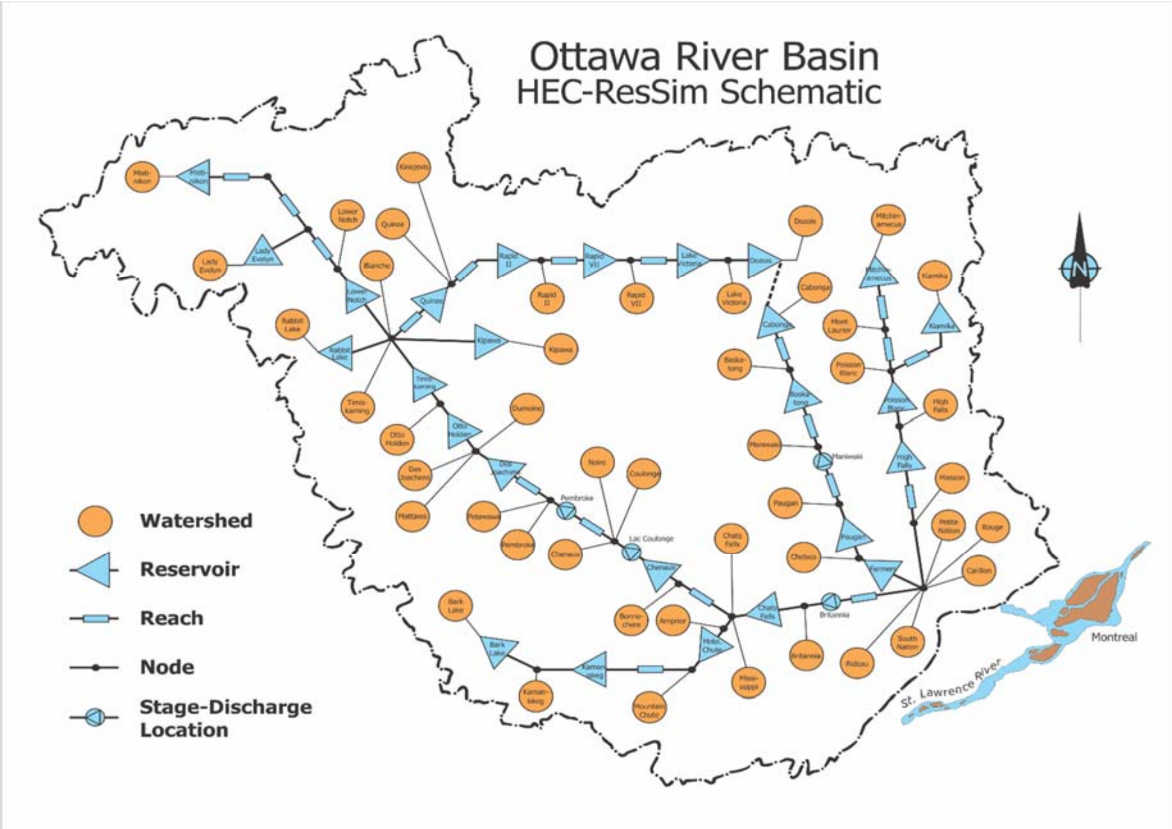


Fig. 5.2-4
HEC-ResSim schematic of the Ottawa River basin

For routing purposes, the physical river system is reduced to a set of interconnected stations of which there are three types. Transfer points are simply nodes in the system through which no routing is done. They typically serve to sum the flows from different branches of the river and as convenient point to introduce measured data. Flows are routed through the two remaining station types: reservoirs and reaches. Combinations of these three station types are linked together for the purpose of computer simulation.

(2) Channel Routing

Reaches are defined as sections of the river system where there is significant travel time (related to the modeling period) and where there is a routing effect on changes in discharge. The HEC-ResSim model uses a time-honored method for stream flow routing that assumes that a reach is divided into a number of increments, each of which is considered to act as a small lake.

(3) Lake Routing

The routing of flow through natural lakes is based upon free flow conditions in which the lake outflow is determined by lake elevation and therefore by hydraulic head. Routing is accomplished by an iterative solution of the storage continuity equation.

(4) Reservoir Operation

The HEC-ResSim model offers three methods of simulating reservoir operation. Free flow routing assumes that elevation-outflow relationships are fixed and that outflow is determined by hydraulic head. Routing is accomplished by an iterative solution of the storage and outflow continuity equation. If time of storage is input as a function of either flow or elevation, the initial estimate for the outflow is obtained from the storage and outflow continuity equation. The outflow is then tested and the calculation is repeated until an acceptable outflow is obtained.

(5) Input of the Model

For the forecasting operations, the model requires the following input:

The reservoir inflow is calculated by the forecasting model HSAMI. The forecasts used are generally the most probable (50% probability) but can be varied depending on the use (e.g. sensitivity analysis).

Changes to bounds for reservoir levels and discharges or changes to any other constraints: all constant or parametric input needed for the operation of the model is built in. The input includes the various physical and operating constraints, the curves that express storage elevation relationships of reservoirs, storage discharge relationships of spillways and channel characteristics.

(6) Initialization of Channel Routing

When the HEC-ResSim model is run, it takes into consideration the previous six days of observed data including calculated inflows, discharges and levels in the system for computing channel routing.

(7) Output of the Model

The output consists of daily or weekly average discharges and water levels calculated at midnight for every daily or weekly period at every specified station applicable to the period of simulation. Note that levels are not provided for a transfer or reach station unless a stage discharge curve for that particular section of the river has been incorporated into the model database. The model currently has four stage-discharge curves, which allows for estimation of water levels at Pembroke, Lac Coulonge, Britannia and Maniwaki.

b) Sensitivity analysis

The ORRC uses sensitivity analyses in various situations to check on the reaction of the system to inflows other than the standard 50% probability of exceedance. It is made possible by the ability of the natural inflow forecasting model to produce forecasts of various probabilities, both in terms of volume and peak. The forecast used for the normal model runs of HEC-ResSim is based on volume and peak with a 50% probability for each inflow site. At times, depending on the situation, it may be useful to see what would happen if the inflows were higher or lower than normal. For example, if there were a particular part of the basin where there was concern that higher than normal inflows would result in a critical situation, the models could be run with a 15% forecast for that section and, perhaps, 50% for the rest of the system.

Sensitivity analysis is used in a wide variety of situations (flood/drought) and it has been the practice of the ORRC to use it whenever requested by the entire Committee or by a single agency concerned about one of their particular sub-systems. The results of sensitivity analysis are standard Short and Mid-Term HEC-ResSim and are made available to all member agencies. If after reviewing the results of a sensitivity analysis, one agency decides to modify its declarations, then HEC-ResSim is run again with the new proposed declarations, and the revised Short and Mid-Term HEC-ResSim results are made available.

c) Sharing of model results

All the models for the ORRC, with the exception of the natural inflow forecasting model, are currently run at the Secretariat. These models are run after the relevant data and forecasts are received from the participating agencies and the results are posted on the Ottawa River Regulation Secretariat FTP site. The format of the model results has been developed and refined over the years to satisfy the needs of the ORRC. Results of the HEC-ResSim Short-Term and Mid-Term models as well as any sensitivity analysis are posted on the ORRS FTP site. Also posted on the FTP site is a weekly report that summarizes the status of the basin.

Snow survey data from different agencies are compiled in a table and presented on a map of the basin indicating the snow cover in water equivalent and in terms of percentage of normal, all posted on the ORRS FTP site.

The results of the models are currently made available to all agencies represented on the Planning Board and the Great Lakes-St. Lawrence Study Office in Cornwall. However, the sensitivity analysis results are only available to the ORRC. This is mainly to ensure that outside agencies do not misinterpret the output of these models.

The ORRS FTP server is an internet-based communications system that allows uploading and downloading of files such as measured data, forecast and model result files. Access to the ORRS FTP server is limited to agencies involved in the regulation of the Ottawa River and those that use the model results for information purposes.

For most agencies, the short-term HEC-ResSim model is a very important tool for decision making. Indeed, for some, this model represents the only hydrologic forecast available. In order to review model results and facilitate planning within the Regulating Committee, multiple conference calls are typically held during the freshet period. The Members discuss current and forecast conditions and determine appropriate reservoir management.

5.2.4. Dissemination of forecast river conditions to government agencies and the public

The hydrological forecasts that are generated as part of the integrated management of the reservoirs are made available by the ORRC to governmental agencies that are involved in the issuance of flood-related messages and emergency response.

The Planning Board uses its website (www.ottawariver.ca) as the main tool for issuing hydrological forecasts to the public. Current and forecast conditions on the Ottawa River along with conditions at the major reservoirs in the system are available on the website. A general four-day forecast is also provided at key locations within the basin during the spring freshet period or other high water events.

5.2.5. Acknowledgment

The author hereby extends thanks to ORRB and relevant organizations (ORRC and ORRS) for providing basic data concerning the comprehensive management of big reservoirs in the Ottawa River basin. The model description is basically derived from ORRPB management guideline (ORRPB, 2017), which has been proved very useful in preparation of this document. My sincere thanks also go to Mr. Martin Fairland, the chairman of ORRC. He has provided helpful assistance in communication and supplied the above file.

5.3. Integrated operation of cascade reservoirs on the upstream of the Yangtze River in China

The Yangtze River is the longest river of China and Asia. In the whole world, it ranks after the Niles and Amazon in terms of length, and after the Amazon and Congo River in terms of ocean-bound outflow. The total length of the mainstream is 6,300 km, the total area of the river basin is 1.8 million km², and the annual average ocean-bound outflow is about 960 billion m³. The section from Yichang upward is the upstream, which has a length of 4,504 km, an area of 1 million km² and an annual average runoff of 451 billion m³. There are 48 tributaries of the Yangtze River each with an area of over 10,000 km², and 9 tributaries each with an area of over 50,000 km² (Yalong River, Minjiang River and its tributary Dadu River, Jialing River, Wujiang River, Yuanjiang River, Xiangjiang River, Hanjiang River, and Ganjiang River).

The upstream of the Yangtze River is rich in water resources. The Jinsha River, Yalong River, Dadu River, Wujiang River and Yangtze River upstream are the five planned hydropower bases with an aggregated installed capacity of 175.64 GW, accounting for about 59.23% of total installed capacity of the thirteen biggest hydropower bases of the nation. There are 39 in-operation reservoirs playing important roles in flood control, power generation, navigation, etc. China Three Gorges Corporation ("CTG") has 6 giant hydropower projects on the mainstream of the upper reach of the Yangtze River, with the Three Gorges Project enjoying worldwide fame. These six giant projects have strategic importance in terms of cascade reservoir operation, and the experience accumulated can serve as benchmark practice for similar projects. Therefore, there is a good basis for integrated operation of cascade reservoirs on the upstream of the Yangtze River with the Three Gorges reservoir at the core, and it is reasonable to believe that integrated operation of cascade reservoirs will play vital roles in the social, economic and ecologic development of the economic belt along the Yangtze River.

5.3.1. Introduction

CTG is responsible for the construction and operation management of six giant reservoirs on the Yangtze River basin. These six reservoirs play crucial roles in flood control, navigation and power generation of the Yangtze River basin. The aggregate flood control capacity of the finished reservoirs is 27.703 billion m³, accounting for 70% of total flood control capacity on the upstream of the Yangtze River. The Three Gorges Project controls 95% of the inflow to the Jingjiang River reach with the biggest flood control pressure at the mid and down-streams of the Yangtze River; therefore it is of paramount importance in the flood control system of the Yangtze River. The length of the navigation channel in the reservoir is nearly 2,000 km, about 40% of the total length planned for the Yangtze River Economic Belt. The capacity of hydropower stations managed by CTG is about 53% of in-operation installed capacity on the upstream of the Yangtze River. All the hydropower generating units each with capacity of over 700 MW on the upstream of the Yangtze River are managed by CTG. Among the five biggest hydropower stations, each has an installed capacity ranking among the top ten in the whole world. CTG boasts 30 plus years of experience in large scale reservoir operation and power dispatching, and also enjoys prestigious advantage in basin water & rainfall regime forecasting and integrated operation of reservoirs. In long-term cascade operation, CTG has developed amicable partnerships with water resource conservancy, navigation, energy, meteorology, power grid and other agencies and organizations; therefore its experience in integrated operation of reservoirs is widely recognized.

Fig. 5.3-1

Map of hydropower stations on the Jinsha River downstream - Three Gorges cascades

5.3.2. Technologies for integrated operation of cascade reservoirs

CTG collects the water and rainfall regime as well as reservoir information of the above four large water resource and hydropower complexes, conducts precipitation and runoff forecasting, and prepares and implements a real-time reservoir operation plan and power generation schedule, thereby realizing integrated optimal operation of cascade reservoirs on the upstream of the Yangtze River.

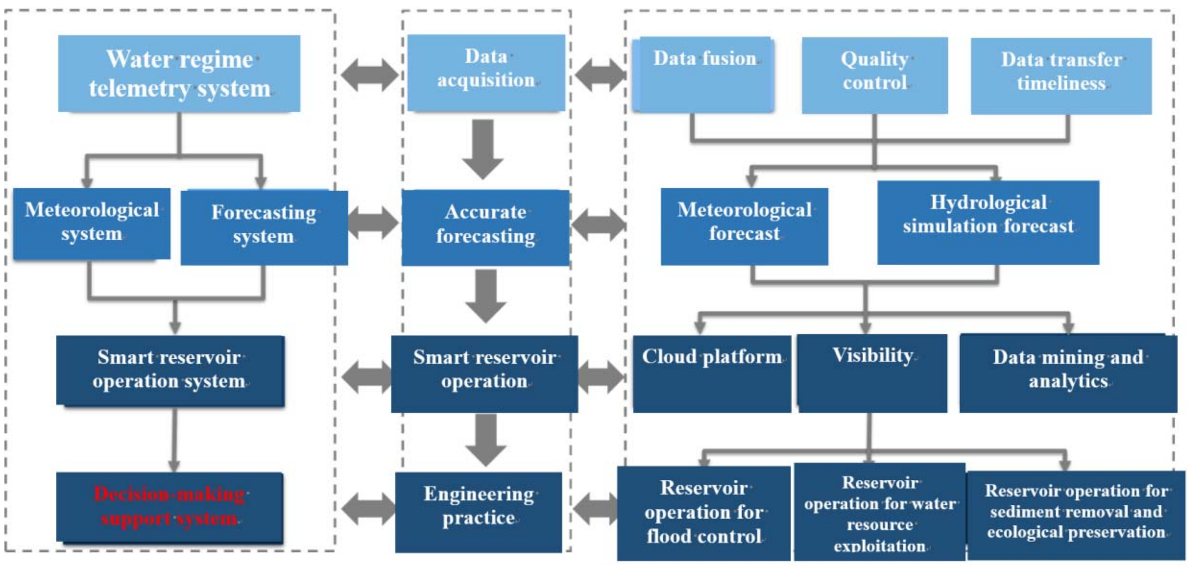


Fig. 5.3-2
Flow chart for integrated operation of cascade reservoirs

5.3.2.1. Data acquisition technology

CTG has installed the biggest and most versatile in-basin water and rainfall regime telemetry system in the Chinese hydropower industry. The system includes nearly 1,400 self-constructed or jointly-constructed telemetry and water regime stations, which control 580,000 km² of area on the upstream of Yangtze River. Every 10 minutes, the stations upload new data acquired, which are used for real-time in-basin water and rainfall regime monitoring. The acquisition, storage and processing of in-basin information is dynamic and continuous. Three main types of data below are acquired and transferred:

(1) The automated reservoir operation master system connects with the Three Gorges water regime telemetry center via the information acquisition and exchange platform, and collects the precipitation, water level, flow, station status and other information of the telemetry stations. The water & rainfall regime and other hydrological information are acquired and registered in real-time.

(2) The automated reservoir operation master system connects with the water regime report interface via the information acquisition and exchange platform. Using the available water regime report network, the system collects the precipitation, water level, flow and other information reported/shared by local hydrological and in-basin regulation agencies, and submits the reservoir dynamics to the flood control command center.

(3) The automated reservoir operation master system connects with the meteorological system via the comprehensive data platform, and collects meteorological forecast, precipitation, temperature, wind speed/direction and other information.

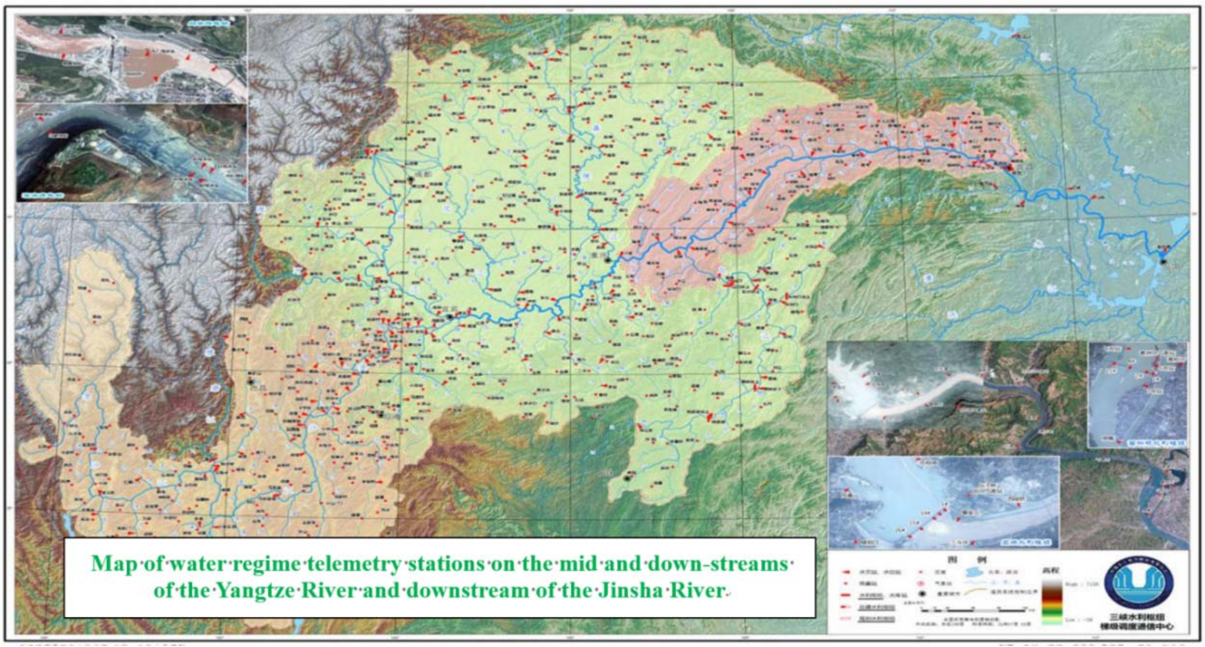


Fig. 5.3-3
Map of water and rainfall regime stations on the upstream of the Yangtze River

5.3.2.2. Meteorological forecasting technology

CTG has installed a meteorological system based on engineering needs. The system is composed of data processing, forecast analytics, information service and other modules. The system features the most advanced technology in the hydropower industry. Supported forecasts include: short-term and mid-term precipitation process forecast, as well as extended period and monthly precipitation trend forecast of 11 areas on the upstream of the Yangtze River.

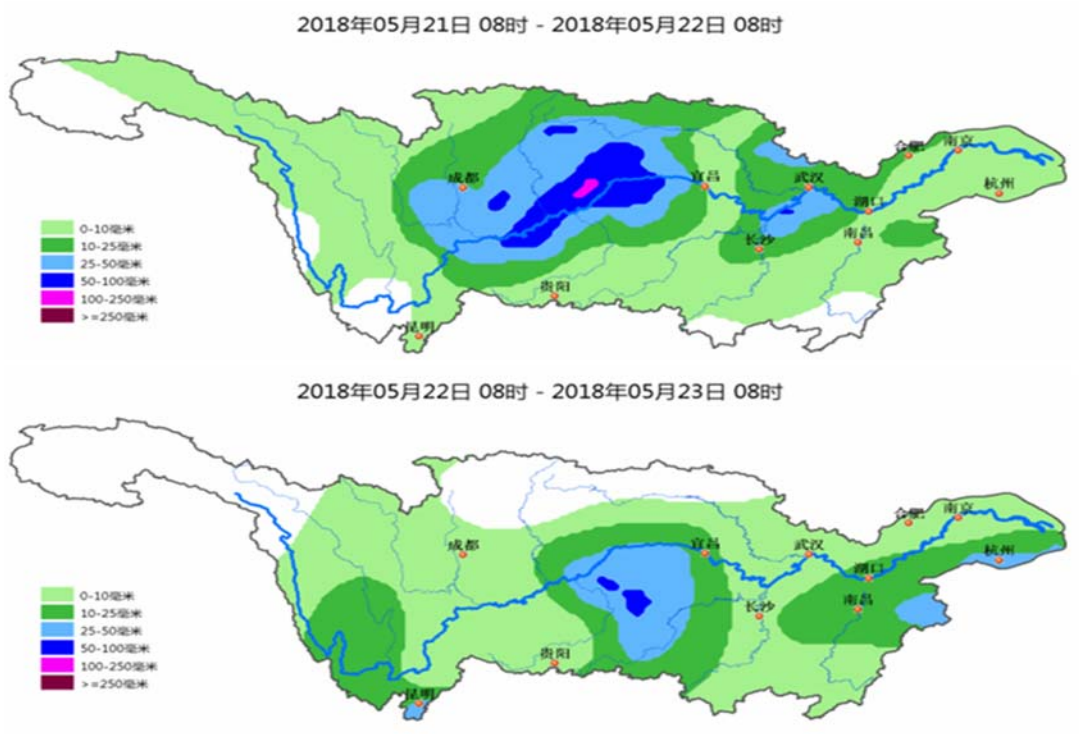


Fig. 5.3-4
Meteorological prediction results

5.3.2.3. Hydrological forecasting technology

CTG has established hydrological forecast plans for the upstream of the Yangtze River, which cover 60 forecast cross-sections and 21 reservoirs. A complete hydrological forecasting system has been developed. The in-basin hydrological forecast length can be up to 7 days, and the accuracy of 24-hour flow forecast is over 98%.

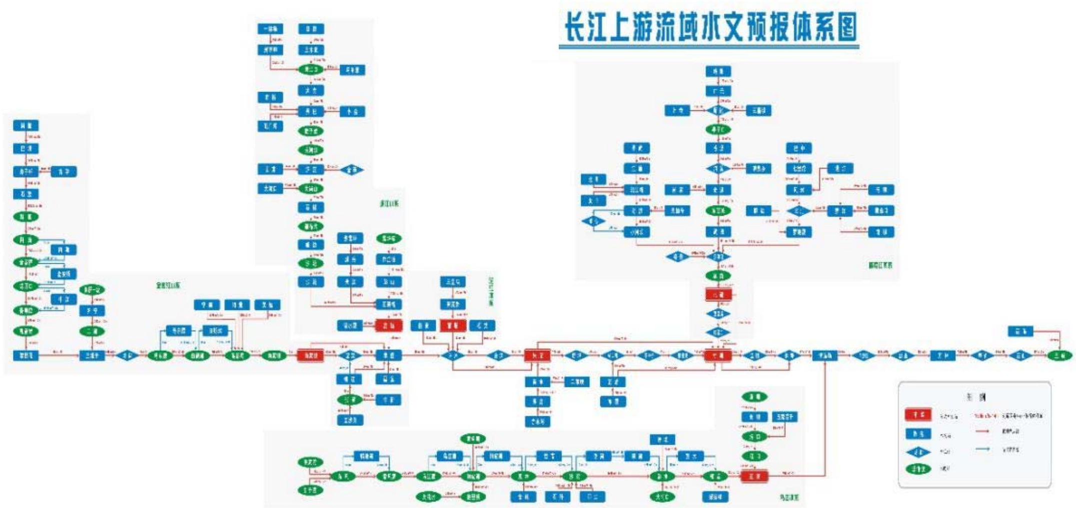


Fig. 5.3-5
Hydrological forecast framework

5.3.2.4. Optimization of reservoir operation

Cascade reservoir operation plans provide technical support for integrated optimal operation of cascade reservoirs, and serve as guidelines for cascade reservoir operation during the drawdown period, flood period and impoundment period, with the ultimate purpose of improving the power generation output of cascade hydropower stations. Here is a brief introduction to common reservoir operation calculation and optimal reservoir operation calculation.

a) Common reservoir operation calculation

Calculation is made step by step according to control period end water level, inflow and outflow balance, control period outflow, control period output (readable forecast or output dispatching), reservoir operation map, control period electricity quantity, period end water level + average output, outflow + output, gate control and other operation modes.

b) Optimal reservoir operation calculation

Cascade hydropower stations' short-term, mid-term and long-term optimal operation model (maximum power generation output, maximum benefits, minimum surplus water [short-term and mid-term]) is created. Flood control, navigation, water supply and other objectives are converted to restrictions of the model, and water balance theory is used as the calculation basis. Water level, water volume, outflow, output, generating unit oscillation area, power generation load ratio of power station on left and right banks, electricity tariff and other conditions in different periods are also considered. Dynamic planning, microsystem, artificial intelligence (AI) and other methods are used to calculate the model. Short-term optimization results are also considered to optimize the output of the hydropower station. The short-term, mid-term and long-term optimal operation plans are intended for most economic and productive operation of the hydropower station. Operation optimization is done step by step: long-term optimal operation plan → mid-term optimal operation plan → short-term optimal operation plan (power generation plan) → economic operation of the hydropower station.

5.3.2.5. Decision-making support system

To solve the problems encountered during integrated operation of cascade reservoirs on the Jinsha River downstream - Three Gorges, and to meet flood control, navigation, power generation, water supply and other needs, an expandable and widely compatible decision-making support system that features operation plan preparation, evaluation, implementation and feedback has been developed, with the ultimate purpose of eliminating all the technical and engineering problems in reservoir operation.

The system uses the cascade reservoirs on the Jinsha River downstream - Three Gorges as research object. The system has three parts: reservoir and river channel simulation, cascade reservoirs optimal operation model, and forecast & reservoir operation evaluation.

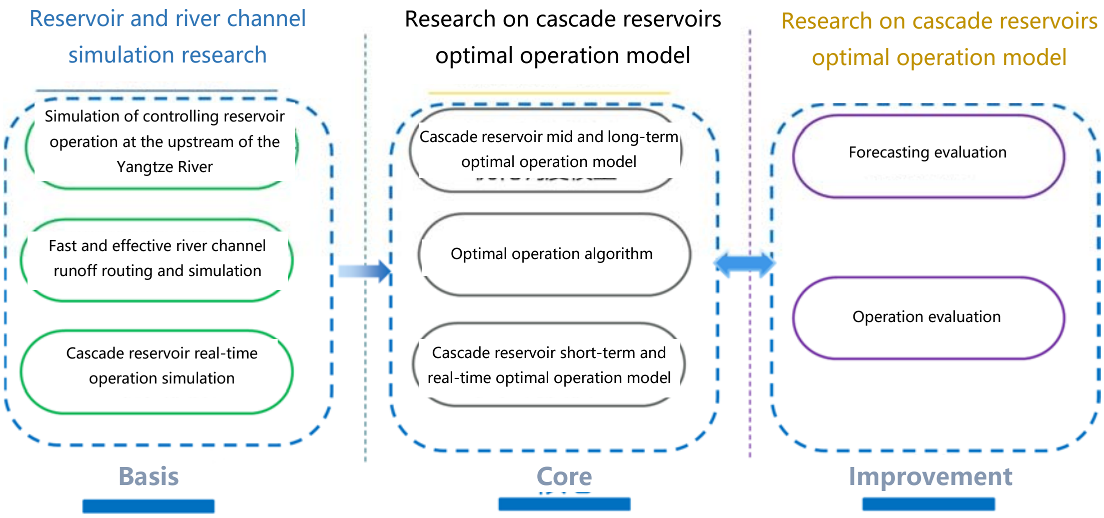


Fig. 5.3-6
Water resources DSS framework

5.3.3. Benefits of integrated operation of CTG's cascade reservoirs

5.3.3.1. Flood control

In 2010, the water level of the Three Gorges reservoir after impoundment reached 175 m. Since then, the reservoir has been used for 41 flood control regulations. The volume of flood retained in the last 8 years amounts to 126.6 billion m^3. Flood control pressure at the downstream is greatly alleviated, flood control cost is reduced, the level of the Jingjiang River reach on the mainstream has been kept below the alarm level, and the level of Chenglingji Hydrometric Station below the safety level.

5.3.3.2. Power generation

By the end of 2017, the cascade hydropower stations of CTG had generated 2,002.7 TWh of electricity, roughly 20 times the power consumed by Beijing in 2016, and one third of the total power consumed by the whole nation. The energy-saving and emission reduction effect is significant. The hydropower generated is equivalent to reducing 1.71 billion tons of carbon dioxide and 18 million tons of sulfur dioxide. The water level drawdown, flood regulation and post-flood storage strategies of cascade reservoirs are determined, a real-time optimal operation plan is implemented, surplus water is minimized, and average operation water head is improved, thereby improving water resource efficiency.

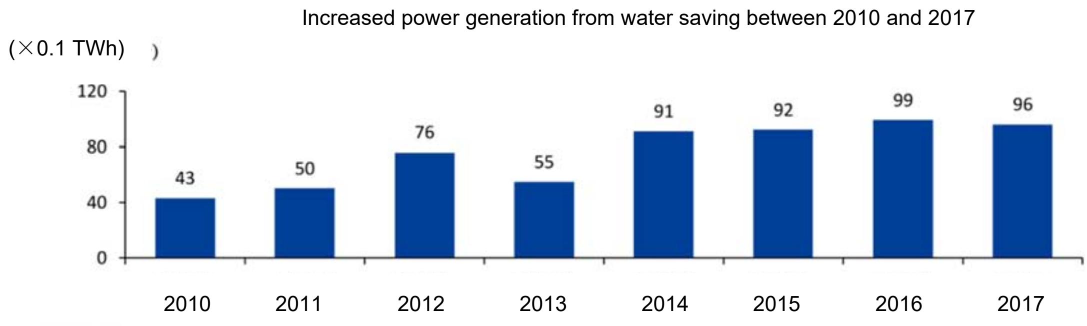


Fig. 5.3-7
Increased power generation of cascade hydropower stations from water saving

5.3.3.3. Navigation

Since 2010, the goods shipped through the navigation locks of Three Gorges have been up to 830 million tons. In the last four years since 2014, the annual amount of goods passing through the navigation locks reached 100 million plus tons and grew significantly each year. In 2017, the throughput volume was equivalent to 7 times the volume before the reservoir was constructed.

5.3.3.4. Water replenishment

Since 2010, the Three Gorges reservoir has replenished 157.2 billion m³ of water into the downstream (21~25 billion m³ each year). The replenishment helps meet household and industrial water demand at the downstream. The navigation channel at the downstream has been deepened by 0.95 m, reducing a lot of cost related to channel dredging.

5.3.3.5. Ecological preservation

In 2011~2017, 10 ecological dispatch tests were conducted in the Three Gorges reservoir. The total test duration was 58 days. During this period, 1.84 billion eggs of four major Chinese carps were monitored at the Yidu cross-section, accounting for 38% of all eggs of four major Chinese carps caught at the Yidu cross-section during the spawning period (May 15 ~ July 15) in 2011 ~ 2017. In 2017, the first ecological dispatch test was performed at Xiangjiaba reservoir. The purpose is to facilitate spawning of floating fish eggs. At Yibin section, 5 million fish eggs are detected; at Jiangjin section, 106 million fish eggs are detected.

5.3.3.6. Sediment removal

Based on relevant research, a real-time sediment monitoring and forecast model of Three Gorges reservoir was created. The model can reveal the asynchrony of water and sediment spreading in the Three Gorges reservoir, as well as the sediment scouring and silting rule at the end of the reservoir. The dynamic operation mode of “retaining clean water and discharging sediment” for new sediment regime was proposed. A sediment operation model was created and successfully implemented in practice.

5.3.4. Prospect

To reinforce the flood control system of the Yangtze River, maintain protection against flood in the river basin, guarantee safe operation of national strategic fresh water resources, improve the nation's management of river basins, and better exploit the water resources, it is necessary to conduct integrated operation of cascade reservoirs & hydropower stations on the upstream of the Yangtze River.

According to the above analyses, composite benefits have been generated after conducting integrated operation of cascade reservoirs & hydropower stations on the upstream of the Yangtze River with the Three Gorges project at the core. For flood control, peak flood caused by unnecessary flood discharge can be avoided, and the flood control capacity of key cities along the Yangtze River has been improved. If a flood like the one in 1954 reoccurs, the dike works and flood diversion channels can be used to reduce economic loss up to RMB 175 billion at the Jingjiang River area on the midstream of the Yangtze River. Thanks to integrated operation of the Three Gorges Reservoir and Qingjiang River cascade, the flood return period of the Jingjiang River area has been improved from 100 years to 130 years. For navigation, the navigation channels in the reservoir area have been greatly improved, the navigation is much safer, and the cost has been reduced. For water replenishment, about 90 billion m³ of water can be replenished to the midstream and downstream of the Yangtze River during the dry season, greatly improving water supply capacity. For power generation, according to preliminary calculation, the 33 major hydropower stations on the mainstream and tributaries of the Yangtze River's upper reach can generate extra electricity of 42 TWh (annual average value) after integrated operation. The extra electricity comprises two parts. The first part is extra power generated with supplementary flow: after the cascade reservoirs are constructed, the natural river runoff regime is changed, surplus water in the flood season is reduced, power generation in the dry season is increased, and an extra power of 26 TWh is generated by the hydropower stations. The other part is the extra power of 16 TWh generated after integrated optimal operation of cascades. The energy-saving and emission reduction benefits are significant. The extra power of 42 TWh is equivalent to reducing 34.7 million tons of carbon dioxide and 112,000 tons of sulfur dioxide each year.

Integrated operation of cascade reservoirs is the necessary solution to fully exploit the water resources of the Yangtze River basin. This strategy needs several supporting measures. Firstly, top-level arrangements are necessary. National policies, laws and regulations concerning river basin management must be enacted and improved. Secondly, in-basin cascade joint forecast and operation decision-making support system must be created, and an integrated operation coordination mechanism must be established. Thirdly, the commercial developers in the river basin can form a consortium in which each interested party is required to fully cooperate with the integrated operation arrangement. Fourthly, a compensation and sharing mechanism shall be created. Under par performance will be compensated, and above par benefits will be shared, so that every member of the consortium is willing to work closely in integrated operation.

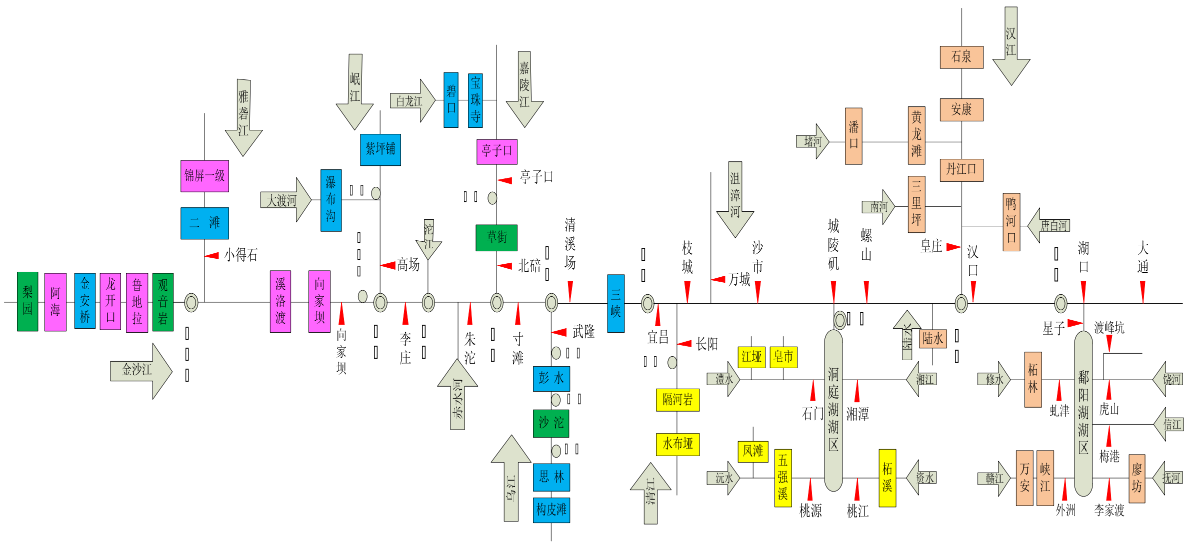


Fig. 5.3-8
40 reservoirs in the upper and middle reaches of the Yangtze River under integrated operation

5.4. GIS-based decision support system for water resources planning and management in IRAN

Two scenario-based spatial decision-making support systems (SDSS) have been developed for Karun and Karkheh, the two major river basins of Iran. The systems can be used in water resource planning, and short-term operation planning of reservoirs and hydropower stations in the river basins.

5.4.1. Introduction

Water resources planning and management is usually carried out by mathematical models. An information-technology framework has been used to link the models in a convenient platform to make results of evaluation more tangible. The diversity of water resources modeling, file formats, and data structures with a large number of required data, makes the modeling more complex. Systemization of computer-aided collaborative processes in this area helps to resolve the complexity that is achieved by many researchers.

Regardless of the subject of evaluation, the common challenge of water resources planning and management is evaluating and comparing different scenarios. A scenario-based Spatial DSS (SDSS) was developed in order to address the stakeholders' interests and meet the minimum requirements of hydro-systems in the decision-making process for the planning stage in the main basins of Iran. The main purpose of the SDSS is to plan and review design features of projects based on overall net benefits, taking into account environmental and social impacts. Additionally, the DSSs are able to screen planning scenarios based on predefined criteria and to determine optimum features of projects. Decision making in river basins is difficult, since many state and decision variables and criteria are engaged for screening planning scenarios. Firstly, the criteria must be quantified in river basins and then planning scenarios should be prioritized based on requirements and stakeholder interests.

Flood risk reduction can be achieved by reducing either the flood magnitude or the vulnerability of the area. Non-structural approaches to flood management mostly focus on mitigating the vulnerability of the region. An early flood forecasting system (EFFS) and inundation model were developed to evacuate the vulnerable areas before or during the flood events and to mitigate potential damages in the main rivers of Iran.

The SDSSs were applied and validated for Iran's two largest rivers in the southwest. One of the main questions at the planning stage of the Karun and Karkheh rivers was choosing storage or run-of-river schemes for hydropower station development in certain reaches. After 5 years of discussion and pending the decision, the developed DSS helped answer the question by analyzing and comparing the stakeholder and decision maker's interests. EFFS was implemented in the Karun river basin after two successive major floods took place in 2004 and 2005 and washed away the cofferdam of the KARUN4 dam, which was under construction.

5.4.2. The SDSS features

The DSS includes public domain software such as ArcGIS, HEC series, MODSIM, ARSP, and TOPSIS. Subprograms were also developed for extra evaluations e.g. groundwater conjunctive use, water quality, and optimization of the planning scenarios as well as two-dimensional flood inundation models. Integration of analytical modules and GIS in the DSS has made them robust tools with various capabilities. The capability of the public domain models was enhanced in order to meet the requirements of the hydro-system. In addition, the DSS was developed so that adding new elements such as dams and hydropower stations to the river system is possible for calculating required data and generating new schematics of the hydro-systems. A spatial MCDM is used to evaluate the scenarios based on different indices and illustrates the results for per-defined areas or individual projects, separately. The main modules of the SDSS are described as below:

5.4.2.1. Reservoir simulation module

The river basin simulation module was developed by upgrading the Acres Reservoir Simulation Program (ARSP) for the big Karun basin. The Modular Simulator (MODSIM) engine developed jointly by the Colorado State University (CSU) and the Bureau of Reclamation’s Pacific North West Region, was used for the Karkheh River. Both models are stationary so that operation policies, river system network, and requirements do not change in time steps of simulation. The ARSP model determines optimum policy for water allocation at each single time period via an kilter algorithm (OKA) in a penalty structure framework. In order to remove computational restrictions (such as the number of dams), the model was upgraded by using C++ programming.

Physical components of river system such as channels, confluences, and reservoirs were defined by flow/demand channels and junction nodes with and without reservoirs. Power channels were used to define the installed capacity, power generation, minimum power requirement and firm energy for hydropower stations. Other inputs were also defined in a penalty function approach to determine priorities to release in multipurpose reservoirs and to define operating levels, dead storage, and rule curves.

The MODSIM engine applied to the Karkheh river basin includes a GIS platform for analyzing spatial data. Although the Geo-MODSIM has been developed for the lower Arkansas River basin, in this research the main model developed previously was modified and coupled with other modules in the GIS platform. The modified model does not have any computational limitations in terms of number of reservoirs, priority for releases, and number of time steps. A framework of flow networks including nodes and links/arcs was applied for connecting nodes in the module. The MODSIM engine was customized to call all state variables and objective functions from other subprograms of the SDSS. A subprogram code was developed using the .NET programming language to define reservoir operating policies, to provide input and output data sets for other modules, and to link MODSIM to database and user interface. By linking MODSIM to GIS, it is possible to generate spatial data reports.

5.4.2.2. Optimization modules

Particle Swarm Optimization (PSO) and Ant Colony optimization (ACO) algorithms were used to develop optimization modules for the Karun and Karkheh river basins, respectively. Although both algorithms have a similar computational base, the converging mechanisms of the algorithms are different and it may lead to different run time and accuracy.

a) Water quality module

The water quality module determines EC, TDS, DO, and BOD along the river based on auto-respiration of the rivers. Water temperature, BOD, and DO concentrations were obtained by mass balance at confluences and bifurcations. Then the critical concentration of DO corresponding to critical time was considered as the minimum requirement for in-stream flow demand. TDS and EC parameters were determined based on mass balance eq. in confluences and bifurcations by assuming stationary along the river.

b) Demand module

Water demand was estimated for in-stream and consumption uses in monthly time steps. In-stream use demands consist of minimum environmental flow, power flow, and power control flow. Consumption demands include agricultural, domestic, and industrial uses. Beside estimation of the water demand and return flow amounts, the demand module determines the reliability and deficit of water demand fulfilling for each sector, separately. The reliability and deficit of agricultural demand in the river basin was determined by an individual irrigation networks feature and a weight for each network based on the ratio of average annual water demand of the network to total agricultural demand. Agricultural gross water demand was determined based on cultivation area and crop pattern for each irrigation network as well. At the same time, the module provides a capability to the user to change the crop patterns and irrigation mechanisms as a scenario. Moreover, the module adjusts irrigation areas by available water resources based on predefined design criteria for different water user sectors.

c) Groundwater module

The groundwater module determines groundwater mass balance and recharge for conjunctive use of surface and groundwater resources. The module determines maximum recharge of groundwater for water supply so that the balance does not change on a long-term scale. Inflows to the groundwater resources include infiltration of precipitation, infiltration of return flows from irrigation networks/industrial and domestic sewage, karst flow, and direct infiltration from the river bed. On the other side, outflow of groundwater contains recharge flow to adjacent aquifers, drainage to the river, water withdrawal (by well, source, and aqueduct), and evaporation. Conjunctive use was simulated by exchanging the data between surface water and groundwater modules at three steps. In the first step, it was presumed to fulfill the demand using surface water resources and then groundwater mass balance was determined based on the result of the surface water simulation module. In the second step, maximum recharge from groundwater was allocated to water users in case of not fulfilling the demand in the first step and the surface water simulator was run to determine annual withdrawal from surface and ground water resources. In the third step, groundwater recharge changed to satisfy constrains and maximum permissible recharge from the groundwater in the long term horizon and a trial and error procedure was used to achieve a margin of error of less than 5%.

d) Economical evaluation module

The economical module was basically needed for the evaluation of water resources planning scenarios from an economical point of view. The module computes agricultural and hydropower benefits along with flood inundation damages based on crop income, power network characteristic, and floodplain properties. Then economic indexes such as cost/benefit ratio, net benefit, and internal rate of return are determined by investment and operational costs and the benefits of the projects for each scenario.

For agriculture purposes, investment cost was directly related to irrigation network development and the operational cost covers annual maintenance costs such as labor wage, equipment, pumping, and pesticide costs. Then, agricultural net benefit was determined by deferential net benefit at situations with/without project for each scenario. Agricultural scenarios include crop patterns and irrigation mechanisms beside other scenarios related to basin features.

e) Flood forecasting system

An early flood forecasting system (EFFS) was developed for dam operation and damage mitigation during floods. A GIS database was also developed to store and retrieve geo-data such as precipitation and geographic maps. HEC series software of hydrology and hydraulic was linked through the HEC Data Storage System (DSS) to create a tailor-made system for flood forecasting. As shown in Figure 5.4-1, numerical weather, rainfall runoff, and inundation modeling were the main parts of the flood forecasting system. Figure 5.4-2 illustrates a schematic of the EFFS, showing the digital elevation, spatial estimation of precipitation, and time series modules.

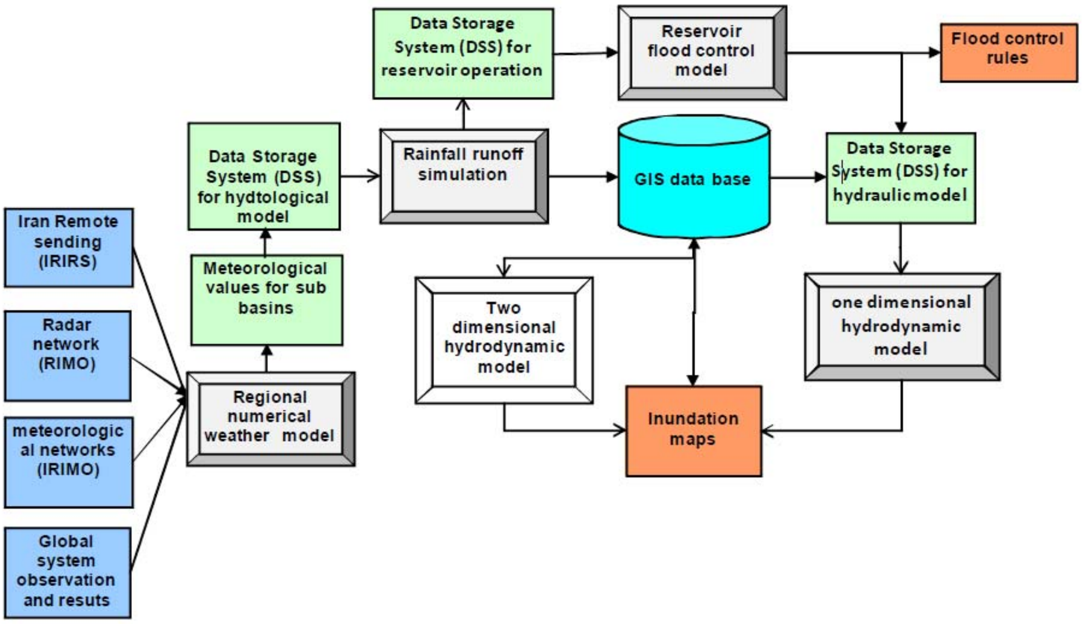


Fig. 5.4-1
Components of the early flood forecast system (EFFS)

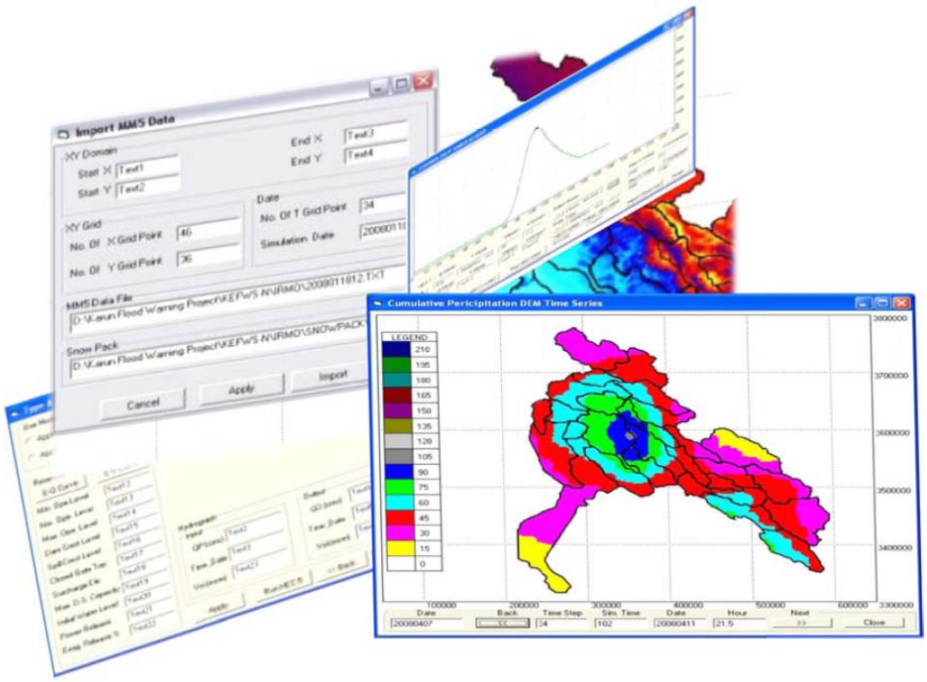


Fig. 5.4-2
GIS-based tailor-made software for flood forecasting

f) MCDM module

In order to evaluate the planning scenarios, the MCDM module uses tangible and intangible indices of decision making by dividing the main indices to subgroup-indices. Subgroup-indices were determined in a pairwise weighting mechanism after pre-processing the indices. Then, the subgroup-indices were aggregated to obtain ultimate decision indices.

5.4.3. Case study area

The Karun river basin consists of the upper Karun and Dez rivers that join together at the downstream. As it is shown in Figure 5.4-3, six large dams and hydropower stations including Karun1, Masjed-E-Solayman, Karun3, Karun4, Gotvand, and Dez are operational and Khersan 3, Bakhtiary and Rudbar are under construction. The rest of the dams out of 16 large dams are under study in the basin. The Karun basin contributes 78% of hydro electricity generation of Iran in the full development scheme. Additionally, many irrigation networks are located downstream with a total cultivation area of 800,000 hectares including developed and under-developed irrigation networks.

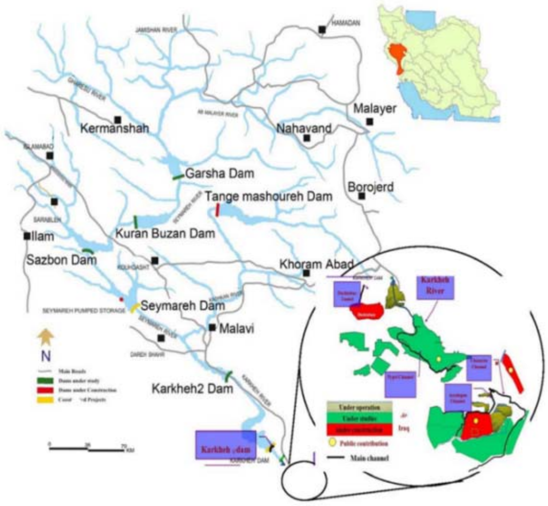


Fig 5.4-3
Hydropower stations and irrigation areas of the Karun river basin

5.4.4. SDSS application results

The two developed DSSs described in the previous sections were applied to the Karun and Karkheh hydro-systems. The Karun river basin deals with water quantity challenges such as inter-basin water convey systems, priority of demands, and flood damages; whereas the Karkheh river basin`s challenges include water quality problems due to an enormous number of pollution sources, eutrophication of the reservoirs, upstream and downstream provinces conflict, high water scarcity, and growing population. A limited number of SDSS modules including simulation, optimization, and MCDM modules were applied to assess Karun and Karkheh water resource projects.

5.4.4.1. Sediment module

The sediment module was applied for the Karun river basin to estimate sediment in different locations of the basin based on observed sediments of the Karun1 and Karun3 reservoirs that have been under operation since 1977 and 2005, respectively. The sediment deposition which was surveyed two times during operating period was used to calibrate the soil erosion models and Discharge (Q) - Suspended Sediment load (Q_S) relationships of gauge stations.

5.4.4.2. Reservoir simulation module

Simulation of cascade reservoirs was carried out to evaluate different development schemes in the Karun and Karkheh River basins. Two different scenarios for the Karun2 dam were assessed in the Karun basin. The Karun2 dam site is located between the two existing dams of Karun3 and Karun1. Two scenarios including storage and run-of-river hydropower stations were evaluated in this research.

The module simulates a multi-reservoir and multi-purpose river system for different scenarios of development schemes considering irrigation and electricity demands, design criteria and requirements of the hydro-system. The design criteria and minimum requirements are automatically fulfilled by changing the state variables such as irrigation areas and installed capacity in the module.

5.4.4.3. Optimization module

An optimization module was applied to determine optimum features of multi-purpose projects. In the Karkheh basin, the project under study, named Tang-E-Mashoureh, was optimized in terms of dam height, installed capacity of the hydropower stations, and water transfer system from the reservoir for agricultural purposes.

5.4.4.4. Flood forecasting

a) Rainfall forecasting

A Regional numerical weather Forecast System (RFS) was set up by the Iranian meteorological organization in 2005 based on initial and boundary conditions from the results of the Global weather Forecasting System (GFS). A radar network was also set up to survey the precipitation data and patterns in the basin and to update the results of numerical weather models. However, the calibration of the radar data still needs revision and was not valid for application in the system. The resolution and time interval of the model was enhanced for the Karun and Dez rivers basins in 2006. At the moment, time step of the model and resolution of the raster-based weather data for the basins have been improved to 3 hours and a 15*15 km^2 pixel size, respectively, after establishing a cluster-based framework. The numerical weather models used are MM5 and WRF, which forecast meteorological parameters in a maximum lead time of 104 hours. The comparison between measured precipitation and weather forecasting result indicates that the accuracy of forecasting model decreases as the length of lead time increases. The forecast with one-day lead time has the least deviation. In many cases, the storm center forecast based on the data of rainfall station is not accurate, but sensitivity analysis is performed by enabling EFFS the ability of changing hydrologically-modelled storm center.

b) Rainfall – runoff modeling

Rainfall-runoff (RR) simulation was performed by the HEC-HMS (USACE, 2006) and the HEC1 (USACE, 1998 b) models in parallel. The RR models, which were designed as single event-based simulation models, were calibrated based on observed data and were validated during real-time application of the system. For a single event-based simulation, a unit hydrograph model, exponential infiltration method, and degree-day method were used for direct runoff routing, loss rate estimation, and snow melt simulation, respectively. In order to improve the simulation accuracy, the basin is divided into 26 sub-basins. See Figure 5.4-4.

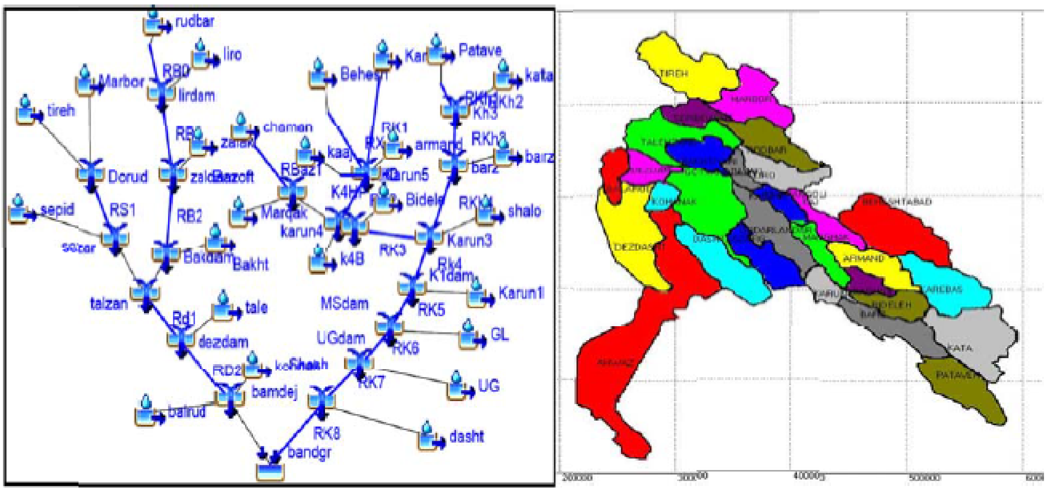


Fig. 5.4-4
Sub-basin division and forecast nodes of the Karun River basin

c) Flood routing and inundation model

Modeling of flood routing was performed by the kinematics wave method in the upstream catchments, for which there was no cross section data. A two-dimensional hydrodynamic flood routing model named NAMROUD was used with the one-dimensional hydrodynamic model of HEC-RAS for the downstream floodplain areas for which there were accurate cross section data. The hydrodynamic model not only demonstrates the result of flood attenuation in the river reaches but also determines flood inundation areas and depth, as well as flow velocity in flood way. Islam et al (2010) used remote sensing data using products derived from satellite images to validate inundation maps of the hydrodynamic model.

d) Real-time reservoir management

There are several reservoirs that are under operation in upstream of floodplain areas and real-time management of these reservoirs helps attenuate flood peak discharge in the downstream areas. Moreover, the forecasting system determines the expected volume of the flood in the short term and the dam operators can then coordinate with the dispatch center to increase the power generation in the hydropower stations before flood events.

e) Emergency action plan (EAP)

The purpose of the EAP is to reduce the risk of injury and loss of human life and to minimize property damage during an unusual event or an emergency.

5.4.4.5. Multi-purpose decision making module

One of the main challenges of water resources planning is to screen the best scenarios among possible scenarios based on tangible and intangible criteria. The multi-purpose decision module is used to evaluate the planning scheme according to user-defined objectives. For example, in the Karkheh basin, water shortage is one of the major challenges between upstream and downstream industries. A large number of soil resources in the plain area downstream of the Karkheh basin are suitable for the development of irrigation networks. Decision-making indicators of each stakeholder's interests can be compared by using the decision support system. Figure 5.4-5 shows the results of the priority allocation of water resources in the basin based on the needs of some stakeholders. Green areas are the priority provinces.

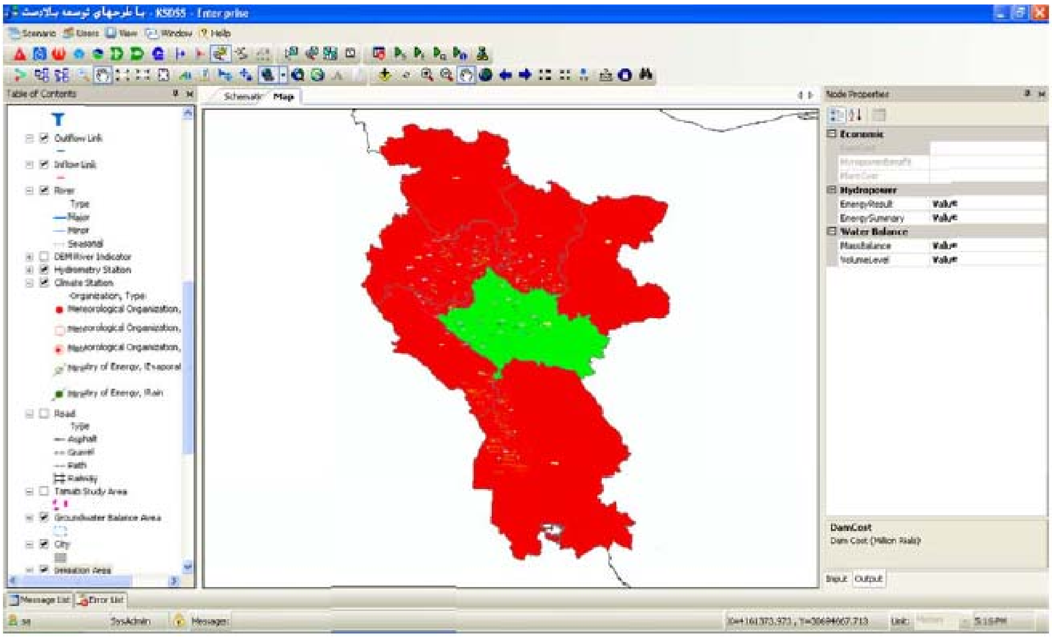


Fig. 5.4-5
Priority areas for water supply in the Karkheh basin

5.4.5. Conclusion

Two tailor-made SDSS are developed and applied in the modeling of the Karun and Karkeh river basins in the southwest of Iran. Unlike generic software (such as WEAP and Mike Basin), the SDSS has flexible analysis and decision-making tools, which can combine water resource scenario generation, economy and MCDM screening in the calculation process. The spatial variability of MCDM index can be considered. Scenario-based analysis helps compare the result of planning scenarios and evaluate them by quantifying decision indexes and considering the stakeholder interests. The developed SDSS is interactive and more practical in water resource planning, since the interests of the stakeholders and the decision-makers are not always in good agreement. These tools allow multi-index evaluation. Many quantitative indexes such as technical, social and environmental indexes are supported. The MCDM application of Karun River leads to the selection of Karun2 HPP. The saved alternative of Sazbon HPP is the best replacement of Karkeh River basin after quantization of the decision-making indexes. The best size for parallel or cascade dams is determined using the optimizing module. Compared with separate research result, when the dam height increases, the minimum operative level of the reservoirs in Karkeh River decreases. By using the optimization module, the total effective volume of the reservoir is changed from 6,595 sets to 8,056 sets. The forecasting system supports flood forecasting with long lead time. The damaged center and in-operation reservoir can be evacuated, so the flood management is very flexible. When dam fracture or extreme inundation happens, EAP proves to be an effective short-term mitigation measure. The characteristics of local area can be included in the development process. Damage compensation for the residents living in the path of flood has been calculated. Rescue map of the major cities of Afghanistan and other vulnerable areas has been developed. The utmost efforts were made to develop the SDSS in a more flexible and adaptable manner so that users are able to change the assumptions and inputs. In the case study, the input data and model parameters are deterministic, and the uncertainty of data has been discarded. But the capability based on scenario facilitates the consideration of new scenarios based on parameter variability and uncertainty of indirect analysis.

5.5. Integrated optimal operation of the Kiso River in Japan

5.5.1. Outline of hydropower stations and dams in the Kiso River system

5.5.1.1. Outline of the Kiso River

The Kiso River originates from Mt. Hachimori (EL 2,446m) in Kiso village, Nagano prefecture, Japan, passes through the Gifu prefecture along Nakayama road towards the south-east, merges with the Hida River and other rivers on the way, and finally enters into Nobi plain and Ise Bay, which has a catchment area of 5,275 km^2 and a 229 km long river course as shown in Figure 5.5-1.

Fig. 5.5-1
Outline of the Kiso River, Japan

5.5.1.2. Dams on the Kiso River

There are 16 dams along the Kiso river, of which 12 dams are used for hydropower and are owned by the Kansai Electric Power Company ("KANSAI") and 3 of 4 multipurpose dams, namely the Makio dam, Misogawa dam, and Agikawa dam, are owned by the Japan Water Agency, and the remaining Maruyama multipurpose dam is jointly owned and operated by the Ministry of Land, Infrastructure and Transport (MLIT) and KANSAI (Annex 1).

5.5.1.3. Hydropower station development on the Kiso River

There are 33 hydropower stations on the Kiso River as of the end of December 2017 with a total installed capacity of 1,064 MW and annual generation of 4,600 GWh (refer to Annex 2) .

The first hydropower generation in Kiso River was initiated at the Yaotsu hydropower station in 1911 (closed in 1974) and consequently 6 hydropower stations were commenced until 1925, then the area of the Kiso river became one of the leading hydropower areas in Japan at that time and the generated power was sent to the Kansai area where electricity demand was much higher than the adjacent area of the Kiso river. Around 1936, Kasagi PS, Nezame PS, Imawatari PS and Tokiwa PS had started operation and the Miura Dam was completed in 1945 at the most upstream of the Kiso River for the purpose of consistent development in the whole river system and increment of river flow thanks to regulation function at the Miura Dam. Originally each hydropower station was constructed, owned and operated by small independent power producers but after World War II (1945), electricity companies were restructured and 9 large electric power companies were established including KANSAI in Japan. During the restructuring, all the hydropower stations on the Kiso river merged into KANSAI based on the policy under which "each power producer must belong to the company where its electricity is consumed". Thereafter, the Mio PS, Kiso PS, Inagawa PS and other power stations have been developed so far.

All the power stations need to use river flow in the Kiso River and the owner of each hydropower station is required to obtain an approval for river flow usage right from MLIT. The approval is effective for around 20 years, though it might vary; the owner needs to apply for an extension in order to extend its operation. This system has been defined and applied under the River Law in Japan since 1964.

5.5.1.4. Hydropower operation in the Kiso River

a) Operation policy of hydropower stations

Hydropower stations on the Kiso River are operated with an integrated operation policy under which intake water at an upstream hydropower station is directly used for generation in a downstream hydropower station The annual integrated operation plan is made by using historical annual river flow records and based on the annual maintenance plan of each hydropower station to maximize electricity generation (kWh) and its value in the whole river system. Based on the annual integrated operation plan, daily and weekly operation plans were drafted and adjusted in accordance with changes of electricity demand, rainfall / weather conditions / forecast, and requirement of water release from relevant authorities. Basically, the Miura dam located at the most upstream of the Kiso River has a larger storage capacity than that of other dams in the downstream and uses up the storage water before the timing of snow melt water (February to April) and then starts to store the water again for the summer season when electricity demand becomes high.

b) Operation with high water level

Dams other than the Miura dam located in the most upstream of the Kiso River regulate the water level in their reservoirs on a daily basis within their capacity, namely to store the water in the night time and release the water in the day time in order to match electricity demand. This operation also includes keeping the water level in each reservoir as high as possible so that the generation efficiency of turbines and generators is kept high.

c) Selection of optional waterways

(1) Kiso-route and Nezame-route

There are two options for power generation in the upstream area of the Kiso River, which are called "Kiso-route" and "Nezame-route". Kiso-route is the way to Kiso PS and Nezame-route is the way through Nezame PS, Momoyama PS, Suhara PS and Ohkwa PS. Basically, Kiso-route is selected because the hydropower stations of the route have higher efficiency than the Nezame-route and larger installed capacity. In case the river discharge is more than 60 m^3/s, the Nezame-route is also used and takes excessive river flow for power generation.

(2) Hydropower stations on the downstream of Yomikaki Dam

Each dam on the downstream of the Yomikami Dam (Yamaguchi dam, Ochiai dam, Ohi dam, Maruyama dam, Kaneyama dam and Imawatari dam) has two intakes (power stations) and a hydropower station which has higher efficiency for generation (new route) takes priority (as shown in Annex 1).

(3) Other considerations

When there is room for storage in the Miura dam in case of a flood, the river water is to be stored as much as possible in the Miura Dam. On the other hand, in case that there is little room in the Miura Dam and continuous heavy rain is forecasted, the Miura Dam and other dams in the downstream are controlled to release the stored water with power generation and to lower the water level in the reservoir in advance in order to lower the water level before the flood.

Maintenance works which need to suspend power generation are limited during the period when average flow is relatively low (winter season) and/or there is less electricity demand.

5.5.2. Flood control in the Kiso River and role of hydropower stations

5.5.2.1. Flood control of Kiso River and role of dams owned by power utilities

a) Flood control system in the Kiso River

It was found that a flood control project in the Kiso River has been initiated in 1593 in order to restore the region after a large flood in 1586. In recent years, the Maruyama Dam for flood control on the Kiso River with the design flood of 14,000 m^3/s which is equivalent to the flood in July 1938 was completed in 1956. Consecutively, corresponding to a revision of design flood in the Kiso River to 16,000 m^3/s in 1969, the Agigawa Dam and Misogawa Dam were constructed in 1991 and in 1996, respectively. In addition, a flood higher than the design flood was recorded in 1983, and a plan to upgrade the existing Maruyama Dam was started in 1986. At present, design flood in the Inuyama area is 19,500 m^3/s, and 6,000 m^3/s out of 19,500 m^3/s is planned to be controlled by dams including a Maruyama Dam upgrade project.

b) Role of dams owned by power utilities

Basically, dams for power generation do not have sufficient capacity to control floods; however, the River Act of Japan requires each dam owner to preserve an original capability or function of each river even after completion of the dam and one of the requirements is to lower the water level at a certain level in case a flood is forecasted. The power generation requirement for each dam (other than flood control purposes) is different among dam types, which are also classified into 4 categories.

Category 1 dam

A Category 1 dam is a dam which has a relatively large reservoir capacity, is situated at the upstream of the river and therefore, might cause increment of flood risk. The dam must keep enough reservoir capacity and store the river flow in the reservoir in case of flood in order to mitigate the risk. The Miura dam is classified as a Category 1 dam and the dam has to reduce peak flood discharge equivalent to 30 minutes volume of peak flood. The Makio dam which is just downstream of the Miura dam is also classified as a Category 1 dam.

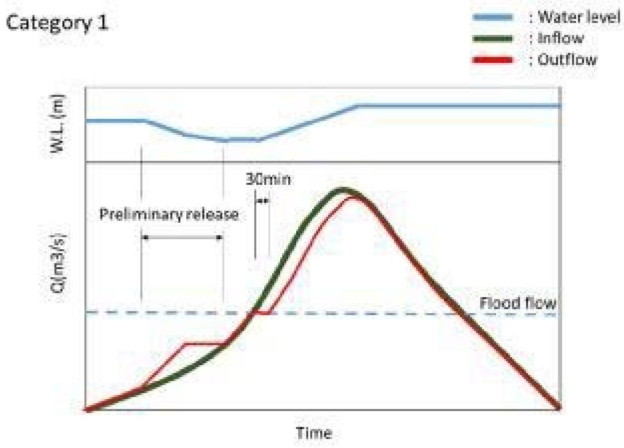


Fig. 5.5-2
Category 1 dam

Category 2 dam

A Category 2 dam is a dam where the riverbed is raised by sedimentation and the dam is obliged to lower the reservoir water level at a certain level in advance of a coming flood in order to prevent inundation of the upstream end of the reservoir. The Inagawa dam, Yomikaki dam, Ochiai dam, Ohi dam, Kasagi dam and Kaneyama dam are classified as Category 2 dams.

Category 3 dam

A Category 3 dam is a dam whose catchment area is relatively small compared to expected design flood to the reservoir; therefore the spillway gate of the dam might be opened suddenly in order to prevent overflow of the dam, or there may be a relatively large number of spillway gates and, due to its complexity, the dam should lower the water level in the reservoir in advance of a coming flood. The Tokiwa dam, Kiso dam and Imawatari dam are classified as Category 3 dams.

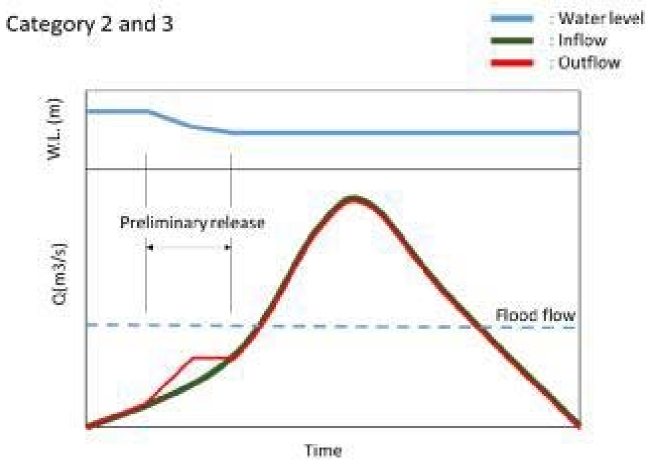


Fig. 5.5-3
Category 2 and Category 3 dams

Category 4 dam

A Category 4 dam is a dam which allows the water level to stay normal even during a flood because the discharge from the dam has no impact on the upstream or downstream area. The Ohtaki dam is classified as a Category 4 dam.

Other than the dams mentioned above, the Misogawa dam, Agigawa dam and Maruyama dam have multiple purposes including flood control; therefore, the dams store the river flow in the reservoir during floods according to the relevant dam operation regulation.

5.5.2.2. Multipurpose use of reservoir water and role of dams owned by power utilities

a) Water resource usage of the Kiso River

Since old times, the river water of the Kiso River has been used for agriculture, fishery and timber transportation (Kisohinoki is a valuable tree in Japan) until the 1890s. The supply of water by the Kiso River to Nagoya City was started in in 1914 and, thereafter, the area of water supply has been expanded to other areas at present. Furthermore, the water is used for industrial and agricultural purposes in the downstream area.

b) Conditions for usage of the Kiso River water

As mentioned above, in the downstream of the Imawatari dam, there are a lot of existing water usage rights for water supply, industrial and agricultural purposes. The water usage rights must be obtained and secured legally and approved by MLIT. Also dam owners and the local government had an agreement titled “Basis for Integrated Operation in the Kiso River and Hida River” among dam owners including KANSAI, and all of the dam owners whose dams are located in the upstream are not allowed to store the river water in each reservoir when the river flow is lower than 100 m^3/sec but can store the river flow when river flow is higher than 100 m^3/sec.

c) Uniform flow and re-regulation of river flow

Under the “Basis for Integrated Operation in the Kiso River and Hida River” as agreed among relevant parties, the Imawatari Dam is obliged to store the river flow from the upstream and flow out the stored water uniformly to the downstream. At the upstream of the Imawatari Dam, there is a confluence of the Kiso River and Hida River. The operators of the Imawatari Dam have to collect the river flow data and discharge amount from upstream dams both of the Kiso River and Hida River and make a plan for discharge amount to the downstream area.

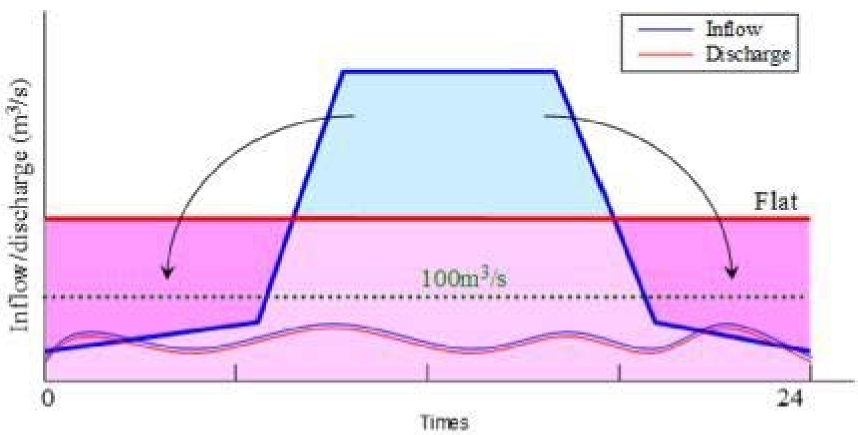


Fig. 5.5-4
Critical flow for water storage

5.5.2.3. Navigation and necessary facilities at the dam

In previous time, some dams had docks or inclines for navigation or fishery / timber transportation. But following the development of a paved road network along the river, the volume of navigation has been significantly decreased, and therefore, the dock gates are no longer usable and have been removed and only limited small boats that have certifications (as vested interest) can pass the dam through the incline.

Fig. 5.5-5
Incline for navigation on the Imawatari Dam

5.5.2.4. Environmental consideration

a) Minimum Flow

In terms of environmental conservation of rivers, a regulation under the River Law of Japan was established and requires all dam owners to release an appropriate minimum flow from dams since 1988 when the owners renew the water usage right or a new dam/weir is constructed. The minimum flow is currently in the range of 0.1 m^3/sec to 0.3 m^3/sec per 100 km^2.

b) Fish Passage

A fish passage was installed on both the left bank and the right bank of the Imawatari Dam which is the most downstream dam in the Kiso River. But there are no fish passage facilities in dams in the upstream of the Kiso River.

Fig. 5.5-6

5.5.2.5. Reservoir operation for multipurpose usage

The Misogawa Dam and Agigawa Dam, which have flood control capacity, keep the water level high during non-flood season and drawdown to the minimum water level before the flood season. The Maruyama Dam has a capacity of 20.2 million m^3 for flood control through a year as the surcharge. Other dams which do not have flood control capacity release the stored water in the reservoir for generation as much as possible and make an effort to lower the water level in the reservoir in advance of floods according to flood forecast and other data and to minimize release from spillway for effective water usage in the reservoir.

5.5.3. Conclusion and summary

5.5.3.1. Hydropower generation

It is very important to use and maximize river flow throughout the year while considering flood season, snow melt flow and dry season with dams and to minimize impacts on the downstream river course to maintain the minimum flow according to laws and/or agreements, and then, without spill from dams, the river flow has to be utilized for power generation and discharged to the downstream area according to electricity demands. Corresponding to electricity / water supply demand and innovations of construction techniques, dams and hydropower stations have been developed year by year in the 1990s. At the same time, river flow usage has to be reviewed and agreed among relevant parties.

5.5.3.2. Flood control

Most dams owned by electricity utilities basically have no flood control capacity, but, in terms of utilization of the river flow and creating flood control capacity on a cooperation basis, the stored water in the reservoir would be used for generation in advance of large rainfall as much as possible. Needless to say, dam owners must operate dams so as to avoid losing the original river function (without creating artificial floods) and comply with relevant regulation/laws.

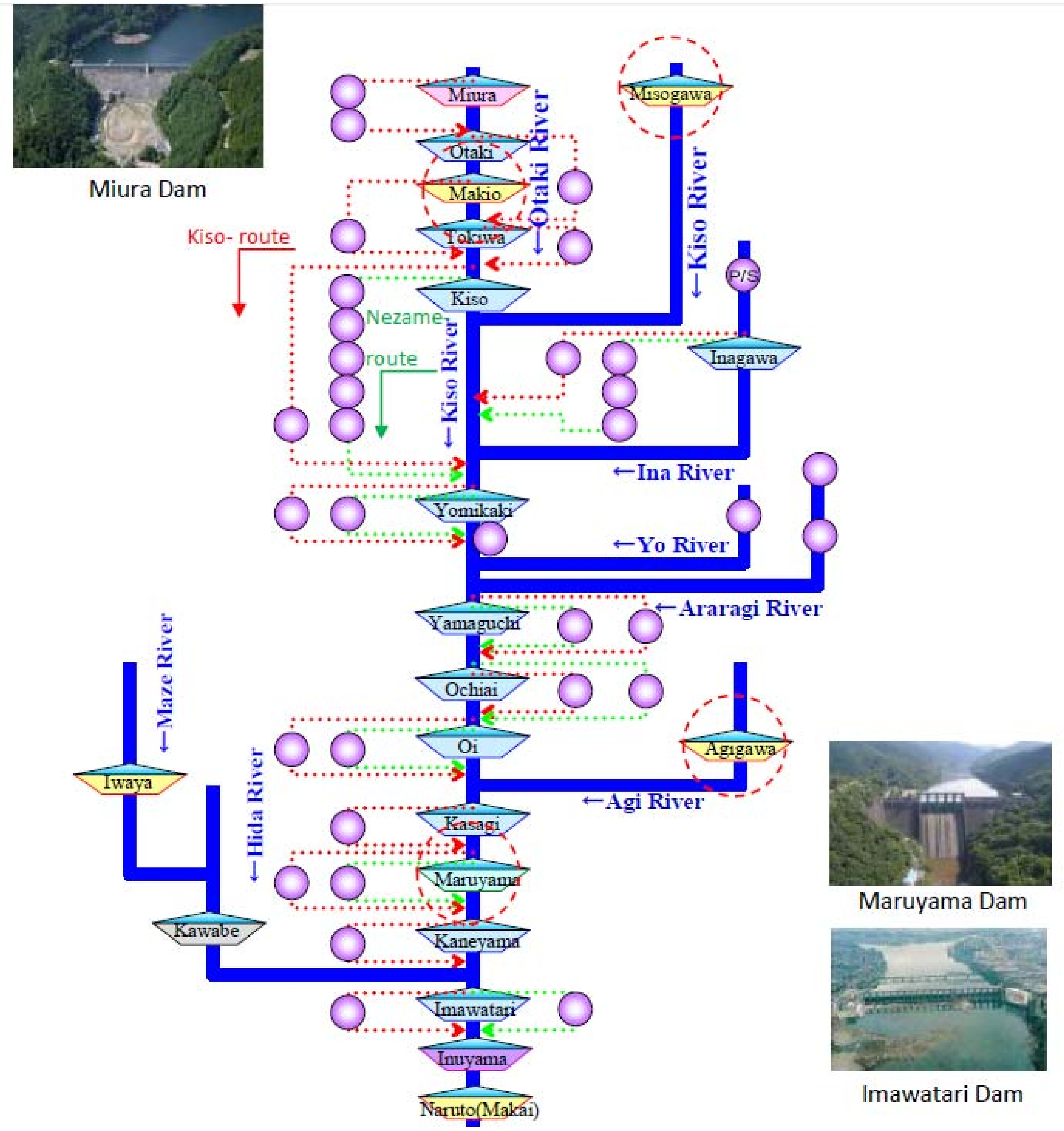
5.5.3.3. Environmental consideration

Minimum flow as an obligation of dam owners in terms of environmental conservation measures has been established at each dam in accordance with laws / regulations / guidelines when the water right is renewed. Furthermore, fish passages were installed at the Imawatari Dam (on both banks); however, they are not required at all dams.

5.5.3.4. Navigation

Previously, some dams had a dock or inclines for navigation or fishery / timber transportation. But following the development of a paved road network along the river, the volume of navigation has been significantly decreased, and therefore, the dock gates are no longer usable and have been removed, and only limited small boats that have certifications (as vested interest) can pass the dam through the incline.

Annex 1 – Kiso River Hydropower Station and Dam Map



pressured tunnel)

：Waterway (for old HP; open channel)

：Hydropower plant

：KEPCO (Regulating pond (11)

：CEPCO (Chubu Electric Power Co.)

：JWA (Japan Water Agency):4

：KEPCO and MLIT (1)

：MAFF (Ministry of Agriculture, Forestry and Fisheries)(1)

Annex 2 – List of Hydropower Stations on the Kiso River

Number of stations：33

Total installed capacity (kW)：1,064,050

Station Name	Installed Capacity (kW)	Effective Head (m)	Maximum Station Discharge (m^3/s)	Operation Commencement Year
Miura	7,700	52.7	17.5	1945
Takikoshi	28,900	185.5	17.5	1951
Ontake	68,600	229.2	34.4	1945
Mio	36,700	137.2	30.9	1963
Tokiwa	15,000	35.6	48.8	1941
Nezame	35,000	64.3	65.8	1938
Agematsu	8,000	21.1	48.7	1947
Momoyama	25,600	79.6	37.6	1923
Inagawa	40,700	438.0	11.0	1977
Suhara	10,800	34.9	36.2	1922
Kiso	116,000	225.9	60.0	1968
Inagawa-No.2	21,600	399.5	6.5	1986
Ainosawa	6,200	243.8	3.1	1938
Takou	2,500	108.8	2.8	1924
Hashiba	1,900	55.8	4.1	1929
Okuwa	12,600	39.1	38.4	1921
Okuwanojiri	490	22.5	2.8	2011
Yokawa	1,760	135.4	1.7	1927
Yomikaki	119,000	112.1	120.9	1923
Tsumago	2,800	182.0	1.9	1934
Araragigawa	1,200	55.6	2.8	1925
Shizumo	16,300	49.7	44.0	1933
Yamaguchi	42,000	62.4	78.0	1957
Ochiai	14,700	22.0	83.5	1926
Shin-ochiai	18,900	22.1	100.0	1980

Oi	52,000	42.4	139.1	1924
Shin-oi	32,000	44.0	85.0	1983
Kasagi	41,700	30.4	165.8	1936
Shin-maruyama	63,000	78.1	93.0	1971
Maruyama	138,000	80.9	192.9	1954
Kaneyama	39,000	23.2	200.0	2006
Imawatari	20,000	12.2	200.0	1939
Minokawai	23,400	12.4	220.0	1995

5.6. Reservoir operation based on real-time inflow forecast in Switzerland

5.6.1. Introduction

During the last decade, flood risk management became a major concern in Switzerland. This is partly due to the obligation to establish hazard maps. In the Canton of Fribourg, the local authorities have decided to be proactive to reduce future potential damages. In collaboration with local hydropower producer Group E, they set up an active flood management system for the Saane River basin. The first aim of the project was to define the potential of discharge reduction due to preventive power production operations based on hydro-meteorological forecasts. The second goal consisted in the design of an operational Decision Support System (DSS) leading to an optimal power generation (Jordan F., 2012).

The Saane River basin is mountainous, which has several incidences on the hydrological cycle. First of all, the pluviometry of the region is relatively high: 1,500 mm/year on average, but more than 2,000 mm/year in the upper part of the basin. Secondly, a non-negligible fraction of the precipitation consists in snow. This has a strong influence on the hydrological regime of the river. Indeed, the snowpack stores a large amount of water during winter, which can cause snowmelt flood if the temperature rises above 0°C.

The natural discharge is characterized by high water during spring and low flow during winter. Nevertheless, the various hydropower stations and factories located along the river change its daily and annual regime considerably.

In the lower part of the basin, the Saane River flows through the City of Fribourg. In case of a flood event, the economic and environmental damages can be very important, reaching tens of millions of Euros.

On a national scale, the Saane river is an important tributary of the Aare river (catchment area: 17,800 km^2, 43% of Switzerland). An optimal management of both rivers is required in order to prevent floods in the Swiss plateau located downstream. In particular, it is important to be able to avoid simultaneity of peak discharges at the confluence of the Aare and Saane rivers.

Several reservoirs are located along the stream. The retention volumes and installed power capacities vary greatly from one scheme to the other. A sensitivity analysis of peak discharge and power capacity points out the most relevant artificial lakes: Gruyère and Schiffenen. The lake of Gruyère is located upstream of the city of Fribourg. This reservoir, with a volume 162 million m^3, is one of the largest in Switzerland. The power capacity of the power station is 75 m^3/s and the bottom outlet capacity is 100 m^3/s. The Schiffenen lake (volume: 33 million m^3) is located in the lower part of the basin, downstream of Fribourg and thus is used to regulate the discharge at the outlet of the watershed. The installed capacity is 135 m^3/s. In case of emergency, the maximum operating flow of 186 m^3/s can be used instead of the bottom outlet.

5.6.2. Hydrological and hydraulic model

The hydrological model used in this study is a conceptual semi-distributed model named RS 3.0. It is based on the GSM-SOCONT concept (Schaefli et al. 2005) developed specifically for high mountainous catchment areas. The basic equations can be found in García Hernández et al. (2007).

First, the catchment area has to be divided into sub-basins and then into 300 m elevation bands. This discretization makes it possible to consider the elevation-dependent processes. The general principle of the hydrological model is presented in Fig.5.6-1. The first step of the computation consists in interpolating the meteorological variables (precipitation, temperature) as a function of the elevation and location of the elevation band. Afterwards, the different hydrological processes can be computed.

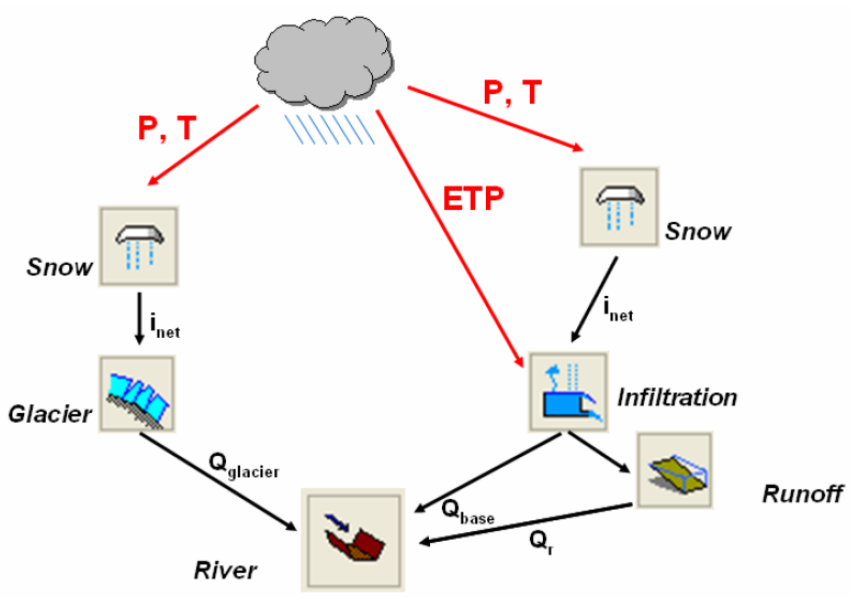


Fig 5.6-1
Description of the hydrological modeling concept GSM-SOCONT

The model differentiates regions with and without glaciers. When glaciers are present in the basin (Fig. 5.6-1, left part), the model is composed of a snow cover on top of the glacier. The snow model computes the evolution of the snowpack, its water content and the melting process with the help of a degree-day equation. As long as the glacier is snow-covered, the ice is protected and will not melt. When the glacier is snow-free, it begins to melt according to a degree-day model. Then, the water is transferred into a series of linear sub-glacial reservoirs. The model is also able to compute the global mass balance of the glacier and its long term evolution.

When the watershed is free of glaciers (Fig. 5.6-1, right part), the model is slightly more complicated. The snow model is the same as before and computes the evolution of the snowpack. The water resulting from the melted snow is then transferred to the soil. When there is no more snow on the ground, the precipitation is directly transferred to a non-linear soil infiltration model. This model is based on the GR3 equations and has been adapted for specific applications. The evapotranspiration and infiltration depend on the water content of the soil. The base discharge is computed by a series of reservoirs and varies principally with the soil saturation. The surface runoff is computed with the SWMM model, which solves the kinematic wave equation on an inclined plane. The main parameter of this model is the surface roughness. Finally, the total discharge coming from glaciered and un-glaciered bands is routed into a river channel.

The main strength of RS 3.0 is to easily integrate hydraulic structures such as reservoir, power generation, spillway, and bottom outlet or water intake in the simulation. In order to automate the power generation and bottom outlet operations, a specific algorithm has been developed. The general principle of this tool is to optimize preventive operation (power generation or bottom outlet) in order not to exceed a critical discharge downstream (Fig. 5.6-2). The operator defines a time horizon in the future (named prediction time) and threshold values (critical discharge, max. volume, etc.). Depending on the free volume in the reservoir and the forecasted inflow, the algorithm determines the best solution: do nothing, produce power or release water through the bottom outlet.

Moreover, the model takes into account the electricity market price in order to generate during periods of high demand. The aim is to maximize the economic income and avoid losing water.

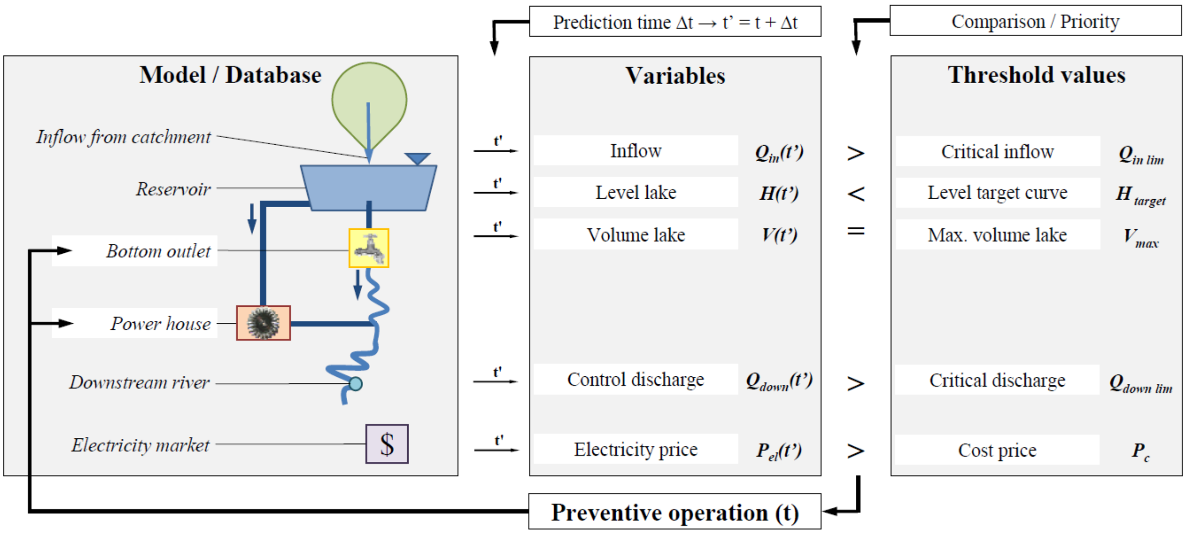


Fig 5.6-2
Preventive operations optimization process

The RS 3.0 model has been applied successfully for several years in Switzerland (Jordan, 2007 and Jordan et al., 2010). Moreover, it has been used operationally by Group E as an inflow forecasting system since 2007. Consequently, the model has already been calibrated and validated in the Saane River basin.

5.6.3. Data sources

Hydrological modeling requires several data sets either as input data or as control data. The meteorological data come from different measuring networks. The Federal Office of Meteorology and Climatology (MeteoSwiss) has 7 automatic weather stations located in the Saane River basin and the surroundings. These stations measure the temperature and the precipitation at a 10-minute time step. In addition, daily precipitation is also collected at 29 stations. These data are then disaggregated to an hourly time step with the nearest stations. Group E operates six weather stations in the catchment that measure temperature and/or precipitation at a 15-minute time step.

The Swiss Federal Office of Environment operates several gauging stations along the Saane River basin. The most important ones are located in Fribourg and Laupen (close to the basin outlet). These two measuring stations are used as reference to quantify the peak discharge reduction. Group E provides the system the general characteristics, the rules of operation and the historical data of the different hydropower schemes. Finally, the electricity prices used in the optimization process come from the European Energy Exchange (EEX).

5.6.4. Historical events and scenarios

The choice of historical events for calibration is not straightforward. The availability of meteorological and hydrological data is often a limiting factor. Moreover, initial reservoir levels and turbine operation are not always known precisely. Finally, two historical flood events have been chosen: August 2005 and August 2007. The return periods of these two events are 60 years and 30 years respectively and they can be considered as the largest floods since the construction of the dams (1944-1964). For each event, the following scenarios are computed.

The first scenario named Reference is supposed to reproduce the reservoir management observed during these events. No preventive operation is carried out and during the flood peak, the motto is "Business as usual". Turbine operation is optimized according to safety rules and electricity prices but regardless of the downstream discharge. This scenario is compared with measured discharge in Fribourg and Laupen to validate the model.

In the second scenario, all hydraulic structures are removed from the model. This scenario represents a hypothetical natural state of the river. By comparing it to the Reference scenario, one can determine the flow attenuation induced by dams. Indeed, the reservoirs will retain a non-negligible volume of water even if no preventive operation is done.

Finally, the third scenario considers preventive operations. For a given time horizon (Δt), it is assumed that the reservoir inflow is forecasted correctly. Consequently, the model will optimize the power generation and bottom outlet operation in order not to exceed a given discharge downstream. In addition, the algorithm will minimize the overflow and then, maximize the electricity production. The aim is to obtain a full reservoir at the end of the event. The general principle of reservoir management is presented in Fig 5.6-3.

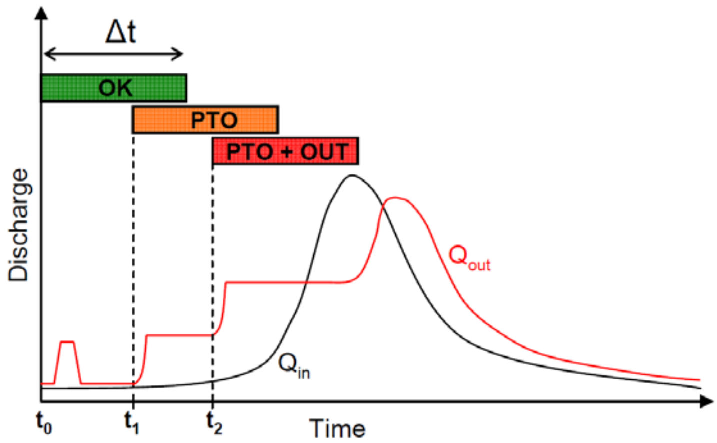


Fig 5.6-3

Principle of reservoir management. OK is the normal production programme, PTO means preventive turbine operation and OUT is for bottom outlet.

At t0, the situation is normal: the forecasted inflow is low and the available volume is enough. The normal production programme can be achieved. At t1, the inflow becomes more important and if nothing is done, the lake will overflow through the spillway. Then it is decided to produce power beyond what is planned to lower the lake level. At t2, the situation becomes critical: the forecasted inflow is very important. A water release by the bottom outlet is necessary. Finally, the downstream peak discharge is shifted in time and reduced in amplitude in comparison with the inflow. The situation is re-assessed every hour; this enables a very precise flood management. In reality, the flow forecast is based on weather forecast. Consequently, the uncertainties are non-negligible and are limiting in the choice of the prediction time.

5.6.5. Operational decision support system

Preventive operations enable electricity producers to reduce the water overflow significantly during the event. Depending on the scenario, the water loss can be reduced by 10% to 30%. The additional production reaches several hundreds of MWh which is non-negligible. Based on previous results, an operational Decision Support System (DSS) has been set up. This tool is available on the web and is accessible to authorities and electricity producers. Basically, the DSS contains two different parts. The first one is a map interface of the Saane River basin (Figure 5.6-4) with the various hydrological and hydraulic elements. The user can click on these objects and quickly access information. The web technology is based on the Google Maps Application Programming Interface (API). The available information on the website is: measured and forecasted discharges, reservoir level evolution (in the past and in the future) and optimal preventive operations to minimize the downstream peak. The hydrological forecasts are based on the global ECMWF model, and the regional COSMO2 and COSMO7 model.

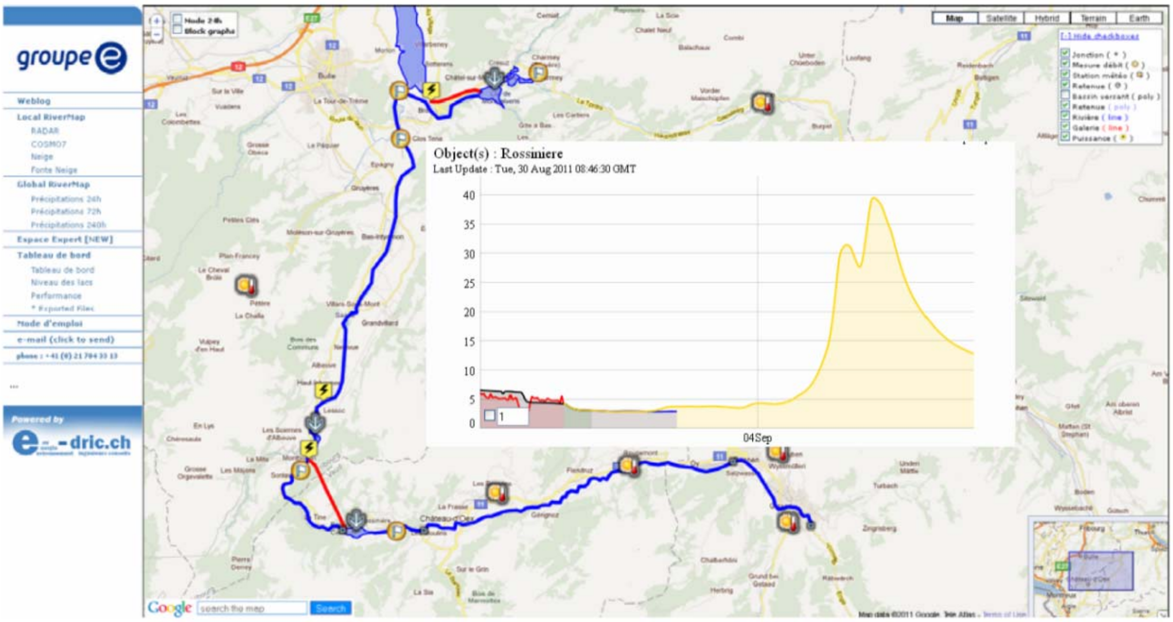


Fig. 5.6-4
Web interface of the Decision Support System

The second unit of the DSS is a GIS database named Expert Area (see Figure 5.6-5). The catchment is divided into six large zones that are coherent from a geographical and hydrological point of view. These entities make it possible to synthesize the hydro-meteorological information and give a global vision of the basin. Based on the simulation, the following maps are computed:

- Total precipitation for 24 hours and 48 hours;
- Snow cover and snow melt;
- Net rainfall;
- Soil saturation;
- Air temperature (altitude of the 0°C isotherm); and
- River discharge and available volume in the reservoirs.

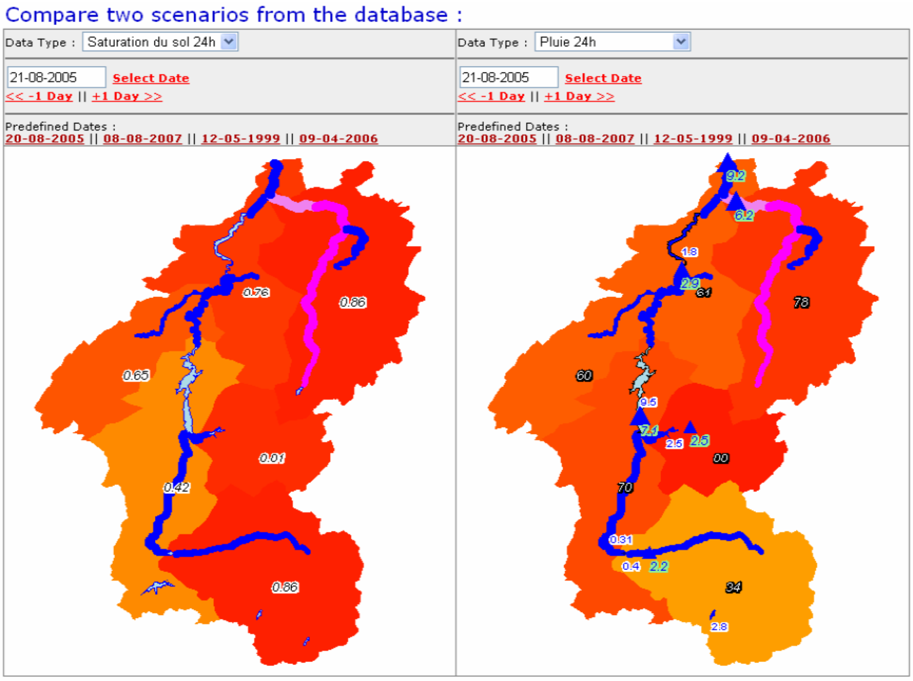


Fig. 5.6-5
User interface of the expert area in the DSS: map of soil saturation [0-1] (on the left) and daily precipitation [in mm] (on the right) in August 2005

The aim of these maps is to highlight relevant hydro-meteorological processes leading to flood events. Based on these maps, the decision-makers can understand which processes are critical: Is it a snowmelt flood? What is the spatial extent of precipitation? What is the initial state of the watershed (in terms of soil saturation or snow cover)?

The maps are computed in real-time for the recent past and the near future, based on hydrological forecast. Moreover, these maps are updated every hour. Thereby, the decision-makers have up-to-date information. When a new weather forecast is available or if the meteorological or hydrological conditions change suddenly, the preventive operations can be adapted or stopped very rapidly. The database has been incremented permanently since November 2010. In addition, historical events have also been integrated. Therefore, it becomes possible to compare different situations and identify similarities. An automatic algorithm has been developed to determine the maximum likelihood between the current situation and similar events in the past.

5.6.6. Conclusion

An important peak reduction can be achieved by preventive turbine operation of the dams located in the Saane river catchment. This is true even if the decision is taken late (12h before the maximum discharge). The study also shows a win-win situation between the different partners. On one side, the local authorities reduce the potential flood damages. On the other side, the electricity producer maximizes the electricity production. This study points out that an active flood management system is necessary. Therefore, an innovative DSS has been set up to provide relevant information for decision making. The DSS is now operational and a practical use is currently experienced, which will probably lead to future evolutions of this system.