Integrated Operation of Hydropower Stations and Reservoirs

Committee on Integrated Operation of Hydropower Stations and Reservoirs

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Foreword

Life on the earth needs water. Water is an essential need for life and particularly human beings. It is not astonishing that our ancestors developed works for supplying drinkable water and then for agricultural purposes in thousands of years. In China and in Babylonian regions, reservoirs have been built from the antiquity along with the development of agriculture. This need is still vital today. Hydroelectric schemes give access to drinkable water, lands irrigation, production of mechanical and electric energy, participation to transport of people and goods and so on.

Hydropower development started in around the 1870s in the paper industry with the invention of Francis (1868) and Pelton (1879) turbines. The first hydropower station was built in France in 1882 by combining a turbine and a Gramme dynamo.

Decades later, the trend for cascade hydropower developments in a whole basin first appeared in Japan. Then in the 1930s, multi-objective comprehensive cascade development of the Tennessee Valley was proposed and implementation started. At the same time, the USSR started to plan and implement the Volga River development. Currently, there are many well-known comprehensive cascade developments on larger rivers, such as the Columbia River, the Tennessee River and the La Grande River in North America, the Parana River and the Orinoco River in South America, the Ariège River, the Rhone River, the Douro River and the Volga-Kama river in Europe, the Yenisei River, the Kiso River and the Great Karun River in Asia, as well as the Nile River, the Niger River and the Zambezi River in Africa. In China, the comprehensive development in the upper stream of Yangtze and its tributaries is ongoing and the world's largest hydropower system will be formed there in the near future.

In order to facilitate the development of comprehensive cascades and have a better understanding of them, ICOLD decided to organize the Committee on Integrated Operation of Hydropower Stations and Reservoirs and appointed the committee in 2011. Committee activities started from the Kyoto Conference in June, 2012.

The terms of reference for the Committee were:

- Safe operation and management of hydropower stations;
- Integrated operation of hydropower stations with multi-objective oriented reservoirs;

- The optimal operation of basin 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.

The Committee publishes this bulletin as a reference for readers in hydropower and related fields. It gives an overview of the main functional aspects relating to cascade hydropower stations and typical case studies in member countries. It was formed by reviewing of all the related aspects proposed and case studies provided by committee members.

I appreciate the great effort made by former chairman Dr. Cao Guangjing as well as sincere cooperation and enthusiastic participation of all 16 committee members who shared their experience and time for the creation of this bulletin.

I hope that this bulletin serves to give a holistic vision of the various aspects related to the functions and operations of cascade hydropower stations.

CHEN Guoqing

Committee on Integrated Operation of Hydropower Stations and Reservoirs

Committee on Integrated Operation of Hydropower Stations and Reservoirs

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1 Introduction

Dams store water and this may address many purposes and functions. Storage may serve to raise the water level in a river over a particular section to facilitate navigation or to create head for hydropower generation. Storage may also be used to collect surplus flow during floods for later use in supplies for domestic, industrial, agricultural, ecological or hydropower generation needs. In certain circumstances it may be necessary to keep the storage level low to facilitate flood mitigation downstream of the dam. In addition to these many, often conflicting requirements for creating storage, reservoirs may offer significant recreational or touristic potential. Dams need to be designed and operated to ensure that they meet all the anticipated purposes in an economically and environmentally sustainable manner.

Dams are generally built on rivers. As a result the dam structures may cause potentially serious discontinuities in natural river systems, particularly with regard to sediment transportation, fish migration and breeding patterns. The changed flow regime downstream of dams, as well as the new shoreline created inside a reservoir also impacts the riverine environment. Thus, environmental considerations often create operating restraints or requirements.

Dams, being structures built in rivers, also have to be able to safely withstand the full onslaught of the river over very long periods of time, including the impacts of large floods and sediment loads.

More often than not dams are designed, built and operated to serve more than one of the above functions. The various roles may have conflicting design and/or operational requirements so a cost effective workable compromise is often necessary. This situation is often further complicated when multiple dams are built downstream of each other on one river (a cascade). In many countries the complexity is further increased by inter-basin water transfer that then requires integrated operation of reservoirs in multiple river basins. Various complex approaches to systems analysis have been developed over the years to reliably simulate, optimise and control such operations.

As a result of the wide range of water uses requiring storage in reservoirs, integrated planning and operation of water resources is well-developed in many countries across the world, especially the storage reservoirs.

1.1 The role of dams

Dams have been designed, constructed and operated as integral parts of water resources management and development worldwide. Historically, most dams were built with irrigation supply as the primary purpose (from Babylonian or Egyptian times). Nowadays about 25% of large dams have hydropower as the primary purpose, or as one of their main purposes. As head is the primary concern when generating hydropower, it follows logically that a large portion of high dams have been built for hydropower development, with hydropower been the primary purpose for more than 80% of all dams higher than 200m.The ten highest dams in the world all have hydropower as a very important purpose as shown in Table1.1 below.

Table 1.1 List of the highest dams in the world

Dam Name	Country	Height (m)	Type	Primary Purpose
Jinping-1	China	305	Concrete arch	Hydropower
Nurek	Tajikistan	300	Embankment	Hydropower
Xiaowan	China	292	Concrete arch	Hydropower
Xiluodu	China	285.5	Concrete arch	Hydropower
Grand Dixence	Switzerland	285	Concrete gravity	Hydropower
Inguri	Georgia	272	Concrete arch	Hydropower
Manuel Moreno Torres	Mexico	261	Embankment	Hydropower
Nuozhadu	China	261	Embankment	Hydropower
Tehri	India	260.5	Embankment	Hydropower
Mauvoisin	Switzerland	250	Concrete arch	Hydropower

Clearly dams and hydropower are closely related because dams are very effective in storing water and thereby energy for future water resources. It follows that the integrated operation of hydropower stations and reservoirs is a primary concern, albeit as part of a greater integrated role for dams in water supply, navigation and the like.

1.2 The energy pool

Hydropower and associated large dams currently make up significant portions of the national power supply of various countries. The installed hydropower capacity of countries with abundant water power resources are shown in the table below:

Table 1.2 Installed hydropower capacity of selected countries (by the end of 2014)

Country	Installed hydropower capacity (GW)	Hydropower as percentage of installed capacity (%)
China	301.8	22
United States	101.6	8
Brazil	89.3	70
Canada	77.74	63
Japan	49.67	17
Russian Federation	50.47	21
France	25.37	10
Switzerland	15.61	60

Notes: From IHA Statistics

Traditionally the construction of pumped storage hydropower stations has lagged behind development of conventional hydroelectric plants (HPP). This relative lack of development results from the fact that pumped storage schemes are net users of energy as opposed to net generators but the idea was to use cheap energy and store water at period of time where there is no electric need, and to produce energy with this water at period of strong electric consumption, it was an economic concept that lead to pumped storage power plants.. Moreover, they have essential characteristics that make them a very useful tool for stabilizing the electric grid. For example, in the beginning of 1930, the first pumped storage HPP was built at 'Lac Noir' in the eastern part of France, to regulate energy generation and consumption. This aspect will be returned to later. More recently, many large pumped storage schemes have been built. Table1.3 shows a sample of large pumped storage hydropower schemes around the world.

Table 1.3 List of large pumped storage schemes around the world

Country	Schemes	Installed capacity (MW)
United States	Bath County	3003
China	Huizhou	2448
China	Guangzhou	2400
Japan	Okutataragi	1932
United States	Ludington	1872
China	Tianhuangping	1836
France	Grand Maison	1800
South Africa	Ingula	1300
Russian Federation	Zagorskaya-1	1200
Switzerland	Linth-Limmern	1000

Switzerland	Nant de Drance	900

The negative sentiment surrounding large dams in the 1980's and the severe scrutiny and criticism of the Carbon Trading Program brought about the concept that runoff hydro development was renewable, sustainable and environmentally friendly, whereas hydropower schemes involving large dams were non-renewable and environmentally damaging. This perception still lingers today, although the sentiment is declining. Concepts of sustainable development are continuously developing, mitigating environmental and social impacts whilst optimising energy production.

The emergence of more affordable green energy technology in the form of photovoltaic, wind turbines and, to a lesser extent, runoff hydropower schemes has seen the introduction of increased stochastic variability in many national and regional power networks. Introduction of such variability into a grid can be managed only as long as the grid has sufficient flexibility in its current makeup to compensate for fluctuations introduced by green technologies. Such a rapid response is to be found only in hydropower, gas turbines and on a smaller scale, batteries.

In countries where there is large scale reliance on base load generation using thermal and/or nuclear power plants, and/or where there is limited hydropower potential, it will become increasingly important to consider the development of pumped storage hydropower or gas turbines stations to compensate for the unpredictability introduced by green energy development.

2 Reservoir operating criteria

Generally, reservoir operating criteria are determined based on hydro-meteorological considerations, dam safety and emergency responses, flood management operations and water user requirements. Each of them is elaborated on in the following.

2.1 Hydro-meteorological considerations

Hydro-meteorological forecasting is the foundation for reservoir operation. Water resources depend on meteorological conditions; hence both rainfall and runoff are stochastic. Prediction may be made up to 14 days by means of hydrological models (which transform precipitation into runoff). On the long term after 14 days, this is still a research topic and the domain of statistical approach. General meteorological model make prediction up to two months but of course with a great amount of uncertainty. Sufficient research and studied are still needed to extend the prediction period.

2.1.1 The role of runoff

The optimal operation of reservoir is depended on the reliable inflow time series. Otherwise, reservoir modelling will never produce reliable results.

In certain parts of the world, long runoff records are available. However, more often than not, runoff records are either too short or include too many missed or unreliable readings. The question then becomes how such records can be corrected and/or extended. Usually, rainfall records are longer and more reliable available than runoff records. So various hydrological models which transform rainfall into runoff are developed and applied in different countries. They can be extremely powerful tools to extend limited runoff records, but must be used with caution outside the areas where they were developed and proved. For example, a model that has been developed and proven in a semi-arid region may provide completely wrong results in a catchment that generates a substantial part of its runoff from snowmelt. The contrast seems obvious and more subtle differences may affect model results significantly.

If a sufficiently long observed/recorded runoff record is available, or a short record has been extended into a sufficiently long synthetic record (typically about 70 years or more), there are various stochastic generators that can be used to generate a multiple synthetic time series of flow that can be used as input into system simulation models. The generated synthetic sequences keep certain statistical characteristics of the source series. Typically the mean annual runoff, standard deviation of inflows and the like will be maintained. Multiple time series of flow generated by such means allow assurances to be assigned to outcomes from simulation models. Again the caution holds not to use a model that the user does not understand and not to use models outside the area in which they were developed without verifying that the model remains valid.

2.1.2 Hydrological and meteorological forecasting

Hydrological and meteorological forecasting is the qualitative or quantitative prediction of weather and hydrological conditions of a certain water body, area or hydrological station over a certain period of time in the future on the basis of prior or current hydrological and meteorological data and information. Accurate and timely hydrological forecasting is the scientific basis of decision-making for flood control, optimal operations of water resources, and management operation of hydroelectric projects. It plays a crucial role in ensuring the safety of lives and property, enabling hydroelectric projects to deliver intended results, and facilitating social stability and sustainable development.

Since the 1930s, hydrological forecasting technology has advanced rapidly from empirical formulas and lumped models to distributed models, with remarkable results achieved. Thanks to the development of computer, communication and information processing technologies, hydrological forecasting is still developing strongly.

However, the continuity of rivers has been changed with socioeconomic growth, increased exploitation of water resources and a rising number of reservoirs and hydropower stations that are under construction in watersheds. In particular, reservoirs with seasonal regulating capacity have, to a large extent, altered the characteristics of the natural runoff of water systems in watersheds. Moreover, climate change is altering the spatial and temporal distribution and intensity of precipitation; the characteristics of hydrological elements such as evaporation, runoff and soil moisture have changed; and droughts and floods have become more frequent. Thus, global climate change, construction of cascade reservoirs and rapid socioeconomic growth have put tremendous pressure on the development and utilization of water resources in watersheds, and both spawned a series of new propositions in various disciplines and posed new problems and challenges to hydrological forecasting.

2.1.2.1 Weather forecasting

Currently, weather forecasting includes the forecasting of weather situations and the forecasting of meteorological elements. The former involves the forecasting of the movements, intensity changes, formation and disappearance of weather systems (high pressure, low pressure, troughs and ridges, frontal surface, etc.), while the latter involves the forecasting of meteorological elements such as air temperature, air pressure, humidity, visibility, wind, clouds and precipitation, as well as weather phenomenon. The two are closely related. Weather situations are the basis of the forecasting of changes of meteorological elements. In terms of duration of the forecast period, weather forecasting is divided into short-term forecasting, medium-term forecasting, and long-term forecasting. As a general rule, forecasting for the next few hours to 1 to 3 days is classified as short-term forecasting; forecasting for 3 to 14 days is classified as medium-term forecasting; and monthly, quarterly and yearly forecasting covering more than 14 days is classified as long-term forecasting.

Currently, weather stations employ three major weather forecasting methods: the weather chart method, the numerical forecasting method and the mathematical statistics method. The first two methods are mainly used in short-term forecasting, and the last one is primarily devoted to long-term forecasting. In actual forecasting, the three methods are combined to supplement one another.

Weather forecasting applied to the operation of cascade hydropower stations mainly serves the purpose of precipitation forecasting, which provides basic rainfall information and data for hydrological forecasting in order to predict inflows to reservoirs and the flows in between. Some extreme weather may have serious effects on a dam, so it is also necessary to forecast meteorological events like rainstorm, typhoon, thunder storm, blizzard and snow etc.

2.1.2.2 Hydrological forecasting

By content, hydrological forecasting is divided into:

- Forecasting of water level;
- Forecasting of runoff, including forecasting of floods and forecasting of low flows;
- Forecasting of ice conditions;
- Forecasting of sediment situations;
- Forecasting of water quality.

By duration of the forecast period, hydrological forecasting is divided in:

- Short-term forecasting, covering less than 3 days;
- Medium-term forecasting, covering 3 to 14 days;
- Long-term forecasting, covering 15 or more days.

Different methods are employed at different stages of hydrological forecasting on the basis of different boundary conditions. In the runoff yield process, frequently used methods include the method of runoff yield under saturated storage, the method of runoff yield under excess infiltration, and the method of mixed runoff yield. In the confluence process, frequently used methods include the method of unit lines and the method of uniform flow time lines. In the watercourse computation process, frequently used methods include the characteristic river length method, the Muskingum method, and the corresponding river level (flow) method, and the hydraulic river flooding algorithm method. Hydrological models provide strong technical support for hydrological forecasting. In general, these existing hydrological models are divided into empirical models, conceptual models, and physical models, according to the robustness and complexity of the physical patterns of the movements of water flows. Hydrological models are divided into lumped hydrological models and distributed hydrological models according to their ability to reflect the spatial changes of the movements of water flows. Between the two types of modes, there are the semi-distributed models. At present, the main conceptual hydrological models include the Xin'anjiang model, the TANK model, the Sacramento model, and the HBV model while the main semi-distributed and distributed hydrological models include the SWAT model, the TOPMODEL, the SHE model, the VIC model. These models are used to the greatest extent to make the forecasting across the world.

However, different countries have various ways of models classification. For example in Brazil, these models are generally classified into two types, called stochastic models and rainfall-runoff models, and are adopted by almost all the hydropower stations.

Since hydropower production depends on weather and runoff, there should be special departments or specialists responsible for it. Take Japan's Kiso River as an example, there is a specific division making runoff forecasts based on weather forecasting data published by the meteorological agency. Furthermore in China's Yangtze River, both meteorological and hydrological forecasts are made by one special department. It is also important that forecasters should be qualified with understanding meteorological and hydrological situations and utilizing modals to simulate and predict.

Nowadays the accuracy of hydro-meteorological forecasting cannot meet the demands of integrated operation of hydropower stations and reservoirs, especially for medium-term and long-term forecasts, so it needs further development. Future breakthroughs can focus on numerical value forecast technology, hydro-meteorological coupling prediction technology, medium-term and long-term hydrologic forecast technology.

2.2 Dam safety and emergency response

Operating dams and the associated reservoirs in such a way as to ensure dam safety is the primary concern. Evaluating the pertinence and accuracy of hydrological predictions as mentioned in previous sections is important to ensure a feedback on these predictions, to be able to improve them, since they may have an impact on the safety of the dam and reservoir. In the unlikely event of an unforeseen emergency occurring, it is essential to have practical, effective and efficient response systems in place. These two aspects are briefly outlined in the following.

2.2.1 Dam safety

Dams are designed to be stable and remain safe when subjected to all conceivable loads and conditions including physical loads, thermal loading and seismic events. In addition dams need to be able to handle natural floods and the associated sediment and/or debris loads. These are all subjects to various ICOLD bulletins such as:

- Internal Erosion of Existing Dams, Levees and Dikes, and their Foundations(Bulletin 164, 2015)
- Integrated Flood Risk Management(Bulletin 156, 2014)
- Dam Safety Management: Operational Phase of the Dam Life Cycle(Bulletin 154)
- Role of Dams in Flood Mitigation - A Review(Bulletin 131, 2006)

Dam safety requirements are also regulated by laws in various countries.

Safe operation of a reservoir includes consideration of the stability of the dam structure, reservoir basin slope stability as affected by rapid water level variations and impact on the downstream environment.

2.2.2 Dam surveillance

Dam surveillance is fundamental to check and control that the dam and the associated reservoir behave as envisaged during their design. Dam safety is legislated in many countries. It is also highly emphasized in the relevant ICOLD bulletins.

Usually, monitoring and analysis of dam safety should be undertaken when:

- First impounding;
- During regular safety investigations;
- During special investigations after a huge flood, serious earthquake or any unusual circumstances.

When necessary, measures should be taken and results should be reported to related authorities. Dam safety monitoring includes the monitoring of structure deformation, seepage, stress-strain, hydraulics, strong seismic activities etc.

2.2.3 Emergency response

Emergency response procedures are generally developed during the dam design phase. The two most common considerations are dam break analyses in the event of a catastrophic failure, and the need to be able to draw the reservoir water level down over a reasonable time in the event of some structural emergency. Many countries have legislation in this regard. It is worthwhile to note that such emergency drawdown may affect water users in the reservoir as well as those further downstream, but safety is the first stake to be taken into account.

Real time prediction of emergencies is either difficult (e.g. flash floods) or impossible (e.g. seismic event). If an emergency occurs, action must be taken quickly by well-trained competent people. Actions are normally taken in accordance with previously prepared emergency plans. These situations are normally managed by a designated organisation staffed by suitably qualified and experienced people. Some major rivers are shared between several countries with more than one national organization involved. Under these circumstances international agreements usually assign operative responsibility.

In France, as an example, there are two broad principles. The first principle is to overreact and the second principle is to set up a crisis management team. The team will coordinate:

- Technical action and /or interventions;
- Possible rescue teams or missions;
- Communication inside the team as well as with externally affected parties.

The team should have all the necessary technical and logistical support required. In addition they should be trained in handling the media. These principles are simple but real time application is very difficult, operating team has to be regularly trained.

2.3 Water user requirements

Operation of reservoirs is a key part of almost all water supply systems. Reservoirs provide water for various consumptive uses, mainly including irrigation, domestic use, industrial use, ecological demands (including fish-farming), and various non-consumptive uses, including navigation, hydropower generation, and recreation. Usually reservoirs are not designed for all of these uses, they are operated according to their primary purpose and sometimes other uses also will be taken into account. In general, irrigation and hydropower generation are the primary and most common types of water use from dams.

The priority of supply and the assurance of supply to the various types of users is the subject of legislation in many countries. These aspects are elaborated on below.

2.3.1 Irrigation

Most large dams have irrigation supply as their primary purpose, or as one of their main purposes. Such supply generally needs to vary seasonally and may require a relatively low assurance of supply. Accordingly supply may vary from month to month and/or from year to year.

Supply can be effected by:

- The releasing of water from the dam to be abstracted further downstream, possibly from a weir;
- The releasing of water into a canal. The canal may be a gravity feed or may require some pumping from the reservoir into the canal;
- A pressure pipeline through the dam wall.

The means selected to abstract irrigation water from the dam may affect the extent or timing of drawdown of the reservoir that would be desired.

The variable rate of abstraction of irrigation water, both in terms of seasonality and in terms of the level of drought that may be experienced in any one year, together with the relatively low levels of assurance that can be tolerated by irrigators, make irrigation use the single biggest variable in reservoir operation optimisation. Furthermore, return flows from irrigation may affect river flows downstream of the irrigated areas.

The issue of irrigation is a challenge around the world. In France, water shortages during summertime. In this period there are agricultural demands that require water stored in the Ariege cascade reservoirs. While in the Yellow River Basin, China, the demands on water supply for irrigation are great. Due to the variable seasonal water regime, cascade reservoirs are operated together to meet the demands of irrigation especially in the upstream and midstream. The objectives on the Volga-Kama cascade in Russia also contribute a lot to the salvation of eastern Volga areas from periodic crop failures and ensure grain production.

2.3.2 Domestic usage

Per capital domestic use, sometimes referred to as primary demand, is water used for human consumption. In its most basic form it represents drinking water. As failure to supply drinking water may threaten human life, levels of assurance of supply required are generally high.

Per capita domestic water demand generally grows as the affluence of those supplied increases. At higher levels of domestic supply some variability in supply (restrictions) may be acceptable in times of drought.

Although domestic supply is rarely the single biggest water user it is a strategic supply and thus important to account for properly when designing integrated reservoir operating rules.

The Ariège valley and Tennessee River both play an important role in the water supply of their basins. Electricité de France (EDF) has to maintain a water station to provide water for cities around the Ariège valley and has to survey the treatment of water before introducing it into the distribution network. In the USA, water is withdrawn at over 700 points along the Tennessee River and its tributaries to the benefit of approximately 4 million citizens.

China’s South Water to North Project is another typical case of trans-basin water transfer. With the completion of the project, 44.8 billion tons of water every year will be transferred to the north to improve the water quality for more than 7 million people. The water source of one of the three transfer lines is a reservoir which is expanded by heightening the dam to increase storage capacity.

2.3.3 Industrial usage

Industrial water use volumes can be significant and often demands high levels of supply assurance. Strategic supplies may include water supplies to thermal power stations and the like. Water supply to mines and other large industrial users, including the food processing industry, often yield the highest return on the investment in water supply infrastructure. Accordingly, industrial water use is often key to building an economic case for developing new dams. Hydropower falls under this category but it will be addressed later since it is a non-consumptive user of water.

In the Tennessee Valley Authority (TVA) System in the USA, operation of the reservoir system also provides cooling water for TVA's coal and nuclear power plants. TVA coal and nuclear plants provide a large portion of the energy needed for the TVA power service area and therefore increased depend on reservoir operations. Because their availability is essential to TVA's ability to provide reliable, affordable electricity, support of coal and nuclear plant operations by the reservoir system is an important operating objective. It is also the case in France for the cooling of nuclear plants built on rivers.

Coal and nuclear plants require large quantities of cooling water to operate. Return of the cooling water to the reservoir system is regulated (by permit) and includes limitations on the increase in reservoir water temperatures that can result from power plant discharge. These limitations are established to maintain water quality and protect aquatic life. System minimum flows in the Tennessee River are governed in part by the cooling water needs of these plants. Other reservoirs also have the demand of industrial water, such as Dez Dam in Iran and Volga-Kama cascade in Russia.

2.3.4 Ecological requirement

Ecological water demand is the minimum water that is required to be released from a reservoir in order to maintain a healthy riverine eco-system downstream of a dam， including the water requirements of organisms themselves and the water requirements of the environment in which organisms live. In essence, ecological water demand is the volume of water required to maintain the dynamic stability of biocenosis and habitat in ecological systems. Generally there should be regulation of the minimum discharge required for ecological water demands when a reservoir is constructed. Various highly sophisticated methods of determining ecological water demands have been developed in different parts of the world and supply of these demands are legislated in many countries.

Sadly though, there is a lack of such supply in several countries, which has led to the deterioration of many riverine ecosystems. Often such lack of provision goes hand in hand with poor control of effluent from water users which further damages river ecosystems. It follows that the supply of ecological demands ought to be an integral part of developing integrated operating rules for any dam. This is also coming with the raising for conscience of countries about sustainable developing of dams and reservoirs. Allocating such supply provisions can become more difficult if reservoirs are built in series or if they are operated in parallel, either in adjacent tributaries in the same river system or in adjacent rivers if there are some form of inter-basin water transfer present.

Fish-farming requires a stable water level, slow drawdown and impoundment to prevent fish from suffocating and dying, to allow for spawning, and to allow fish to migrate, as well as special obligatory releases to allow for spawning in downstream.

According to their unique situations, many countries have the demand of ecological water. In Canada and the USA, the purpose of ecological regulation in the Columbia River is to help salmon to migrate. In order to accomplish this goal, different engineering measures, such as increasing the amount of water released from reservoirs are taken. The ecological regulation of the TGP, aimed at promoting the spawning of the “four major Chinese carps”, refers to the artificial raising of the water level in the middle and lower reaches of the Yangtze River by simulating the natural water rise process in May and June. In Japan, the basic discharge is also necessary for maintaining regular functions of rivers. The environmental demand of Greater Karun River in Iran is for river water quality control and prevention of Persian Gulf salt water intrusion. Identical measures are taken in other countries, especially in Europe where legislation has been reinforced.

2.3.5 Navigation

Shipping remains one of the most cost effective means of transportation people and goods, particularly heavy goods. Accordingly, many rivers constitute important transport corridors. Often dams, which incorporate ship lifts or locks, are built to either deepen the rivers so that larger ships can be accommodated, or to allow navigation further up the rivers than would otherwise be possible.

Although navigation is not a consumptive water use, it does require that the dams built to facilitate such navigation be kept full or close to full at all times. This may present a significant constraint on reservoir operation, which has to be built into the integrated operating rules.

Guaranteed depths are required for navigation, as well as special releases for waterways, ways leading into ports, and shipyards and locks. Sharp fluctuations of water levels upstream and downstream of dams are unfavourable for navigation as they affect the stability of dredge cuts, worsen conditions for winter moorage and make periodic maintenance work necessary in the canal. Therefore, re-regulation dam construction should be considered downstream of large-scale hydropower stations for regulating the outflow from turbines in order to reduce adverse effects caused by outflow changes and improve navigation conditions.

Taking the Mississippi River in the USA as an example, high importance has always been placed on navigation throughout the development of the river, especially midstream and downstream. The construction of dams and other auxiliary projects has turned the Mississippi River into a ‘golden way’ with stable depth and flow.

A case in Europe is that River Rhine flowing through several countries: Switzerland, France and Germany, is the principal way for transporting goods to Switzerland (from Germany or France). Therefore there are important constraints to ensure its safety by means of a proper maintenance of these works, which have of course an incidence on the hydropower plants of the Rhine cascade.

Another case, this time in China, is the Yangtze River, which is also referred to as a ‘golden waterway’. The Yangtze is the busiest river in the world in terms of goods transported. After the impoundment of the TGP, navigation conditions from Chongqing to the dam site improved significantly because of the elimination of all the shoals and rapids. The dredging depth for this section has been improved and some tributaries have become available for navigation. Moreover, re-regulation of the Gezhouba Project (GZB) downstream has reduced the impact of unsteady flows discharged from TGP.

2.3.6 Hydropower generation

As highlighted in the introduction, hydropower is the primary purpose of a significant proportion of large dams around the world. As world demand for energy increases, the demand for high dams built primarily for hydropower generation will undoubtedly grow.

Although hydropower is not a consumptive use of water, it does affect how reservoirs can or should be operated in many complex ways. Hydropower plants are concerned with reliability and safety of hydraulic structures and equipment, efficient usage of water resources (increasing power output) and the need to increase sales revenues. In the case of the cascade reservoirs and hydropower plants, integrated operation should be taken to maximize the efficiency of water use and sales revenues based on safety of hydraulic structures and equipment, while taking account of other water users' demands.

Some cases given in the bulletin do not introduce hydropower generation in detail, but almost all the relative cascades have the function of hydropower generation. Furthermore some hydropower cascades are mainly built for power generation such as the Itaipu Cascade in Parana River, which plays an important role in energy supply and promotes the development of economy significantly for Brazil, Paraguay and Argentina etc.

2.3.7 Recreation

Recreational users are interested in relatively stable water level in storage or downstream and over a certain time period or season (not all the year).

Canyoning, boating and kayaking are popular, especially during summer time; these activities must be taken into account by power producers for evident reasons of safety, which may result in time constraints, depending on the hydrological conditions of the river. In case of maintenance works on the plant, warnings should be given that conditions on the river will be degraded for a certain period of time. There are also needs for a certain amount of flow rate for boating activities, this is sometimes contractualized for sustaining flow rate during dry season or ensure a minimal activity during summer time (sustained development).

In France and Norway, recreational sites place demands on water in the lower reaches of dams; the Ariège valley in particular is used for many recreational activities. Canyoning, boating and kayaking are popular, especially during summertime, and some places are used as beaches, while an artificial water ski is installed on Lake Garabet during summer. All these activities result in constraints for the producer (the water level or flow rate is imposed for a period of time in summer).

2.4 Flood and drought management

Disaster prevention and mitigation is one of the major purposes of dam construction.

Flood is a severe natural disaster. Many dams are built with primary purpose of flood control, such as the Three Gorges Dam to protect 15 million people lived along the Jingjiang reach of the Yangtze River.

Drought is among major natural disasters as well. As the rapid development of population and economy, water resources shortage has become increasingly serious, which lead directly to the expansion of arid area and aggravate drought degree. Drought has become a global concern and many efforts are made by governments for mitigation, such as “drought response guideline” are established and executed in Korea.

2.4.1 Flood management

Flood management should be highly linked with fine meteorological and hydrological forecasts to prevent or mitigate the damage, even produce benefits. Therefore, the development and application of forecast technology have a profound significance on flood management.

2.4.1.1 Preparatory work

Local conditions may influence practice regarding dam surveillance as well as their appurtenant structures in particular prior flood seasons. Before seasonal floods, it is generally recommended to do the following preparatory work:

- Examine the condition of water-retaining structures and the reservoir waterfront;
- Check the spilling structures if necessary.
- Test gauge indication, gates manipulating function, hoisting systems and automatic control equipments;
- Check stand-by power supply for emergencies, such as diesel engine.
- Accomplish regular maintenance and ensure the availability of generating units.
- Compile contingency plan and train emergency teams.

2.4.1.2 Reservoir drawdown before flooding

Certain reservoirs may need to be drawn down before a flood season to release capacity. For reservoirs with poor geological conditions, the water level drawdown rate should be controlled to ensure the stability of waterfront. Drawdown in earth dams may also need to be controlled. Details can be found in relevant ICOLD bulletins.

2.4.1.3Flood control operation

Many stable dams are responsible for guarantying the safety of lower reaches when facing huge floods. Hydro-meteorological information, forecasting system and operating team should be adopted for a reasonable and scientific flood control regulation.

In the flood control regulation process for the safety of lower reaches, generators are prioritized in the water utilization sequence when their reliability is guaranteed. When the reservoir water level gets close to the flood control high level, regulation by spillway operation is carried out to balance inflow and outflow. If the water level or flow rate continues rising, the flood control regulation method for dam safety is adopted.

When peak flood flow has passed the dam with the highest water level been reached and the inflow is declining, the water level must be reduced as quickly as possible to flood control limit level to provide capacity for the next flood.

In some rivers with the sediment issue, sediment ejection should be taken into account in reservoir operation in order to reduce sedimentation during flood season, that is generally done by flushing through artificial flood.

Many cascade reservoirs across the world have flood control functions, such as Dez Dam in Iran, the Rhone River valley in Switzerland and the Three Gorges Project (TGP) in China. They all have complete organization structure, strict regulations and efficient operating modes for flood management.

2.4.2 Drought management

Dam operators should make a step-by-step plan called “drought response guideline” for preparing the drought situation in advance and carry out the necessary measures, such as the adjustment of water supply in time of event in accordance with the guideline. It must be required to ensure the proper water supply capacity for drought in order to minimize social and industrial effects.

2.4.2.1 Basic direction for dam water supply

Daily standard storage volume in guideline which stably supplies water from dams for the next one year should be set. For the ordinary season, it is flexibly implemented to supply water through conjunctive dam operation in river basin reflecting each dam’s capacity. If the actual storage volume in particular time is lower than standard volume and it is hard to satisfy water demand in spite of conjunctive dam operation, water release from dams should be reduced by stages after the discussion with relevant agencies in order to prevent interruption of domestic or industrial water in the future.

2.4.2.2 Basic principle in drought response guideline

Generally, there are four sorts of water supply from a multi-purposed dam, it would be classified into domestic, industrial, irrigational and river maintenance water supply according the priority. Therefore, drought response stage can be classified into 4 stages in accordance with water demand, namely notice, caution, alert and serious. Standard storage volume by stages which guarantees more than 95% safety for water supply would be estimated by comparing the storage volume reflecting the presumptive inflow with the water demand.

If the dam storage approaches the particular standard storage, the reduction of water supply will be implemented in accordance with drought response guideline. The order of reduction is primarily river maintenance, irrigational, domestic and industrial water.

2.4.2.3 Action plan in stages

Action plans for dam operators and related organizations are made in accordance with drought stage. For the notice stage, it is necessary to adjust water supply to contacted quantity and conduct real-time monitoring and progress sharing with relevant agencies. For the caution stage, river maintenance water should be reduced. For the alert stage, irrigational water should be reduced. For the serious stage, domestic and industrial water should be restricted and sustainable countermeasure including building a new dam, diversification of water sources and connection project cross the watershed can be developed.

3 Hydropower operating criteria

A hydropower station is an integrated facility which converts hydropower into electrical energy. It includes a series of buildings which use hydropower to produce electricity, as well as equipment for the hydropower station. Some hydropower plants not only include necessary buildings, but also have auxiliary buildings for the purposes of flood control, irrigation, navigation and ecological protection.

There are different types of Hydropower stations, including regular hydropower stations, pumped storage and tidal power stations according to the source of water, run-of-river and storage hydropower stations in the light of the adjustment method for natural runoff and multi-year, annual, seasonal, weekly, daily regulation hydropower stations depending on the capacity of the reservoir and inflow into the reservoir in accordance with the adjustment period of reservoir.

Hydropower stations undertake some major tasks in the power system, such as frequency regulation, peak and valley load regulation, voltage regulation and providing a reserve. They are able to rapidly react to load fluctuations and have great flexibility to offer several services for the stability of the power grid. Meanwhile, it is the only way of energy storage in large scale at present. Usually, during the wet season, water should be fully utilized to get more electrical energy, which could be the base load of the power system. During the dry season it should make up the intermediate load and peak load of a power system so that it could fully play an important role in frequency modulation, peak and valley load regulation, and emergency reserve.

3.1 Real time power demand-supply balance

Electric power in good quality should be supplied stably to meet the demand. The capability of the power supply should change to meet consumption at any time and maintain a stable frequency because power demand changes constantly. As the water energy can be stored with storage hydropower stations or pumped storage hydropower stations, it helps the balance between supply and the ever-changing power demand

Changes of Voltage and frequency are likely to affect the operation of electrical equipment and the stability of a power system. When the changes exceed a certain level, they may activate protection of power generators resulting in one generator after another being tripped throughout the power system. Then, a large-scale power failure may be induced. In general, when a breakdown occurs, it will result in a drop of production efficiency if the electricity zone is not put back into operation. It is one of the main functions of HPP to keep the power grid stable.

3.1.1 Energy mix and the role of hydropower

Since each country has its own characteristics of energy mix, the power supply shall use multiple types of energy to fulfil industrial or domestic customers' needs. It is very often composed of nuclear, thermal (coal or gas fired) and renewable energy sources, with hydropower playing a key role in production. They are often further recognized as mass or meteorological dependant energy sources.

Generally, nuclear, coal-fired thermal and run-of-river-type hydropower plants are used for base load. Liquid Natural Gas and oil thermal power plants are major power sources for intermediate load. Finally gas turbine, pumped-storage and dam-type hydropower plants are used for peak load. Production costs for these types of energy are of course very different.

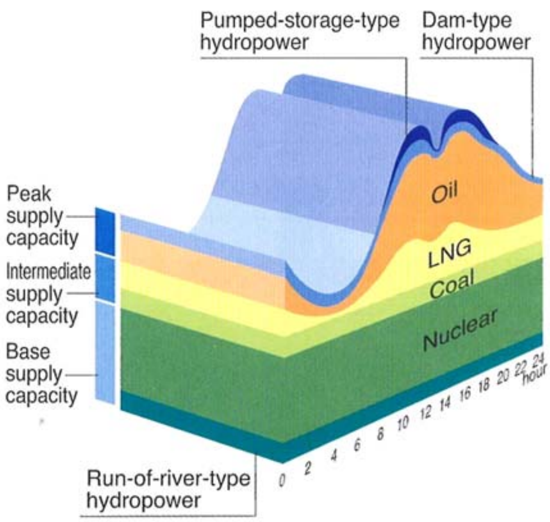


Figure 3.1 From Kiso river (Japan), dispatching of power plants

Each country's energy policy varies according to its own situation. Electricity zones are managed by several centres; the number is dependent on the organisation of each country regarding electricity zones and service areas. There are five regional zones in Western Europe, one in France, two in China and ten in Japan.

Hydropower is generally produced far from places locations of consumption. This is why power grids had been developed since the beginning of the 20th century. Even if new technologies have been envisaged to solve the energy transmission issue such as local grids and smart grid technology, there will be always zones which lack electricity, and transmission grids will have to be developed for many years. The principal aim of the power grid is to optimize the benefit of electricity production.

Hydropower stations contribute a lot to the balance and stability of power grids. Hydropower balances supply and demand efficiently with the benefit of being able to start up and stop within minutes. It meets the reactive power in a system by adjusting the excitation of generator, which also effectively alleviates problems coming from long distance energy transmission (voltage reduction). As generating units of hydropower plants have a better ability to respond to sudden changes in demand than other types of unit, several hydropower plants are equipped with Automatic Frequency Control (AFC), Economic Load Dispatching (ELD), and Governor-free (GF) devices for ancillary service in service areas. When there is an incident in the power supply or the power grid, the frequency would go out of limit. At this time, AFC would be activated to cut some unimportant loads, in order to ensure the stability of the power grid and operational quality of power.

Some countries are rich in water resources, such as Brazil, Canada, China, Norway and Russia etc. Since water resources are far from the places of consumption, hydropower exploitation and power transmission may have the characteristic of long-distance and high capacity. Therefore, the safe operation of a power transmission network may be affected by natural phenomena such as freezing, typhoons, earthquakes, fires, and thunder storms. Among the above mentioned factors, some extreme meteorological situations may also be the concerns of the hydropower production.

3.1.2 Power dispatching

Each country constructs a power grid network according to its energy mix and distribution of consumption and establishes a Central Load Dispatching Centre (CLDC) and one or several Local Load Dispatching and Control Centres (LLDC). They are responsible for power dispatching and guarantee the balance between energy supply and demand in real time to achieve safe and efficient operation.

A CLDC supervises and controls the balance between the supply and demand of power in the entire service area. It supervises different LDCC. LDCC make a request for generation operation to those who operate and control plants, substations, and transmission lines in each service area.

Some countries do not have all these divisions, either because their cascades have a unique purpose that does not include hydropower generation, or because there is a unique actor on the cascade who can manage all the constraints by himself, or because consumption and production areas are very close (no transmission lines). But in general, there is integrated operation of HPP that needs sharing of hydrological and dispatching information among them.

To manage the power system, responsibilities of these numerous actors must be defined. The power grids connect production and consumption areas. When hydropower is produced, it should be integrated locally around the production site before transmitted to the grid.

The CLDC regulate the power output remotely by controlling the AFC , ELD and GF devices in long and short term, responding to periodical load fluctuations by minute or second, as shown in Figure 3.2.

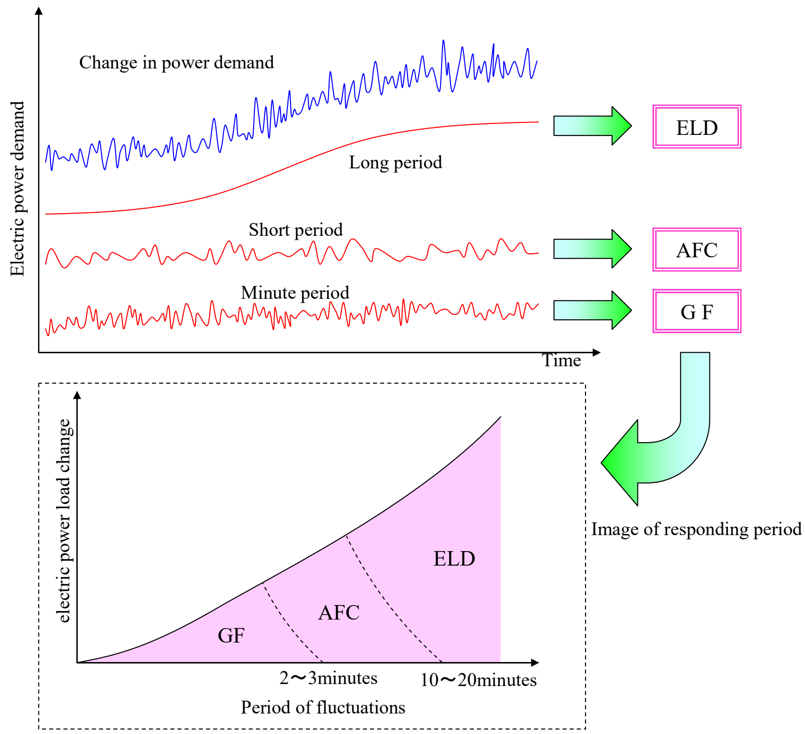


Figure 3.2 Ancillary service in accordance with types of fluctuation in demand

Take a Japanese power utility for example, the related units' chain command and data sharing structure as well as the major duties are shown below.

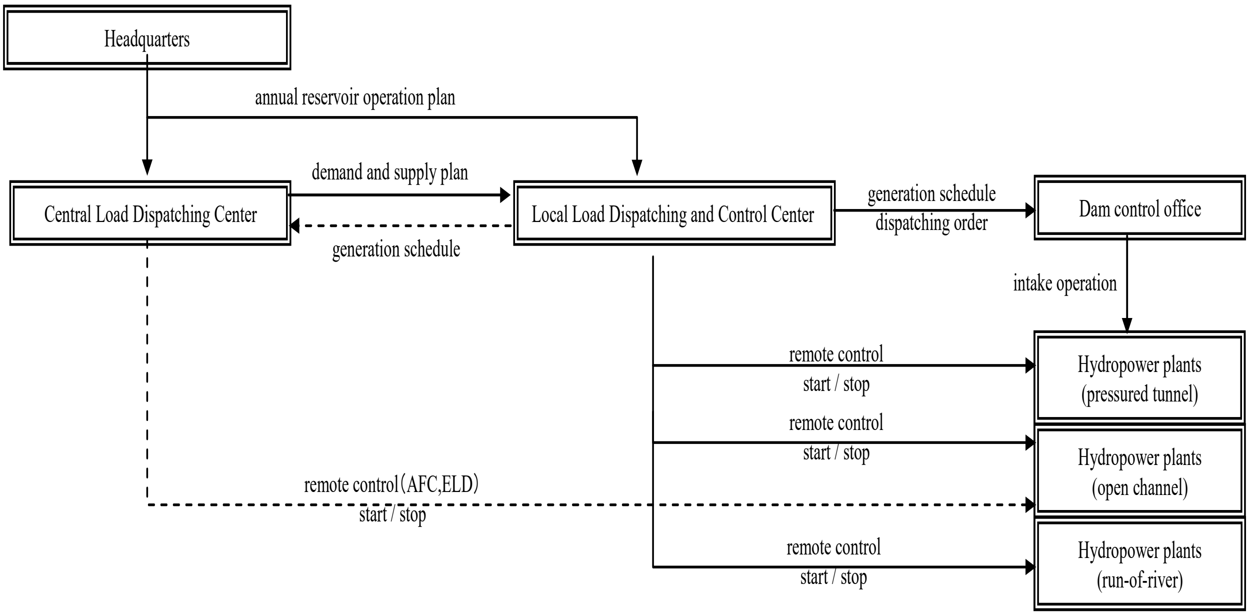


Figure 3.3 Chain of command for operating units

3.2 Reservoir and hydropower station management

3.2.1 Power Production plan management

The Transmission System Operator (TSO) or CLDC which is mentioned above is responsible for power quality and the stability of the power grid. In accordance with the supply and demand plan, the TSO directs generating instructions to producers who have their own organization to dispatch and control production, as different producers are responsible for controlling all the hydropower plants on their cascade.

The TSO studies or forecasts the annual power demand and establishes a production plan for all producers, according to power system division or services areas.

On the premise of secure operation of the power grid and plants, producers shall propose production plans to the TSO, based on the targets, parameters (such as maximum power output, available capacity of regulating pond, priority order in operation, annual outage plan, etc.) and relevant principles of reservoirs and hydropower stations. The procedure for drawing up the plan includes:

- Collecting hydrological and meteorological data, making forecasts of the electrical demand (including short-term, mid-term and long-term) and ensuring the accuracy of the forecasts;

- Utilizing beneficial capacity to balance reservoir storage and control electricity production; in the meantime, giving consideration to the demands of flood control, navigation, irrigation, water supply and recreational activities;
- Based on the analysis of influential factors of power generation capacity, (such as river flow forecasts, reservoir operation plans, etc.), establishing a production plan (includes power generation plan and maintenance plan) for different periods (day/week/month/year);
- Keeping communication and coordination with the TSO during the drawing up of the production plan and submitting the finished plan to the TSO.

Finally, the production plans would be submitted to the TSO, which would then be confirmed and carried out. In countries where there is no energy pool, it is important to maintain communication and coordination with the TSO during the drawing up of the production plan. In countries where an energy pool is in place, the daily program is determined by bidding. After receiving the final daily program from the operator, actual output should follow the programs, which could be changed by bidding on the intra-day market if necessary.

Some countries attach great importance to the usage of the 'value of water'. A specific division has been established in France at EDF to optimize the placement of production groups. The production plans of the hydropower stations are therefore optimized by analysing the 'value of water'. In the USA, the TVA River Forecast Centre (RFC) is responsible for issuing forecasts of hydrological and meteorological data, providing hourly generation schedules for TVA hydroelectric projects and scheduling water releases at TVA dams for other water demands with the goal of maximizing the 'value of water'. In Russia, production plans are made strictly according to certain algorithms based on water regimes and different dispatching lines and zones after taking other limitations into account. The production plan's optimal goal is also maximizing the 'value of water'.

3.2.2 Hydropower management

The TSO and producers should take due responsibility, utilizing computerized supervisory control systems to monitor and control electricity production process, thereby ensuring secure and economic operation of the power system.

3.2.2.1 Real-time production regulation of hydropower stations

A production offer is submitted each day to the TSO by producers, including ancillary services capability, ; the TSO takes up these offers and makes production plan according to the needs of the power grid on a stable and economical basis.

Producers allocate full-time staff for production plans' implementation, equipment operation surveillance and execution of dispatching orders. Each hour, producers may shift units, depending on incidents or other variations in forecasting values. If generation output does not follow the plan strictly in certain period, the producer will be charged or even punished.

For producers that have developed several hydropower stations in the same river basin, they usually implement centralized dispatch and control of their hydropower plants so as to maximize the comprehensive benefit of the cascade and in the meantime give consideration to the demands of flood control, navigation, irrigation and ecosystems. For these reasons, the producers set up centralized control centres, which are responsible for the optimised generation operation and flood control operations of their cascade reservoirs, to receive and implement the dispatch orders. They are also in charge of editing, submitting and implementing power generation plans as well as implementation schemes for storage regulation.

3.2.2.2 Contradictions between hydropower production and other water user requirements

For hydropower stations, there are important matters such as the reliability of the hydraulic structures and devices, efficient utilization of water, as well as electricity sales revenue. Therefore, it is necessary to control and manage the river flow in order to maximize power output on the basis of meeting other demands for water resources. Although hydropower generation does not consume water, there may be contradictories between hydropower generation and other water use demands:

(1) The contradictions between power generation and flood control. For reservoirs with flood control capability, water levels during flood seasons should generally be maintained at the flood control limitation level while the surplus water should be spilt through the gates. It contradicts with the demands of power generation, in which the water should be kept in the reservoir. But with the development of operating technologies and increased accuracy of hydrological forecasting, the flood control limitation level can be adjusted dynamically to reduce the discharged flow as far as possible.

(2) The contradictions between power generation and navigation. On the one hand, the reservoir generally replenishes water to the lower reaches to meet the demands of navigation during drought periods, leaving the reservoir with reduced power generating efficiency and a lower water level. On the other hand, hydropower stations play a key role in peak and valley load regulation of the grid due to their flexibility, thus the discharged flow is unstable so that it is contradictory with downstream navigation, which requires a stable water level.

(3) The contradictions between power generation and the comprehensive utilization of water in the lower reaches. In order to meet industrial and residential water demands requirements , as well as demands to relieve drought and salt tides, some reservoirs may lower the water level during drought periods, thus reducing power generating efficiency.

For a multi-target reservoir, each aspect of comprehensive operation has its unique operation schedule; these schedules are related but sometimes contradictory. It is necessary to take all the water demands into consideration and keep a balance between them, comparing different management strategies and selecting the best one in terms of maximising the “value of water”.

3.2.2.3 Maintenance arrangement

Maintenance programs are anticipated at least one year in advance, and important operations must be integrated at the beginning of the year for the following year. For hydropower stations, joint operations should be taken into consideration, especially for units on a river cascade.

Regular maintenance should be reasonably arranged and adjusted dynamically according to latest situations, not only to ensure the reliability of units and other equipment, but also to reduce water spillage and enhance water utilization rates.

Remote dispatch and control of field equipment has mostly been realized in many countries through advanced technologies and management, yet a certain number of specialized staff must be assigned to field device maintenance in some large or important HPPs. They should be in charge of the maintenance of discharge facilities, confirmation of equipment status and emergency responses to meet the requirements of dispatching, control and operation of hydropower stations.

3.2.2.4 Dispatch and control

Staffs on duty are mainly in charge of real-time reservoir dispatch and power production, conducting real-time monitoring and control of reservoir operations, spillway structures, electrical equipment, mechanical equipment and auxiliary devices, as well as implementing power generation plans through reliable automation systems. In addition, they play a key role in emergency responses to ensure stable operation of hydropower stations.

Some developed countries have implemented remote start and stop for most of their generating units. In Japan, 13 dams and 33 hydropower plants on the Kiso River system and all of the power plants are unmanned. In France, HPPs are generally unmanned, except those by which maintenance and operating teams are needed on site. Generally speaking, a central point is in charge of several HPPs. And all large HPPs are remote controlled. Other countries have semi-automatic programs that have to be confirmed by the producer, who is responsible for the safety of its plants (regarding runoff in the river in particular). Solutions vary depending on the watershed characteristics of the hydropower stations and their role in the power grid.

In France at EDF, one of the main producers, there are four dispatching centres that operate about 20% of the HPPs, but represent more than 80% of the hydroelectric energy produced. The rest of the HPPs are operated by producers, according to semi-automatic procedures. In China, Xiluodu and Xiangjiaba hydropower plants on the lower reaches of Jinsha River have realized remote centralized dispatch and control of giant generation units as well as sluice gates.

3.3 The role of pumped storage power plants

Pumped storage power plants are equipped with upper and lower storage reservoirs. The water in the lower storage reservoir is pumped up to the upper storage reservoir using pump turbines and low-cost electric power during the night when power consumption is low. Power is generated during the day at peak power consumption, when energy prices are high by releasing water from the upper storage reservoir into the lower storage reservoir. Thus pumped storage power plants minimize output from thermal power plants that are costly and emit large quantities of CO_2. Although there is a loss in energy efficiency across the energy transfers, it is still a kind of clean energy that is better than gas turbines and furthermore plays a key role in peak and valley regulation.

Power can be stored as potential energy by pumping water into the upper storage reservoir. This is currently the only possibility for mass storage of energy, even if batteries are developing a lot these times, reservoir storage remains competitive. The generators are activated and stopped more quickly than thermal or other power sources (except gas turbines, which are not environmentally friendly). Pumped storage power plants therefore also serve as a large battery alternative in cases where a large-capacity power plant is brought to an emergency stop. They play key role in balance of supply and demand.

Approximately 30% of energy, however, is lost in each cycle from power generation to water pumping because of such factors as the mechanical inefficiency of generators and friction loss in the headrace channel. This seems to be a little bit negative, but is compensated by the interest of the price differences between low and high consumption periods, apart from other advantages of storage of energy and so on.

Several countries have recently undergone a policy shift to using power generation from renewable sources with reduced dependence on fossil fuel generation. Since they are more meteorological dependant and still have difficulties to be stored, using renewable power sources such as solar and wind power in large quantities has an impact on the variability of the production that has to be compensated by other sources of energy, particularly hydropower because of its specific qualities. The supply and demand adjustment capacity of the entire power system needs to be greatly enhanced in the future.

Numerous pumped storage power plants are scheduled to be constructed in some European countries where renewable energy sources have a large share of the market and in adjacent countries (mainly Germany, Austria and Switzerland), with a view to enhancing supply and demand adjustment capacity. They will be built at 60 locations throughout Europe by 2020, providing a capacity of 27 GW, increased by 60% on the present 45 GW provided by existing pumped storage power plants.

The variable-speed pumped storage power generation system is being operated at pumped storage power plants under which the rotational speed of pump turbines can be set freely when water is pumped from the lower storage reservoir to upper storage reservoir as a new means of adjusting output. The conventional type of plant could be pumped only at a fixed speed and output was not fit for adjusting to power supply and demand. The variable-speed pumped storage power generation system enables the adjustment of power during the pumping operation and makes great contributions to supply and demand adjustment during the midnight period when demand is low and the adjustment capacity from thermal power plants is insufficient in some power grids.

3.4 Coordination with other renewable sources

As society develops, environmental degradation becomes an ever more serious problem. For this reason, many countries want to increase the proportion of renewable energy production, such as wind and photovoltaic energy in their energy mix.

Nowadays, many countries have made policies to enhance the development of renewable energies. These policies can be divided into two systems, fixed-price systems and fixed-quantity systems. In fixed-price systems, a fixed price is formulated by the government and the quantity is determined by the market. The alternative is fixed-quantity systems, which are also called renewable-quota systems. In this type of system, the government restricts the amount of renewable energy production but the price is determined by the market. These policies largely benefit wind and solar production plants, and are implemented in order to ensure that renewable energy can compete with traditional energy in the market.

However, wind and solar photovoltaic production are very sensitive to weather conditions, so the fluctuations they may cause in the global mix of energy are of increasing importance, which is a real issue for power grids.

Wind energy, as an alternative to fossil fuels, is plentiful, renewable, widely distributed, clean, and produces no greenhouse gas emissions during operation. Since wind energy is random and intermittent, wind farms cannot provide stable power. Due to the instability and discontinuity, power system would face a big challenge when wind energy is transmitted to the grid. The operation of wind energy generators is also be limited by load demand in the power system. Wind energy plants can benefit from the characteristics of hydropower units, including pumped storage power units, which have the characteristics of quick reaction, fast ramp-up and can store energy.

Power generation from photovoltaic is a clean and sustainable energy which draws upon the planet’s most plentiful and widely distributed renewable energy source-the sun. However, it is also a weather-based energy that is not stable. Nuclear power plants have lower operating costs and create less environmental pollution, but the fuel used by generators is at risk. If nuclear fuel is leaked, the surrounding environment will be devastated. At the same time, as the capacity of a nuclear power plant is huge, the impact on the power grid system will be great if the unit shuts down for maintenance. Building large scale hydropower station or pumped storage power stations could help meet the variation of consumption, thus enhance nuclear power plants' fuel efficiency. In this way, it would not only reduce the risks associated the nuclear fuel, but also cut the operating costs.

Compared to the other renewable energy power plants, large hydropower stations and pumped storage power plants are the most reliable and economical, with the longest life cycles, and play an important role in power grids due to their high-capacity energy storage devices. Therefore, wind turbines, photovoltaic and nuclear power plants will benefit from the building of supporting large hydropower stations and pumped storage power plants. For nuclear power generators, it will reduce the cost of operating and extend the life of unit. For wind turbines and photovoltaic, it will not only reduce the impact on the power grid system, but also improve the stability of the system.

Nowadays many countries across the world are devoted to developing sustainable energy and reduce the usage of fossil fuels to comply with the regulations of treaties such as the Kyoto Protocol. Hydropower stations with big reservoirs and pumped storage power plants will play an ever more important role in power grids by coordinating with other sustainable energy.

For example in Europe, which is at the vanguard of employing renewable energy sources, countries are connected to one another via power transmission lines, and the supply and demand are adjusted on a country-to-country basis. A country with large quantities of hydropower adjusts supply and demand in another country where large quantities of solar power and wind power are used for power generation. Norway, for example, where hydropower generation accounts for approximately 95% of total power generation, plays a role in adjusting supply and demand in Denmark where approximately 20% of total power is generated by wind power. Adopting renewable energy power sources needs to solve the problem of their varying power outputs. European regulators are writing new legislation to cope with this new issue.

In Japan, hydropower plants generate only approximately 20% of total power, even though there are numerous rivers. It is therefore important to make efficient use of the adjustment capacity of thermal power generation plants or pumped storage power plants.

3.5 Power market

Generally speaking, large hydropower dams with reservoirs provide significant benefits to an electricity system. Firstly, the potential energy can be stored in large quantities within the reservoir during periods of low demand and be available when the demand rises. Thus the production from hydropower at peak hours could compensate for other power sources with less flexibility, such as nuclear and thermal power plants. Secondly, the low variable costs of hydropower production and its short ramp-up time mean it is more rapid and less expensive than thermal generators when responding to drastic load fluctuations in the power grid. This flexibility gives it a remarkable advantage with which other generating sources cannot compete. Thus, hydro facilities are the most efficient sources of ancillary services because of their good dynamic flexibility and they may earn a substantial profit if ancillary services are purchased in a competitive market. These advantages also make hydropower a useful complement to the higher penetration of intermittent renewable energy sources described above. Apart from these aspects, hydropower is also used for many other non-commercial and social activities and makes full use of the “value of water”.

Power sector marketization is the general trend for the electricity industry across the world. From the 1980s, it has been introduced into developed countries and areas through deregulation and the introduction of competition in order to improve efficiency in the electricity industry. At present, many countries and areas have established their typical electricity markets, especially in Europe: Britain, Nordic countries, France, Spain, Portugal, etc. where an electric net is settled. Also in Japan, in the US: PJM (Pennsylvania, Jersey, Maryland), California, Ontario, in Australia and New Zealand etc. China and other emerging economies are also actively exploring route of power sector marketization reformation.

The current competitive power market method is based on introducing competition into power production and retail, while maintaining regulation for transmission and distribution. Competition in the field of power production means privatization and restructuring in the power production parts of original vertical integrated power companies and formation of two or more power producers on an open wholesale power market which is also open to new producers. The wholesale market includes a bilateral contract market, daily market, intraday market, ancillary services market and forward market, etc. The transaction centre where the competitive electricity wholesale transactions occur is the soul of the market.

4 Integrated operation of hydropower stations and reservoirs

The development of a modern society needs the support of power. As energy issues become more and more important, people become more concerned with energy utilization efficiency. The integrated operation of hydropower stations and reservoirs can improve the efficiency of water use significantly and realize the "value of water" to a large extent. Integrated operation has become a worldwide trend.

4.1 Analysis and assessments for integrated operation

4.1.1 Multi-target comprehensive utilization and regulation

With social and economic development, utilization of water resources at a single water conservancy project in a specific location is gradually evolving into comprehensive utilization of the water resources of whole drainage basin. Reservoirs tend to have a larger scale and a full range of functions to respond to all of the expected needs. However, because of regional economic development and population expansion, contradictories between supply and demand of water resources have continuously been intensified. This is of course related to the increasing demands placed on water and energy.

Cascade reservoirs are normally used for diversified purposes, including power generation, flood management, water supply, navigation, sediment blocking and ecological protection. These purposes sometimes conflict with one other or are even incompatible (for example production of energy in summer and irrigation at the same time). Comprehensive utilization and regulation of reservoirs means maximizing water supply and power generation benefits, minimizing flood risks and meeting various environment protection requirements. Therefore, it is a typical multi-target optimisation issue that needs appropriate decisions.

This issue involves a very complex multi-target decision-making process, which touches on multiple aspects. It is generally assumed that it can be divided into the several dependent parts, such as flood management, power generation, water supply and navigation etc.

The value of integrated operation of cascade reservoirs can be described as an additive value function. The value function can be broken down and expressed as the value of various target properties. It generally utilizes the targets of reservoir regulation and uniformizes them until they can be compared via physical values. To take into account the relative importance of targets, weights are allocated according to the consensus made by stakeholders or legislative verdict. Weights of various goals determined in this manner are more objective and closer to the goal of maximizing benefits from general utilization.

This tool aims to help decision makers to take the right decisions. These people who are responsible for the process will take one or several decisions to solve the issue at different periods of time. Although there are differences, due to the methods adopted in each country, the goal is the same: optimizing distribution of water and fulfilling different usages.

4.1.2 General assessments of cascade operation

With the multi-target integrated operation of cascade reservoirs and hydropower stations in the drainage basin, considerable attention has been placed on the maximization of general benefits linked to this operation. Thus the importance of assessment for such general benefits is highlighted. These assessments are necessary for understanding a hydropower station's efficiency of regulation, operation and management. Reasonable modification of the operating modes of various reservoirs is necessary to increase the integrated operating benefits of the cascade.

(1) Fulfilment rate of power generation

The fulfilment rate of power generation refers to the ratio of actual power generation to theoretical maximum power generation of a power plant. Theoretical maximum power generation refers to a power plant's theoretical maximum power generation with certain boundary conditions. The theoretical maximum power generation of a specific year refers to the maximum power generation based on the actual water flows of the year through optimal regulation and tapping various factors to the utmost. Theoretical maximum power generation varies at different boundary conditions.

(2) Rate of additional electricity from flood regulation and optimization

Rate of additional electricity from flood regulation and optimisation refers to the ratio of additional electricity generated from additional water to the electricity actually generated. Additional water from the flood regulation and optimization is the extra water volume obtained by flood detention, dynamic control of flood water level limits and other regulation measures. It is expected to reflect the benefits of additional electricity gained from optimised management of floods.

(3) Water utilization improvement rate of hydropower stations

The water utilization improvement rate of hydropower stations is a very important dynamic index. It refers to the improvement ratio of actual power production to expected power production.

The method is:

- Firstly, calculate the difference between actual power production and expected power production, which is calculated by model according to actual inflow and operation diagram;
- Secondly, get the result of the ratio between the difference and expected power production.

The ratio reflects the better utilization of water resources. The producers run reservoirs and hydropower stations in an optimised way to achieve better rates, such as gaining higher water head, repetitively utilizing limited storage capacity, etc.

(4) Assessment of flood management

Flood management benefits are mainly social ones, which include avoiding relocation of residents and property losses, preventing interruptions in industrial and commercial activities, etc. They are hard to quantify, but there are methods to assess impact of flood.

(5) Assessment of energy saving and emission reduction benefits

This assessment describes the benefit of increased power hydroelectric production from optimization. The benefit is composed of energy saved which could be evaluated by standard coal, as well as emissions reduction of CO_2, NO_x and SO_2.

These assessments can help us clearly evaluate commercial and social benefits brought by integrated operation, and find deficiencies during operations so that more improvements could be made.

4.2 Information technology tools for managing HPPs and reservoirs

With the development of information technology, the information technology tools used for managing and operating HPPs and reservoirs are more and more advanced and reliable.

Supervisory Control and Data Acquisition System (SCADA) and Reservoir Dispatching System (RDS) are common information technology tools for managing and operating HPPs and Reservoirs. When data have been collected through these tools, checking their validities is critical before inputting them into function modules or presenting them to the public. In certain countries, RDS is integrated into the SCADA.

4.2.1 Supervisory Control and Data Acquisition System (SCADA) of power generation

4.2.1.1 Evolution of SCADA

SCADA is a real-time data source for the automation of electricity power systems and provides a large amount of real-time data for Energy Management Systems (EMS). The SCADA works to monitor, control and analyse the power generation process of a hydropower station, and provides production information. With the development of computer communications technology and industrial control technology, SCADA basically develops in three stages:

- First stage– trial stage: some hydropower stations have realized automatic measurement and data processing in production. The SCADA starts to be used to record and monitor the operating parameters of the stations;
- Second stage – operational stage: the SCADA involved in closed-loop control.
- Third stage – maturing stage: the SCADA continues to develop as it gradually becomes popularized across the world.

Nowadays, the system is not only surveying the operating process, but is also aimed at surveying behaviour of works and equipment to detect any abnormal situations and produce maintenance programs to prevent breakdown or failure of equipment. In this bulletin, the SCADA is mainly focussed on integrated operation of hydropower stations and reservoirs. Different countries usually have their own characteristics in the process of establishing SCADA, and here just introduce the general situation.

4.2.1.2 Introduction to the general functions of the SCADA

The hydropower station SCADA realises real-time production information exchange and receiving of regulation instructions via a communication interface. It generates a sequence of events and alarm information through various data processing methods. It displays them to the operator via graphs, curves and audios. Meanwhile, it also saves historic data as the basis for statistics, accident tracing or posterior troubleshooting. Authorized operators can monitor, control and adjust the production process on a real-time basis via the human-machine interface.

Moreover, the SCADA normally has Automatic Generation Control (AGC), Automatic Voltage Control (AVC) and other advanced applications in order to reduce the workload of operators and increase the quality of electric power generation.

4.2.1.3 Structure of monitoring systems of cascade hydropower stations in drainage basins

Hydropower stations are normally located far away from consumption areas, therefore it is necessary to adapt the unattended operation in order to reduce the number of staff in the field and increase productivity. A cascade SCADA shall be developed to monitor and control the whole cascade hydropower station.

The SCADA of the cascade stations within drainage basins normally has three layers, namely a field layer, a station layer and a centralized control layer. On the field layer, the system is distributed according to the objects, one generator unit forms a Local Control Unit. On the station and centralized control layers, the system is distributed according to functions and different functions are deployed on different nodes within the network of the system to complete tasks collaboratively.

Various layers and applications are interconnected via field bus or Ethernet. For higher system reliability and efficiency, the network and hardware shall have a redundancy configuration. The international standard communication protocol should be applied for the communication between cascade SCADA and station SCADA so that various stations of the cascade can be connected to the cascade SCADA at lower cost.

4.2.1.4 SCADA development trends

Hydropower is one of the major energy sources for electric power grids. In order to build a smart and robust electric power grid, it is necessary to further increase the reliability, electricity quality and utilization ratio of hydropower. As a result, SCADA needs to satisfy the standards of smart power grid. Moreover, there will be more diversified advanced applications of SCADA. In particular, research on economical operation, historical data mining and status analysis of cascade hydropower stations will provide technical support for the operation of hydropower stations.

4.2.2 Reservoir Dispatching System (RDS)

4.2.2.1 Features of RDS

The RDS is an important constituent of the Energy Management System. Its core function is to provide support and services for the regulation, operation and management of the reservoir, especially at aspects such as monitoring, forecasting and regulating. In a word, it offers technical supports to ensure safe and cost-efficient operations of the reservoirs.

The system can accurately acquire the hydrological, meteorological, reservoir and generation information through advanced data capture, communication and computer application technologies. It uses computer technology and mathematic optimization theories for online hydrological forecasts, optimized regulation, and hydraulic calculation and provides optimized regulation plans that cover flood control, power generation, navigation, irrigation and water supply to realize the automatic and efficient regulation of hydropower stations and power grids.

4.2.2.2 Structure of RDS

RDS has a redundant dual-network system. The two networks are completely independent and furnished with corresponding applications to ensure that single-point fault will not affect the operational reliability of the system. In order to increase reliability and security, an intrusion detection system and a firewall should be deployed in the network. Globally, cyber and information security is becoming more and more important to hydropower stations.

RDS comprises four parts, i.e. reservoir regulation application module, external data interface, telemetric capture receiving terminal and data communication. Its structure is as follows:

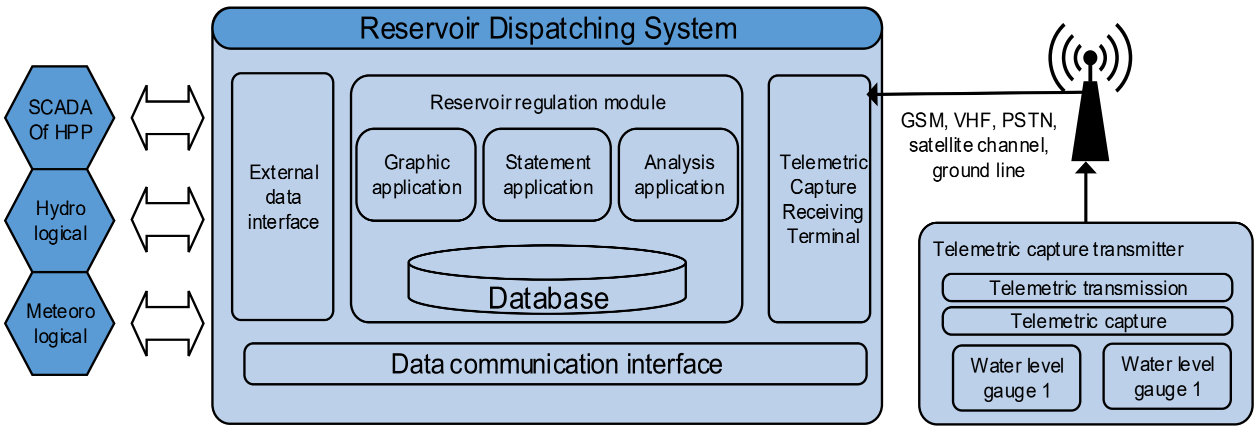


Figure 4.1 Structure of RDS

The reservoir regulation application module enables the regulation and operation of the reservoir and provides hydro-meteorological services, electric data communication, navigation, power generation and other cascade reservoir regulation services.

The reservoir regulation application module comprises a human-machine interface, a business logic processing layer and a background support layer. The human-machine interface displays hydrological, meteorological, power generation, generator units and sluice gate information graphically together with the necessary status display, statistics, analysis and calculations. The business logic processing layer mainly completes the reservoir regulation process. The background support layer summarizes and integrates the data captured by the telemetric subsystem. These systems have to be controlled and provided by the data communication module, they are kept on file and system operation monitored.

The external data interface allows data exchanges between the electricity regulation system, hydrological system, meteorological system, office system, drainage basin administration and power grid administration.

The telemetric collecting & receiving terminal receives the rainfall, water level, soil moisture content, wind speed, wind direction and other hydro-meteorological data transmitted back by the telemetric collecting device and saves them in the database of the reservoir regulation and application platform.

Data communication interface is liable for the data exchange with other reservoir regulation systems and other third-party systems on the database level.

4.2.2.3 Water regime telemetric subsystem

Water regime telemetry is an inseparable part of RDS and the data support to the integrated operation and control system of water and electricity. It is very important to establish an accurate, real-time and reliable water regime telemetry subsystem.

Water regime automatic detection and report technology is a combination of multidisciplinary applications, including sensor, survey and control, communication, computer application and hydrological forecast. The telemetric capture device acquires the rainfall, water level, evaporation, soil moisture content, temperature, humidity, wind speed, wind direction and other hydrological, meteorological and water quality data, hence offers real-time water regime, rain condition and meteorological data for reservoir regulation and flood forecasting.

After data collection, the telemetric station transmits the collected data via multiple communication channels. The central station (a collective of hardware and software deployed in the dispatch and control center) receives the messages from the telemetric station via the data collecting software, interprets the messages according to the predefined message protocol and finally writes the data into the reservoir regulation system database.

The TGP water regime telemetric system has undergone expansion, upgrading and improvement a couple of times since it was launched in 2003. So far, 633 telemetric stations that cover a total area of 580,000km^2 have been established.

4.2.2.4 RDS developments trends

The development of RDS is driven by strong market demands, ever-developing technologies and in-depth research. Its development basically undergoes four stages.

The first stage mainly involves data reception, processing and storage. The second stage mainly involves application of a system configuration frame. The third stage mainly involves the application of middleware. The fourth stage is the in-depth application stage which is mainly reflected by the platform's deeper and more complete supports for forecast, regulation and other reservoir regulation applications as well as the availability for more diversified display methods including a Geographic Information System (GIS).

Future RDS shall be designed for giving full consideration to quantitative rainfall forecasts, flood forecasts, smart regulation decision-making theories and methods, regulation decision-making risk analysis and GIS technology and with full reference to the optimized regulation technologies and algorithms of cascade reservoir flood control, power generation, electricity market, environment protection and other general benefits. It will be gradually applied in cascade reservoir regulation and become an inalienable part of a smart hydropower plant.

5 Conclusions

（1）Hydropower development plays an increasing significant role in energy industry. In the context of energy crisis and environmental ecological problems, the exploitation and utilization of new energy has become a hot spot in the world. Hydropower is a high quality energy. Its exploitation and utilization across the world especially in the developing countries has got widespread concern. Cascade hydropower stations and reservoirs is a main form of hydropower exploitation, which are widely used in the aspects of power supply, irrigation, flood control, navigation, industrial water supply and etc. Hydropower not only provide a great help for economic and social development, but also are of great importance to alleviate the greenhouse effect and promote low-carbon development of the world.

（2）Hydropower stations and pumped storage power plants have a great adjustment ability. Compared with other new energy, large hydropower stations and pumped storage power plants are the most reliable and economical energy storage devices in the power grids and have the advantages of stable power output, quick reaction and fast ramp-up. By coordination with wind energy, photovoltaic and nuclear power plants, hydropower stations and pumped storage power plants could make up for their deficiencies efficiently and reduce the risks of power grids.

（3）Integrated operation of hydropower stations and reservoirs is imperative. As an efficiently technology measure, integrated operation of hydropower stations and reservoirs can improve the utilization efficiency of water resources, ensure the safety of downstream from flood risks, save production cost and make sure that every hydropower station operates in an appropriate and economical way. It has played a very important role in the safety and stable operation of power grids. Integrated operation of hydropower stations and reservoirs has become a trend of hydropower exploitation; many countries are devoted to establish the operation platform integrated with Supervisory Control and Data Acquisition System (SCADA), Reservoir Dispatching System (RDS), Water Regime Telemetric System, Communication System and etc. to improve the management level for higher production efficiency.

In the special period of transformation of global energy structure and the rapid development of new energy, hydropower will get attention with its unique advantages and get a new greater development opportunity.

6 Specific cases

The following cases in ten countries are related to the contents described above, but their emphases are different according to their unique conditions. Some cases are similar and plentiful, referring to hydrological forecasting, multi-target comprehensive utilization and regulation, supervisory control and data acquisition etc. However, there are also differences. In some cases the emphasis is on one or two aspects. For example, the case from Japan mainly introduces generation operations, the case from Switzerland explains flood management, the case from Korea introduces water resource management in drought and the case from Brazil introduces its basic information and challenges. Details of all cases are shown below and the ten cases are ranged alphabetically.

6.1 Hydropower generation in Brazil

6.1.1 Introduction

Brazil holds 12% of the planet's fresh water and has the third largest hydroelectric potential in the world (250,000MW). Today Brazil is the world’s second largest producer of energy from hydroelectric plants and continues exploring its hydroelectric potential, but the socio-environmental policies and legislation began to restrict the construction of new projects, particularly the ones with large reservoirs.

The Brazilian Integrated Power System is primary in charge of the country’s hydro and thermal power generation with 139 GW of total installed capacity. It covers 2/3 of the total country area of 8.5 Million square kilometres and supplies 97% of the total consumption of the country. The hydro part of the system distributed among 8 large hydrographical basins, the Amazon being the biggest one, consists of 69 multi annual or seasonal regulation reservoirs and 144 hydropower plants with an installed capacity of 86.7 GW by the end of 2014. The integrated system optimizes the operation of plants, sources and costs resulting in important synergetic benefits for the consumers.

6.1.2 Main socio-environmental restrictions

Brazil has modern legislation and a consolidated institutional framework for the regulation of projects and activities that may affect the environment, such as power generation projects. The main socio-environmental issues and restrictions affecting the development and implementation of a hydro projects in Brazil can be summarized as follows:

- The very restrictive socio environmental policies, laws and plans;
- The issues related to the resettlement of populations;
- The legal environmental protection areas;
- The legal Indian reservations;
- The national and international pressure applied by non-governmental organizations and other social groups;
- The social and economic effects during construction time;
- The social and economic effects of the demobilization of construction on the project region.

6.1.3 The present situation of reservoirs and future consequences

There is a rapid growth of energy demand however due to the strict socio-environmental restrictions. The Brazilian power sector authorities have been given preference to the run-of-river hydropower stations with daily or weekly storage capacity. The official generation expansion planning forecasts an increase of 45,000 MW of the hydro installed capacity from 2014 to 2023. However this planning considers that the correspondent energy that can be stored in associated reservoirs is estimated to increase only by 7,000 MW.

As a consequence, Brazil is giving up some important social and economically benefits. The lack of large reservoirs increases the complexity of the integrated operation of the system. At this moment in the very dry years of 2013, 2014 and 2015, the Brazilian Integrated Power System is clearly being affected by the lack of additional storage energy capacity reservoirs, impacting its reliability, costs and risk of insufficient generation capacity.

However it is important to mention that the socio-environmental issues have always been considered in a very responsible way in the large hydroelectric projects that have been implemented in Brazil as well as there are countless examples of important development in the regions where large hydroelectric projects were built.

6.2 Three Gorges-Gezhouba Cascade Complex– a case study in China

6.2.1 Introduction

6.2.1.1 Climatic and Geographic Conditions

The Yangtze River is the longest river in China, with a total length of approximately 6,380 km and a total drop of 5,400m, covering an area of 1.8 million km^2. It discharges more than 960 billion m^3 of water into the sea a year on average and accounts for 36% of China's total water resources.

In terms of terrain characteristics, the area of the upper reaches of the Yangtze River features a complex topography. In terms of climatic characteristics, due to the wide differences in terrain, topography and altitude within the watershed, there are two significantly different climate zones: a plateau monsoon climate zone and a subtropical monsoon climate zone. The bulk of the plateau monsoon climate zone is located in the upper and middle reaches of the Jinsha River and in the upper reaches of the Mintuo River. Within this climate zone, the annual precipitation ranges from 200mm to 600mm. The subtropical monsoon climate zone includes all the other watersheds and the annual precipitation range from 800mm to 1,600mm.

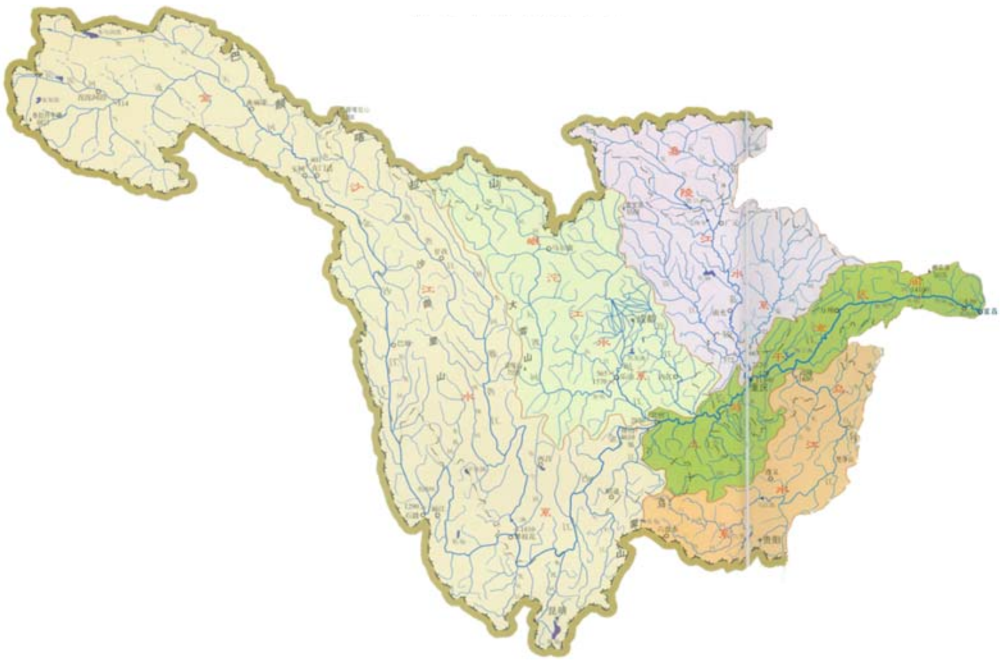


Figure 6.1 Water system in the upper reaches of the Yangtze River

6.2.1.2 Runoff Characteristics

The Three Gorges-Gezhouba Cascade Hydropower Complex (TGP-GZB) is located in Yichang City, Hubei Province. The main stream of the Yangtze River has a large, steady annual runoff, with an average annual flow of 14,100m^3/s and annual runoff of 446 billion m^3 from 1878 and 2010. The trends of change remain steady over the long series.

The runoff in the watersheds upstream from TGP on the Yangtze River primarily comes from precipitation. The pattern of annual runoff distribution is similar to the pattern of precipitation, and distribution is uneven over the year. The flow of the trunk stream of the Yangtze River in the flood season accounts for 70% to 75% of the river's total annual flow, the flow of the trunk stream in the upper reaches is mainly concentrated in the period of June-September.

6.2.1.3 The TGP-GZB Cascade Complex

The TGP is a multi-objective development project designed to produce integrated benefits in terms of flood control, power generation and navigation. The reservoir has a normal storage level of 175m, a crest elevation of 185m, and a maximum height of 181m, with a total storage capacity of 39.3 billion m^3 and a flood-control storage capacity of 22.15 billion m^3. The reservoir can significantly improve the maneuverability and reliability of flood control operations in the middle and lower reaches of the Yangtze River. The Three Gorges Hydropower Plant has a total installed capacity of 22,500MW and is equipped with 32 mixed-flow (Francis) water-turbine generating units.

The GZB, located 38km downstream from the TGP, is the world's largest run-of-river hydropower station with a low water head, a large flow and a capacity of 2,910MW.

6.2.2 Comprehensive operation and dispatching

6.2.2.1 Precipitation forecast and hydrological forecast

(1)Precipitation Forecasting

The professional meteorological observatory mainly forecasts short-term rainfall zones, medium-term rainfall processes, and long-term rainfall trends in the upper reaches of the Yangtze River. At present, for rainstorms causing floods in the upper reaches of the Yangtze River, forecasts for 1-3 days are accurate and reliable; precipitation process forecasts for 4-7 days are useful; forecasts for 8-10 days may not be accurate, but can still be used as a guide for future precipitation trends.

(2)Short- and Medium-term Hydrological Forecasting

Hydrological forecasters provide 12h, 24h and 48h (3-7 days) forecasts of inflow to the Three Gorges Reservoir. The main rainfall runoff forecasting models for the Three Gorges watershed include the Xin'an River Model, the Water Tank Model, and the API Model. The main forecasting models for the flow on the Three Gorges section of the river include the Muskingum Flow Routing Method and the Hydrodynamics Model.

(3)Long-term Hydrological Forecasting

Long-term hydrological forecasting is intended to facilitate the preparation of long and medium-term power generation plans, reservoir drawing-down schemes, reservoir flood-season-coping schemes, and reservoir storage schemes. Such forecasting mainly includes monthly average reservoir inflow forecasting, flood season (April to October) forecasting, annual forecasting etc. The main long-term hydrological forecasting models currently used include the autoregressive model, the multiple regression model, and the threshold autoregressive model.

6.2.2.2 Operating methods and power transmission

These TGP generating units are located in different sections and are operated independently of each other without any electrical connection. The GZB is equipped with 21 generating units distributed in two independent powerhouses.

Electric power from TGP is consumed by ten provinces and municipalities in the economically vibrant central, eastern and southern parts of China. Electrical power from GZB is all consumed in central China.

6.2.2.3 Integrated operations of the cascade hydropower complex

As they are hydraulically connected, the joint operations of the two dams require the TGP-GZB to be operated by one entity.

The reservoir starts water storage on September 15, reaching its normal water level by the end of October. The reservoir generally operates according to the operating chart. The GZB primarily plays a reverse regulation role for the TGP. When the TGP undertakes the role of peak and valley regulation for power grids, the GZB helps stabilize the water level in the lower reaches of the river and ensures that the water level downstream is no lower than a certain level to facilitate navigation.

6.2.2.4 Flood control operations

Playing an essential role in the flood control of the middle and lower reaches of the Yangtze River, the TGP is operated by different divisions according to the inflow. There are two types of flood control operation methods, one is normal operating method for ensuring safety of downstream watersheds and the other is for ensuring safety of the hydropower complex.

6.2.2.5 Navigation operations

During the dry season, the TGP operates in a manner that ensures the guaranteed output so that navigation in the river downstream from the GZB can have the required flow level. The current average annual amount of freight is five times that of the highest annual amount before the completion of the TGP.

6.2.2.6 Regulation of sediment

Since the 1990s, the sediment flux to the TGP has steadily declined. Investigations and analyses indicate that the significant reduction of sediment flux to the TGP is primarily attributable to the construction of water conservancy facilities upstream, the execution of water and soil conservation projects, and sand quarrying.

To tackle the potential sedimentation issue of the TGP, the TGP adopts the method of "store the clear and flush the sediment". The amount of water and sediment flowing from the upstream section of the river into the Three Gorges Reservoir is distributed very unevenly over the year. As such, during each year's flood season, the water level of the reservoir is maintained at the flood-control limitation level, thus allowing sandy floodwaters (commonly known as muddy water) to be discharged smoothly downstream. In October after the flood season, the sediment flux to the TGP declines and the reservoir starts storing water to generate power and facilitate navigation.

In order to reduce sediment in the approach channel to the ship locks and to facilitate desilting, the engineering method of "navigation in still water and sand flushing in moving water" has been introduced. With this method, most sediment in the approach channels is washed away, with the remainder mechanically removed. During the flood season, when the GZB has surplus water, sediment discharging bottom holes and sediment discharging caverns are activated at the right time to discharge sediment.

6.2.2.7 Water replenishment to mitigate droughts

In especially dry years, the TGP may be called upon to replenish water and operate according to the instructions of relative authorities. The reservoir will change the operational focus from ecological protection, navigation facilitation and electricity supply to the power grid to easing the drought, thus significantly easing the shortage of water for human and animal consumption and for farmland irrigation in the middle and lower reaches of the river.

6.2.2.8 Ecological dispatching

The ecological regulation of the TGP refers to the artificial raising of water level in the middle and lower reaches of the Yangtze River by simulating the natural water rise process in an attempt to stimulate the spawning of the “four major Chinese carps” in the middle and lower reaches of the Yangtze River.

6.2.3 Safety and emergency management

6.2.3.1 Dam safety monitoring

Dam safety monitoring includes the monitoring of structure deformation, seepage, stress-strain, hydraulics, strong seismic activities. Structures under monitoring include the right-bank and left-bank dam sections, the guard dam, the underground powerhouse, the ship lock, the reservoir bank near the dam, and the engineering slopes.

6.2.3.2 Cascade complex emergency management

In the company, there is a complete emergency response organization to cover almost any potential crisis. A 24/7 office is responsible for receiving, disseminating and reporting crisis information when it occurs.

6.2.4 Conclusions

The Three Gorges-Gezhouba Cascade Complex is a typical comprehensive case of integrated operation of hydropower stations and reservoirs. It is the biggest hydropower project in the world and brings enormous economic and social benefits mainly including flood control, power generation and navigation.

After years of operation, the CTG has accumulated valuable experience and established a highly efficient operating system to accomplish its multi-target operation and maximize the value of water. The CTG now frequently communicates with other countries’ power corporations and it will play a more important role in the development of hydropower around the world.

6.3 Ariège Cascades in France

6.3.1 The context of energy production and water resources in France

Hydropower was the first source of renewable energy in France. Its Installed capacity is 25,400 MW in 2011, ranking second in Europe.

In France, hydropower represents 80% of total renewable energy and about 10% of the total electricity production in 2011. But these figures are rapidly changing with the development of wind and photovoltaic production. In 2011 there were 6,640 MW of installed wind capacities and 2,230 MW of photovoltaic capacities.

Hydropower greatly contributes to reaching the objective fixed by the French government: to produce 23% of electricity from renewable energy by 2020. In 2011, this proportion was 12.8% due to a very dry year (it was of 15.1% in 2010). Hydropower is a high-performing tool for ensuring equilibrium between consumption and production during high levels of electricity demand: hydropower plants can deliver their energy within a few minutes.

Electricité de France (EDF) produces about 8% of its power from hydropower plants. Hydraulics and nuclear enable savings of around 13 million tons in fuel a year in France, strongly reducing CO_2 emissions. There are 435 hydropower plants and 622 dams at EDF, for a total capacity of 25, 400 MW. These plants are located in five geographic regions: the East, the Alps, the Mediterranean, the Pyrenees (Sud Ouest) and central France. The annual production was 34.5 TWh in 2012 for hydropower.

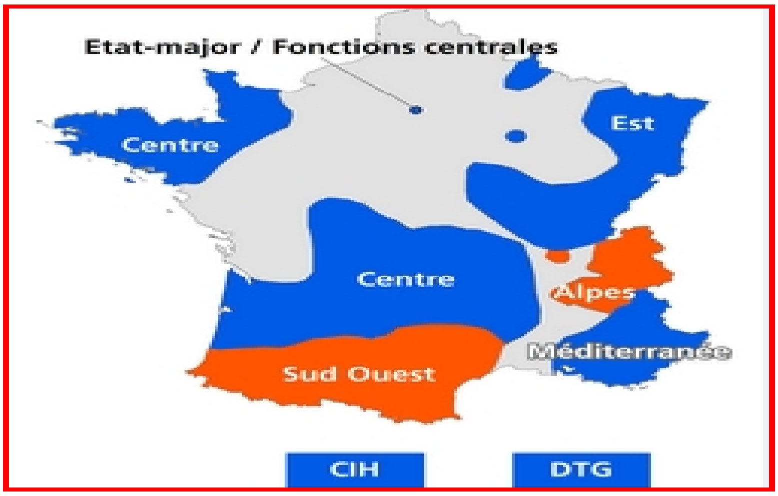


Figure 6.2 Organisation of EDF hydraulic production

6.3.2 Geography and hydrology of the Ariège Cascade

The Ariège Cascade is located in the Pyrenees region. It takes its source at 2,400m altitude, at Font-Nègre circus, on the border between Andorre and France (Pyrénées-Orientales department). It contributes to the river Garonne on its right bank at Portet-sur-Garonne, situated in the south of Toulouse after a 163 km run from its source.

Ariège has a mean flow rate of 76 m^3/s at Pinsaguel for a 4,120km^2 basin (situated just above Portet-sur-Garonne), very near from its confluence with Garonne River. The minimum flow rate which measures are taken to sustain the flow of river Garonne is 20m^3/s, measured at la Magistère, downstream of Toulouse. This is done principally from the Ariège valley that follows a mountain regime: high level during the snow-melting period from April to June, between 113 m^3/s and 156 m^3/s, with lower levels outside of this period, and a low level between August and September each year.

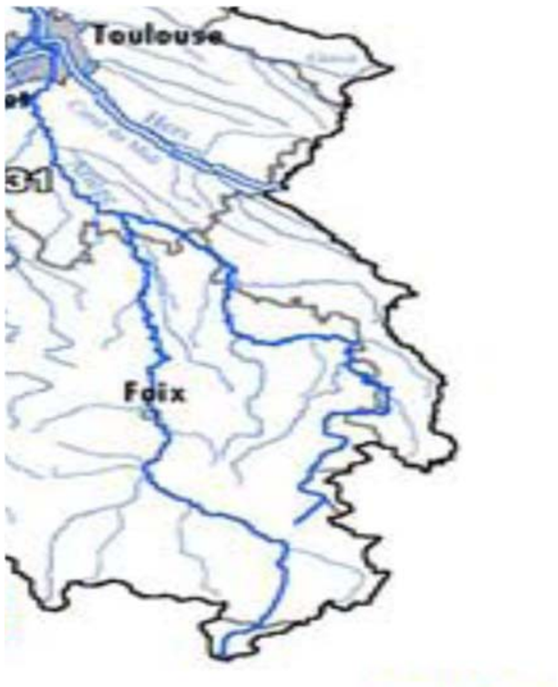


Figure 6.3 Ariege valley

Hydropower developed very early in the Pyrenees, especially in Ariège because of the steepness of the valley. In 1910, the Orlu Hydropower Power Station was the most powerful hydropower plant in the world, with a total head of 950m.

6.3.3 Water resource needs

From its source to its confluence with river Garonne, 17 hydropower plants ranging from 160 MW to a few kW were constructed between 1899 (le Castelet) and 1985 (Ferrières and

Laparan), two of which on the Aston tributary, on the left bank, Laparan and Aston, produced about 392 GWh each year – the largest plant production in the Pyrenees region.

Of course this valley is also concerned with many other activities linked to water resources: agricultural needs, drinking water, fishing and fish breeding, recreational activities (canyoning, boating, kayaking), artificial snow, and finally tourism in general.

6.3.4 Meteorology

Energy production is weather dependant; therefore since the creation of the EDF in 1946, a specialized unit has been in charge of meteorological predictions (called 'Division Technique Générale' DTG).

These predictions help the producer to manage different risks. About 20 people work at EDF DTG in this field, mainly to maintain the meteorological networks, control the measurements, and apply forecast models, and so on.

EDF has data going back to 1950, including flow rates, height of rain, height of snow, temperature of the air and water, chemical composition of water or fluxes of suspended matter, from about 350 flow rate stations, 400 rainfall stations, 160 snow sticks and 35 NRC (a system that measures the height of snow and the cosmic radiation). All of these data are stored in a system called 'Castor', which can be reached at any time through the EDF network.

6.3.4.1 Short-term forecasts

Teams in charge of predictions may be called upon 24 hours a day, especially for telephone assistance. The aim of this organisation is to forecast extreme events such as floods or very low flow rates.

6.3.4.2 Mean-term forecast

Production forecasts concern about 31 rivers and more than 100 key points; predictions of flow rates, temperature of water and solid transportation are made each day, from date J to J+6.

6.3.4.3 Long-term forecast

Probabilistic predictions of water inflows, from several weeks to several months are performed for forty reservoirs.

6.3.5 Production optimization

6.3.5.1 Context

An electricity market has been required by law since 2005.

The transportation and production of electricity are kept completely separate. RTE (Réseau de Transport de l'Electricité) is in charge of the transportation network (U>42 kV). A contract must be signed between RTE and any producer to access the electricity network. Every producer must ensure equilibrium between its production and the consumption of its clients. EDF ensures its own equilibrium. Each day it must establish a production program for the next day around 4:30 pm, detailed to each half hour. RTE controls the total production program that the net can afford.

6.3.5.2 The reference technical framework (Directive Technique de Référence, DTR)

It is the reference to contact a new plant to the national electricity network. It defines the power that may be fed into or taken from the electricity network and the associated prices, as well as the limit of the network.

6.3.5.3 Service system contract

It is signed between RTE and any party responsible for equilibrium. It concerns adjustments for both frequency and voltage.

6.3.5.4 Optimisation of the production

At EDF, a division is in charge of optimizing the placement of production groups: Division of Optimisation Amont Aval Trading, DOAAT.

It is based on the cost of each production plant. For hydraulic, it is based on the value of the water for each group, which depends on the time and situation in the reservoir; there is a model to determine these water cost values.

6.3.5.5 The production program

Then the production of a group is: Pco+NPr+k (frequency-50Hz), where Pco is the scheduled power production of the group, without secondary frequency regulation and a frequency of the net equal to 50 Hz. Pr is the maximum power absorbed or produced for a step of secondary frequency regulation (N level) and N is the secondary frequency regulation sent by RTE and k the automatic primary frequency regulation.

6.3.5.6 Optimisation of the production program

Based on a statistical approach and meteorological prediction of air temperature, RTE establishes a prediction for consumption.

6.3.5.7 Ariège Production

Large groups are linked to the main electricity network, they are programmed by DOAAT, the programs are sent to one of the three operating centres, for Ariège it is attached to the Lyon centre. The two others are in Kembs in the east of France, the first power plant on the river Rheine, the second near Marseille for plants situated in the south of France, for hydraulic especially the Durance River. Other plants are programmed by specific organisations at regional or local level according to the program established by DOAAT.

6.3.6 Safety management

These situations are treated case by case, but in general, there are structures dedicated to:

- First, a 24/7 organisation to deal with all sorts of issues at the level of several hydropower plants (Group of hydraulic plants: GEH Groupe d’Exploitation Hydraulique)
- A crisis cell may be constituted from the management of the GEH; it may be activated in any crisis situation. Well-trained teams will manage these situations.
- As described in chapter 3, DTG and its meteorological prevision cell, give indications of the risk of flooding each day and produce more information when there are floods.
- Risk analysis is done along every hydraulic site, upstream and downstream of the plant.

As for seismic events, an outside structure of the EDF sends messages to the command (PHV: Poste Hydraulique de Vallée).

6.3.7 Conclusions

Ariège is a good example of a water resource that has to be shared between several economic actors, especially agriculture and recreational activities.

Historically, hydropower developed in Ariège at the beginning of the 20th century. Nowadays satisfaction of economic actors, preservation of the environment and production of renewable, and carbon free energy have to be managed. The law on aquatic fields gives the framework and organisation to discuss these issues. It is complex but also necessary for a lasting solution to the treatment of our water resources.

Hydropower production is susceptible particularly to meteorological hazards. Specific organisations have to manage any crisis arising from meteorological hazards or from any other source of hazard such as seismic events.

6.4The Dez River System in Iran

6.4.1 Introduction

The major hydropower plants in Iran, generating firm energy, belong to the Great Karun River Basin, which is located in the south west of Iran with an area of 67,257 square kilometres. The mountainous part of the basin is about 45,994 square kilometres (68 percent) and the rest of 32 percent (21,263 square kilometres) is foothill and flat plains. The Great Karun River Basin is formed from two main sub basins: the Karun, and the Dez River basins, with a total of 12 hydropower dams (5 are under operation, 4 are under construction, and 3 are under study). The Dez sub basin has been selected as a case study for a pilot project for integrated water resources management with hydropower generation as its primary objective.

The Dez River, itself, consists of two sub basins, and when they are confluence, they form the Dez River and shortly enter the Dez dam's reservoir. At present, the power plant at the Dez dam includes 8 units with a total capacity of 520 MW. It is intended to rehabilitate the existing unit from 2013 and prospected by end of year 2016 to increase the capacity of each unit to 90 MW and totally 720 MW. The second unit of the Dez power plant is expected to be ready for operation by 2017, with a capacity of 4*180 MW (with existing rehabilitated units, it will be 1440 MW in total).

The water is regulated in the Dez reservoir for energy generation, water supply for downstream water demands, and flood control. The Dez River finally joins the Karun River at the Band-e-Ghir junction to form the Greater Karun River.

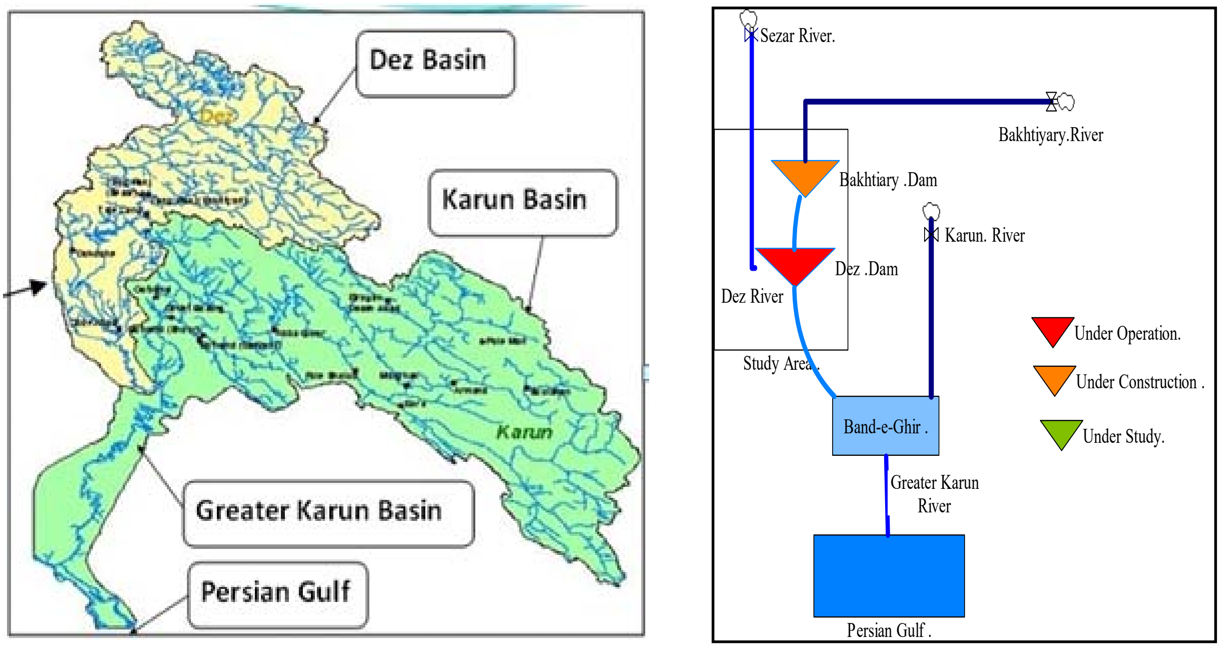


Figure 6.4 Dez River System

6.4.2 Multipurpose operation

6.4.2.1 Water demand

(1) Environmental water demand

The environmental demands on the Greater Karun River are for water quality control and prevention of Persian Gulf salt water intrusion. The environmental water supply for the Dez River is calculated to be about 930 million cubic meters (30 cubic meters per second), which accounts for 90 percent of the whole environmental water supply.

(2) Potable, Industrial and Irrigation water demand

Consumptive water demands for the study area include potable, industrial and irrigation water demands downstream of the Dez dam. The consumptive demands upstream and downstream of the Dez Dam taken in this study are as follow:

- The monthly demand downstream

The monthly demand downstream of Dez Dam can be separated in two major parts: demand from the Dez and the demand from diversion weir.

- Future water resources projects

Based on the official statement, the future water resources development in the Sezar and Bakhtaran sub basin is defined, which are mainly used for irrigation.

- Inter basin water transfer

The Inter basin water transfer is proposed to transfer water from upstream of Bakhtiary sub-basin to the Qom-rud basin.

6.4.2.2 Sediment Dispatching

The total annual suspended sediment inflow to the Dez reservoir is estimated to be 14.24 million tonnes with a bed load of 3.56 million tons per year. Most of the sediment enters the Dam during the wet season in April, May, and June. Due to the problem of sediment deposition in the Dez reservoir, part of the sediment from reservoir was attempted to be discharged by flushing.

6.4.2.3 Flood control

One of the purposes of the Dez dam reservoir is flood control. The normal water level during non-flood season (middle of April till the end of October) is 352 masl, while during flood season (November to middle of April) the water level drops to 337 masl. The flood control volume is designed to control 100 years of flooding.

6.4.2.4 Reservoir operating rules to supply minimum energy during drought period

The main objective of the Dez dam Reservoir is to generate firm energy during peak power demand. Therefore, energy supply with acceptable reliability is crucial. In order to fulfil this objective, a reservoir rule curve is designed for energy generation during drought period to improve energy generation in drought conditions. Also, a hedging rule has been designed to reduce the energy generation with different coefficients proportional to the reservoir volume.

6.4.3 Conclusions

Based on the objectives of the Dez Dam, the projects which are going to be implemented in this basin can be categorized as follows: small projects under construction, inter-basin water transfer, large projects, and future projects (Dez Dam heightening, upgrading the existing power plant, etc.). These projects may have an effect on water resource potential and different scenarios are carried out to analyse the effects on water resources. The fact that can be drawn from the conclusions is that following projects will reduce water regulation of the Dez Dam for energy generation and water supply downstream of Dez Dam and have negative effects on downstream water consumption.

6.5 Kiso River study in Japan

6.5.1 Introduction

As one of the largest rivers in Japan, The Kiso River is 229 km long originating from Mt. Hachimori in Nagano Prefecture and covering an area of 5,275 km^2 with abundant water resources which is valuable to agriculture and various industries (Figure 6.5). It is managed by the Kansai Electric Power Corporation (KEPCO) which operates 151 hydropower plants with a total output of 8 GW, of which more than half are pumped-storage power plants.

Figure 6.5 The Kiso River basin

In the 1910s, hydropower development of the Kiso River system started to meet growing demands for power, and nowadays almost all the head and flow of the river is utilized to meet the demand for power. With rapid urbanization driven by high economic growth, demands for waterworks, industrial water and flood control increased on the downstream plain areas where populations and industry are concentrated. As a result, construction of multipurpose dams (Figure 6.6) was promoted to unify flood control and water usage.

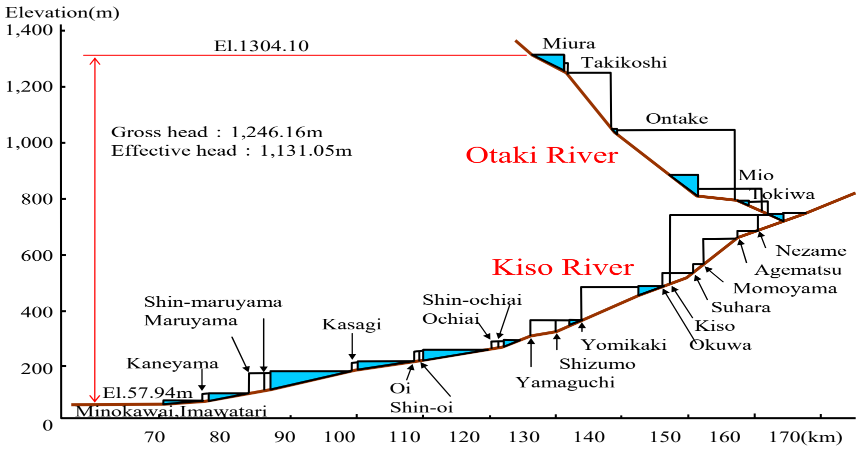


Figure 6.6 Longitudinal Profile of the Kiso River System and Hydropower Facilities

There are 13 dams and 33 power plants on The Kiso River and its tributaries, with total output accounting for more than 1,000MW. All the power generated is transmitted to the Kansai region or large power usage areas. Meanwhile, dams are broadly classified into water use dams and flood control dams according to their purpose, and water use dams are further categorized into irrigation dams, waterworks dams, industrial dams and hydropower dams. And multipurpose dams are also built on the same river system, which are used for two or more of the above purposes.

6.5.2 Comprehensive operation and dispatching

6.5.2.1 Framework for generating operations

Figure 3.3 shows the chain command for related units of the generating operations of the hydropower facilities on the Kiso River, as well as their major duties.

(1)Central Load Dispatching Center (CLDC)

The objectives of the Central Load Dispatching Center (CLDC) are to supervise and control a balance between power supply and demand in the entire service area of KEPCO, and to make a request for generating operation to each Local Load Dispatching and Control Center (LDCC).

(2) Tokai Load Dispatching and Control Center (Tokai LDCC)

Tokai LDCC, one of KEPCO's regional load dispatching offices, can remotely start and stop all the generating units in response to dispatching orders from the CLDC. Depending on the supply and demand, weekly and daily generation schedules for each power plant are drawn up by Tokai LDCC in cooperation with the CLDC.

(3) Dam Control Office

Dam operators are on duty of twenty-four-hour shifts at each dam with spillway gates. Beside flood control, their major role in generating operations is to handle power intake gates at open-channel types of power plant in response to dispatching requests from the Tokai LDCC.

(4) Power System Division

The annual power demand forecast and supply plan for KEPCO's service area are studied by the power system divisions in the headquarters. They prepare the annual reservoir operation plan for the Miura Dam, which is located upstream of the river, and then submit it to CLDC and LDCC for their generation schedule.

6.5.2.2 Major considerations for the generation schedule

The major function of the cascade hydropower plants on the Kiso River is to provide power to meet changing demands of the load during peak and middle peak periods, and try to maximize the total power generation of the entire river system at the same time.

Tokai LDCC and the CLDC cooperate to draw up annual, monthly and daily generation schedules by considering the state of natural river flow, out-of-service periods due to maintenance work, volume of reserve capacity, types of hydropower generation (reservoir type and regulating pond type) and hydropower plant (pressured tunnel type and open channel type), etc.

6.5.2.3 Generation schedule

(1) Annual supply plan

The Power System Division prepares the annual power demand and supply plan to secure dependable capacity corresponding to the forecasted demand at the beginning of the fiscal year. The annual supply plan is drawn up in order to estimate a dependable amount of power output for this forecasted demand.

(2) Monthly generation schedule

The CLDC draws up the monthly generation schedule for three months, in which they try to select more economical operations to compare the difference in operational costs, and they also incorporate the current status of planned outages to secure dependable capacity and reserve capacity in case of an unexpected accident.

(3) Weekly generation schedule

CLDC studies the weekly supply plan based on weekly demand forecasts in order to provide a stable and economical supply of electricity, and then make a request to Tokai LDCC for generating operations during peak demand time running the specific hydropower plants equipped with AFC and ELD devices. Tokai LDCC studies the weekly generation schedule on an hourly basis for each plant to take into account fluctuations of natural river flow while referring to weekly weather forecasts, as well as the reservoir operation plans of the Miura Dam.

(4) Daily generation schedule

The CLDC forecasts the power demand for the next day referring to the latest weather forecast and reviews the details of the daily supply plan by checking the changes in supply power, reserve capacity, reliability on the grid system etc. Tokai CLDC reviews the weekly generation schedule and then determines the final hourly generation schedule for each plant. Tokai LDCC then operates their power plant as scheduled the next day, and makes requests for power intake operations to dam control offices.

6.5.2.4 River flow forecasting

(1) River flow forecasting for the supply plan and generation schedule

River flow or weather forecasting are not applied in the drawing up of the annual supply plan and monthly generation schedule, both of which are based on actual inflow data over 30 years. Tokai LDCC studies and reviews the weekly generation schedule as well as the reservoir operation plan by using weekly weather forecasts distributed by the Japan Meteorological Agency, considering such conditions as atmospheric pressure distribution, location of a cold front, rain area, etc.

Weather forecasts sometimes prove to be wrong and thus it is not predicted to rain on the next day, the river flow for the next day is deducted by a certain amount, which is empirically estimated or based on accumulated data, from the river flow used in the present day's generation schedule.

(2) River Flow Forecasting at the Dam Control Offices

There are two types of river flow forecasting system that are currently in use: one is that runoff extending for 10-minute, 30-minute, one-hour, two-hour and 3-hour periods are predicted with the storage function method as a run-off model. The other is a hybrid rainfall prediction model that is composed of extrapolation model using radar data and meso-scale atmospheric model, which can predict six hours ahead at an interval of 10 minutes. This model is combined with a distributed runoff prediction model to constitute the real-time dam inflow prediction system.

6.5.2.5 Frequency regulation

As generating units of hydropower plants have a higher ability to response to sudden demand changes than other types of unit, several hydropower plants on the Kiso River are equipped with AFC, ELD, and Governor-free devices for ancillary services in the service areas.

6.5.3 Other considerations

6.5.3.1 Restrictions on the storage of water

There is a re-regulation dam, the Imawatari Dam is located at the point most downstream in order to temporally store the fluctuating river flow due to power generation during peak period and then evenly release the water for the downstream. For this purpose, the storage of water at each dam upstream from the Imawatari Dam is restricted when the discharge from it falls below 100 m^3/s on a daily average basis.

6.5.3.2 River basic flow

In order to properly control river comprehensively in the low-water period, the discharge necessary shall be specified for maintaining regular functions of river flow at a major point on a river.

6.5.3.3 Renewal of water rights

It is indispensable for the power utilities to get permission for the operation of hydropower plants. The renewal of water rights is also needed at a certain intervals.

6.5.3.4 Risks in transmitting electricity to the Kansai region

All the generated power is transmitted through 275km transmission lines to the Kansai region more than 200 km away. In order to reduce such risks that would lead to the decrease in expected supply power, there are three transmission lines.

6.5.4 Emergency management

6.5.4.1 Power interchange

There are two types of frequency in Japan: all electricity in west Japan is 60Hz, while that in the east is 50 Hz. Japan has three frequency converter stations, which can convert 50 Hz into 60 Hz and vice versa, but their capacity is quite limited.

6.5.4.2 Drought

Drought conciliation is one kind of management of water use in an emergency. In accordance with river laws, there is an agreement among the parties concerned to establish a special purpose committee for coordination when industrial water, irrigation, waterworks, etc. are impacted by drought on the Kiso River.

6.6 Comprehensive countermeasures against the record-breaking drought in Korea

6.6.1 Background of drought in 2015

In 2015, rainfalls and water levels of major dams in Korea marked the lowest record in history, which was described as the record breaking drought ever since the beginning of official hydrological observation. 20-year frequency drought inflow has been normally used for designing the dam storage volume for water supply. Most of inflows into dams were smaller than 20-year frequency drought inflow. That means 2015 case can be classified into natural disaster. Continuous drought condition since 2014 threatened normal dam operation.

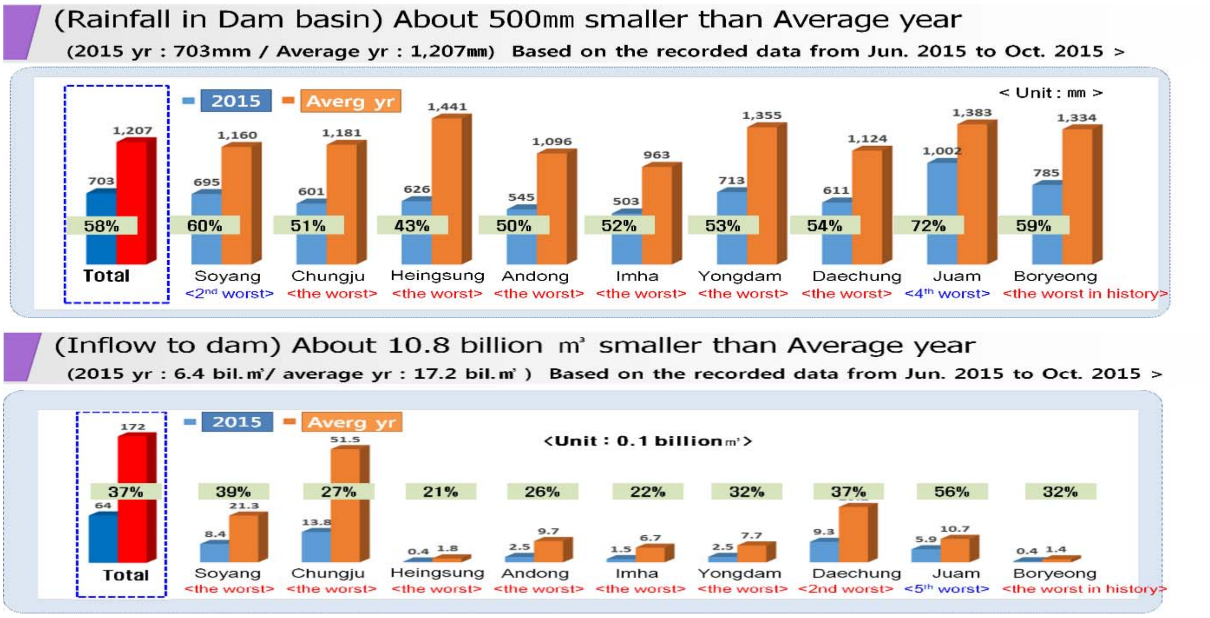


Figure.6.7 rainfall and inflow in Major dams in Korea in 2015

6.6.2 Anticipatory actions to cope with worsening drought

In order to efficiently cope with the drought, Enterprise Drought Task Force Team in K-water had been composed and implemented since July of 2014. Furthermore, a water supply adjustment criterion in time of drought was established by K-water. It has been applied to dam operation after the government approval. The relevant stakeholder including dam operators easily recognizes the current drought stage by this criterion because this provides the particular standard water levels around year and also step by step water supply adjustment plan according to drought stage. As a result of this criterion, fast decision making such as reduce of water supply has become possible.

There are four sorts of water supply from a multi-purposed dam, it would be classified into domestic, industrial, irrigational and river maintenance water supply according the priority as presented in Table.6.1. Drought response stage can be classified into 4 stages in accordance with water demand, namely notice, caution, alert and serious.

Stage	Estimation Criteria in Stages
Notice	Standard storage volume for Caution stage+ Possible to supply water demand 10 days without inflow
Caution	Possible to supply actual water demand for 1 year (Demand : river maintenance, Irrigation, Domestic, Industrial)
Alert	Possible to supply actual water demand for 1 year (Demand : Irrigation, Domestic, Industrial)
Serious	Possible to supply actual water demand for 1 year (Demand : Domestic, Industrial)

Table 6.1 Explanation of standard storage volume in stages

K-water made an effort to preferentially secure the domestic, industrial and irrigational water by reducing river maintenance water because three kinds of water supply directly relate to state of the economy and the public daily life.

6.6.3 Additional countermeasure in time of drought worsening season

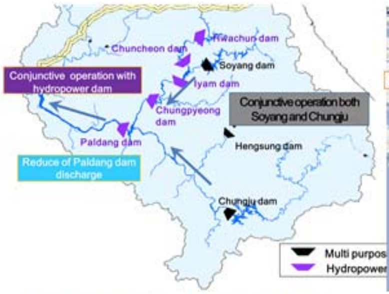
Despite of anticipatory actions, various counter measure were carried out as the drought condition spread out over the whole country and the situation getting worse. In Han river basin which is the main water source of Seoul metropolitan, hydropower dam substituted domestic water supply instead of multipurpose dam due to gradual drop of multipurpose dam water level. Furthermore, absolutely required water was only provided by joint investigation with government ministry and relevant local government for the actual downstream extract.

In Nakdong and Geum river basin, irrigation water from dams had been supplied actual demand since September of 2015. And dam water release had minimized while maintaining the water level of downstream without interruption of extracting water by conjunctive operation among dams, weirs and barrage. In Sumjin river basin, the hydropower dam which used to produce power generation by diverting water to other area with high head had changed its release direction to main stream in order to fill the downstream dam storage volume.

In Boryeong dam, the main water source of 8 southwest local governments, reservoir water level gradually reached to the low water level in spite of anticipatory actions. In order to prevent stopping of water supply from dam, various and urgent projects had been implemented as followings.

Supply Management (Structural)	● **Alternative supply connecting with different multi-regional water supply system** ● **Urgent leakage reduction :** water flow rate 10% ↑ within 6 months ● **Construction of Water Supply diversion canal** **(Geum river→Boryeong dam) :** 115×10^{3}m^3/day

Demand Management (Non-structural)	● **Autonomous adjustment for water supply** : water usage 20% ↓ without compulsory cut off ● **Support fund for water saving** : nation's first, inducement of water saving by incentive pay ● **Water Saving Campaign** : mass media(including press tour), road campaign, etc. ● **24hr call center for civil complaint, Support bottled water and water wagon**



[Joint operation among Multi & Hydropower in Han river basin]

[Alternative supply using nearby WSS in Boryeong dam]

[Construction of water supply diversion canal]

Figure6.8 Additional countermeasure in time of drought worsening season

6.6.4 Successful outcomes by various actions in spite of historical drought

Although unprecedented extreme drought spread out over the whole country, K-water has been stably provided required water to the public by means of comprehensive countermeasure. With anticipatory and active actions against drought, additional storage volume(2.4×109 m^3) among 9 dams was secured and drought stage would be mitigated.

<table>
<tr><th>Description</th><th>SY</th><th>CJ</th><th>HS</th><th>AD</th><th>IH</th><th>YD</th><th>DC</th><th>JA</th><th>BR</th><th>Total</th></tr>
<tr><td>Practical action stage (with water saving)</td><td>Caution</td><td>Caution</td><td>Caution</td><td>Caution</td><td>Caution</td><td>Caution</td><td>Alert</td><td>Caution</td><td>Serious</td><td>-</td></tr>
<tr><td rowspan="2">Without action coping with drought (without water</td><td colspan="5">Under Low Water Level</td><td rowspan="2">Caution</td><td rowspan="2">Alert</td><td rowspan="2">Caution</td><td rowspan="2">Serious</td><td rowspan="2">-</td></tr>
<tr><td>Serious</td><td>Serious</td><td>Serious</td><td>Serious</td><td>Serious</td></tr>
</table>

saving)										
Additionally reserved Storage Volume [10^6m^3]	1,890		23.2	345		13	90	35	10.5	2,405

* SY : Soyanggang dam, CJ : Chungju dam, HS : HoengSung dam, AD : Andong dam, IH : Imha dam, YD : Yongdam dam, DC : Daecheong dam, JA : Juam dam, BR : Boryeong dam

Table 6.2 Additional reserved volume and drought stage

6.7 Cascade hydropower reservoirs in Nigeria

6.7.1 Introduction

Nigeria has huge power supply deficit. Whereas the Power demand (Power Sector Reform Roadmap, 2010) is about 40,000MW, the total installed capacity is about 4,000MW. The Hydropower plants contribute about 1,900MW.

The Nigerian Cascade Hydropower case study presented here involves three main Cascade Reservoirs within the Hydropower generation complex. These are Kainji-Jebba cascade with a capacity of 1,400MW in River Niger, Shiroro-Zungeru cascades with a capacity of 1,300MW on River Kaduna and Gurara I – Gurara II cascade with a capacity of 390MW on River Gurara. Only one of these three (Kainji-Jebba) is fully in production. The Shiroro-Zungeru and Gurara I & II cascades will be in production by year 2018 based on current developments and program.

Figure6.9 Three HPP Cascadesin Nigeria

6.7.2 Meteorological and runoff Characteristics

The Climate is characterized by marked dry and wet seasons and annual rainfall varies from about 2,500mm in the extreme South to less than 500mm in the extreme North. The Kainji-Jebba Hydropower plants operating on River Niger enjoys better hydrological performance in any given year than the Shiroro-Zungeru cascade on River Kaduna because the former exhibits two flood peaks in September and February (See Fig6-10a and Fig6-10b). The River Kaduna cascade enjoys only three months of flood flow between July and October annually while River Niger at Kainji experiences two annual floods. The Gurara, though a smaller tributary of River Niger shows similar flood regime to River Kaduna. In general, the three cascades show marked seasonal variation.

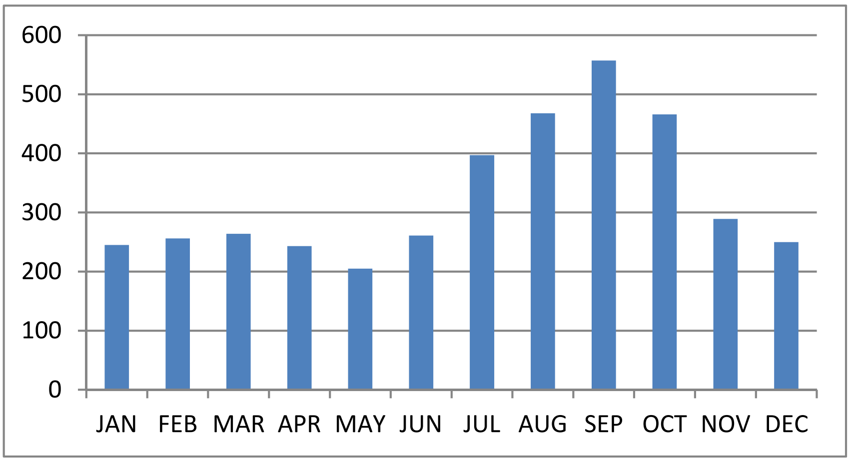


Fig6-10a Average Monthly Runoff of River Kaduna Mean Discharge (m^3/s)

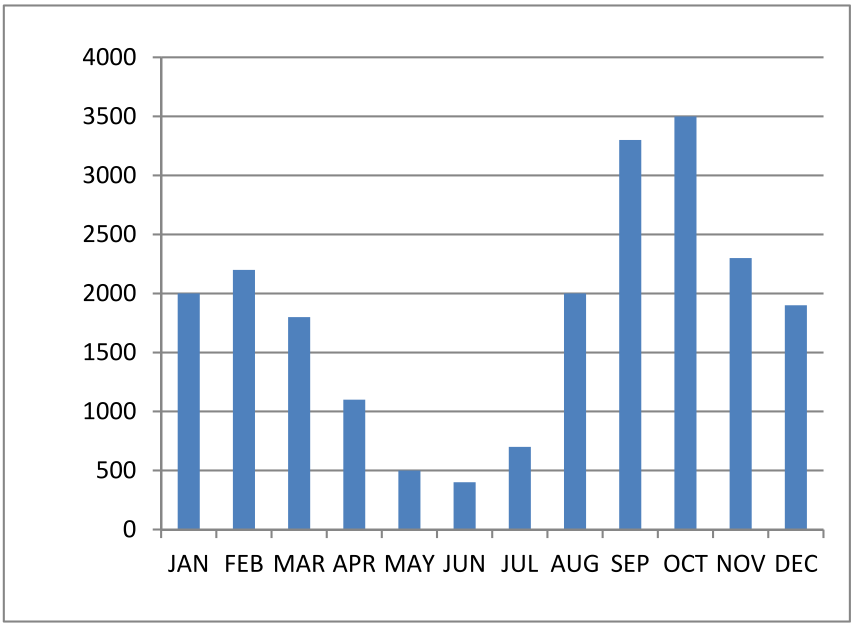


Fig6-10b Typical Hydrograph of River Niger Showing Average Monthly Runoff Discharge (m^3/s) with two Flood Peaks

6.7.3 Comprehensive operation and dispatching

The operators employ water level records without forecasting in three cascades. Hydropower plants in the three river cascades are used mainly for hydropower generation, flood control, sediment dispatching and are available for navigation. The effective management of the reservoirs in response to inflow flood allows high energy generation for certain months.

6.7.4 Conclusions

The scope of the existing practice in Nigeria is very limited and rudimentary. Power generation companies do not have facilities for real time forecasting of relevant hydrological data. The new Investors of the River Niger and River Kaduna Cascades are investing significantly in the rehabilitation of the hydropower plants including technology for efficient operation and dispatching of the hydropower reservoirs.

6.8 Cascade hydropower stations on the Volga River and Kama River in Russia

6.8.1 Introduction

The Volga River is the largest river in Europe located in the European part of Russia and. It is 3530km long originating from a spring in the Valday Hills in Tver Region and covers a catchment area of 1.36 million km^2 with about 200 tributaries of which the biggest are the Kama-river and Oka-river. Cyclones from the Mediterranean Sea bring heavy rains in summer and thaw it in winter, so the Volga has an Eastern European type of water regime with spring floods (April-June), low summer and winter mean inflows and autumn rain floods (October).

There are 9 large reservoirs on the Volga River and 3 large reservoirs on the Kama River. The longitudinal profile of the Volga and Kama river system and hydropower facilities is given in Figure 6.11.

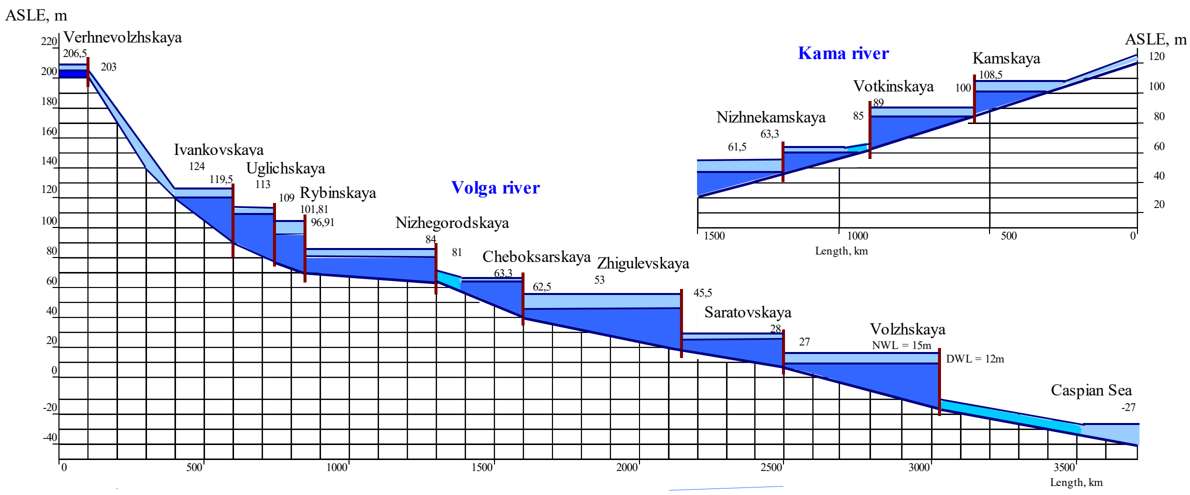


Figure 6.11 Longitudinal profile of the Volga and Kama river systems and hydropower Facilities (full useful volume 85.7 cubic km)

6.8.2 Comprehensive operation

All reservoirs of the cascade are used complexly and creation of Volga-Kama cascade of reservoirs allowed to solve a number of issues for energy, water-transport and irrigation development, as well as to provide industry and utilities with water supply.

The Upper Volga and Kama are energy and water transport sectors, the main function of Ivankovskoye Reservoir is water supply to Moscow (it provides up to 70% of water consumed in the city). On the Middle Volga, irrigation is added to the main demands of the water system, and on Kama River there is timber rafting. On the Lower Volga, in addition to energy and water transport, leading sectors are fisheries (fishery releases) and agriculture (agricultural releases and irrigation).

The objectives of Volga operations are identified as follows: drought management for the salvation of eastern Volga areas from periodic crop failures; ensuring guaranteed grain production through irrigation development; development of electric power through construction of powerful HPP cascades on the rivers Volga and Kama; development of a unified water-transport system that would allow large vessels to transport goods and passengers.

The Volga together with its tributaries are also the source of potable and industrial water for the population and economy of the Volga basin. Potable water extraction from the Volga is about 26 km^3 per year. Irrevocable water consumption is close to 10 km^3 per year. The use for household need is 29.2% of total extraction, 51.4% for industry, 9.1% for irrigation and the rest 10.3% for other purposes.

6.8.3 Dispatching schedules

6.8.3.1 Characteristic lines and zones

In accordance with accepted water practices, the volume of the reservoir is divided into the following specific areas of dispatching schedule:

- Zone of unused volume of the reservoir, which is located below the minimum acceptable in normal use level;
- Interruption zone (reduced return), in which the return of the reservoir is assigned below the guaranteed level;
- Zone of guaranteed return, which is the main work area, where guaranteed return is appointed;
- Zone of high (excess) returns over the guaranteed level. This increase in returns provides the additional effect mainly to hydropower;
- Flood zone prism occurs in reservoirs used for the protection of the downstream hydroelectric facility against flood;
- Zone of maximum idle discharges. In order to ensure the safety of hydraulic structures all spillways are open in this area.

It should be emphasized that the above specific zones change their position in the dispatch schedule, depending on the characteristics of the water phase in any year. In addition, the boundaries of these zones at certain moments and time periods may vary depending on the preceding or predicted values of inflow. The main importance to the dispatch schedule is characteristic lines separating zones and subzones. On these lines, there is a change in management strategy of reservoirs.

6.8.3.2 Algorithm for dispatching schedule

The optimisation algorithm of water energy regimes for reservoirs cascade is presented in the following table.

Title	Long-term planning	Medium-term planning	Short-term planning	Executive planning
Key procedure	Forecasting balance sheet making	Making proposals to inter-authority working group and water discharge calculation after receiving the directives	Making a schedule for the following day and week	Choosing a set of units to perform power schedule
Effect	none	Amplifying the output by discharge before flood period, dispatching of discharge between HPPs and periods using price criteria	Choosing the optimal schedule for avoiding idle discharge, for price criteria and minimizing limitations	Minimizing water discharge
Actor	Federal tariff service, Power forecasting agency	Federal water resources agency	Transmission system operator	Transmission system operator, RusHydro

Table 6.3 Optimizing the water regimes

6.8.3.3 Dispatch operating process

Based on characteristic lines and zones of dispatch schedules, in general, dispatch operating process includes:

- Products: Energy (power supply schedule compliance) and power (declared available power providing);
- System Services: Reservoir level and discharge, voltage level and frequency level in the grid(power supply reserve, and command execution to regulate voltage and regulate supplementary frequency and power flow);
- Transmission lines operator – sets up power supply schedule in terms of delivery of the available power, give directives to regulate voltage, frequency and power flow. Federal water resources agency – sets up water discharge schedule, send directives on water level operating range and discharge;
- Consumers: Wholesale market – consumes energy and power.

Grid operator and Federal Transmission Lines Company consume voltage, frequency and power exchange.

Water consumers – consume volume of water usage.

6.8.4 Limitations and goals of dispatching schedules

When planning the water and power regimes of the Volga River and Kama River cascades, it is necessary to take care of specific features and special aspects of limitations for their operating regimes:

- Instructions made by authorities;
- Climate in the region of watershed basin and in tail-water;
- Geology and morphometry of reservoir area, power site and tail-water;
- Dam safety;
- Power mix in the energy sector and patterns of energy consumption;
- Type of flow regulating at the reservoir (daily, weekly, monthly, seasonal, long-term);
- Requirements of water users and customers for the water regime.

Based on these limitations and relevant parameters, the goals when planning water and power regimes are:

- Safety and reliability of HPP's operating equipment;
- Dam safety;
- Basing the position of company when drawdown and impoundment of reservoir regime is set by the basin authority;
- Maximizing power output or maximizing sales proceeds through optimal water and power regime, taking into account the limitations set by authorities.

6.8.5 Conclusions

The operational management of reservoirs was developed on the basis of an accumulation of experience in the operation of reservoirs, improvements in scientific approaches to the regulation of reservoir flows, and the emergence of new challenges and requirements for reservoir regimes. The rapid development of computer technology and mathematical modelling methods has also exerted a great influence.

6.9 The upper Rhone River valley in Switzerland

6.9.1 Introduction

The Rhone River, originating in the southern Alps, is 812 kilometres long and covers a catchment area of 97,000 km^2. The development of hydropower in the Alps, and especially in the upper Rhone river valley, started towards the end of the 19th century and the beginning of the 20th century. Investors took advantage of the proximity of electrical power generation of to developing industries such as chemical, aluminium and manufacturing. The first hydropower schemes mostly consisted of a water intake located in a lateral valley, possibly combined with a small reservoir, and high chute penstock ending in a powerhouse located in the main valley. With the increasing demand for hydropower, high reservoirs located in more remote upper lateral valleys were constructed, mostly between 1945 and 1980. In order to artificially increase the catchment areas of the major schemes, an important network of water intakes and collecting water galleries was constructed. The total catchment area controlled by high reservoirs represented 27% of the global watershed (5,500 km^2).

Nowadays, the total retention volume of the reservoirs is about 1,200 million m^3 representing 21% of the annual discharge flowing into the Lake of Geneva. Globally, 85% of water is used, at least once, for power production.

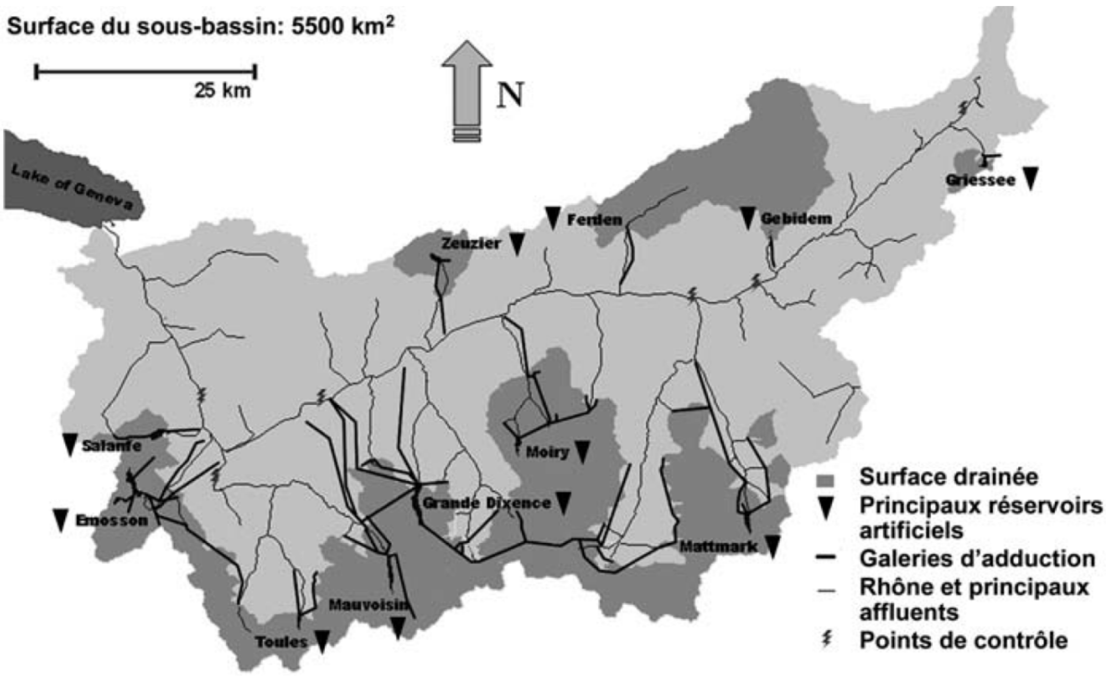


Figure 6.12 Map of the Upper-Rhone watershed (5500 km^2)

Although the most important floods appear in September and October, when the hydropower reservoirs are almost full, these reservoirs offer the potential for reducing the impact of flooding events in the main Rhone river valley.

6.9.2 Improving the effect of flood routing

A first project aiming at improving the flood routing effect of an existing reservoir was developed in 2001 for the Mattmark dam located close to Zermatt and the Matterhorn. An additional retention volume was created by heightening the existing spillway by 2 metres, the normal operating level remaining the same as before. The original freeboard of 7 metres has been reduced to 5 metres without endangering the dam itself. The additional volume in the reservoir contributes therefore to the flood routing.

Nevertheless, it has also been demonstrated that the impact on existing reservoirs and possible improvements of their flood routing effect are beneficial for flood protection only for flooding events of medium importance, remaining of very limited use in the event of more extreme flooding. Further developments aimed at integrating flood and hydropower management require flood forecasting and management decisions in real time.

6.9.3 Managing floods taking advantage of the hydropower reservoirs

6.9.3.1 Flood forecasting

The influence of flood routing from hydropower reservoirs depends highly on reservoir management prior during the flooding event. Optimization of the retention effect during floods requires a flood forecasting system and routing simulations in order to provide real time decision support. The use of a discharge forecast system gives the required information about the hydrological situation in the catchment area and provides the decision-maker with a general view and a predicted evolution of the discharges in the river network. When coupled with an optimization tool, it is possible to directly highlight the key variables of the system and to decide which release or storage operations at the reservoirs have to be performed.

Flood forecasts are based on meteorological data including precipitation, evapo-transpiration and temperature, which are provided 72 hours in advance. A semi-distributed hydrological model integrates this data and simulates the snow and ice melting, infiltration and run-off processes. The river network is also modelled as well as the hydraulic schemes and equipment such as reservoirs, water intakes, spillways, power plants, pumps.

The results of the simulation of discharge at a certain number of control points are then compared to those measured in real time. the model is then updated and the new meteorological data introduced for further forecasting over the next 72 hours.

6.9.3.2 Preventive operation

Preventive operations refer to an anticipated reduction in the volume of water in certain reservoirs. The release of water can be performed by power production or, if necessary, by operating gates. Since the decision is based on hydrological forecasting, the risk of loss of power production, or the risk of power generation during a low economical timeframe exists. It is therefore necessary to validate each decision when comparing forecasting and real time measurements.

6.9.3.3 Performance

A performance analysis of the computed flood management strategies showed the significant positive influence of such preventive operations. Two major historical flood events with about 100-year occurrence periods were simulated. The reduction of the observed peak discharge due to the accumulation reservoirs lay between 6% (1993 flood) and 10% (2000 flood) at the outlet of the Rhone River catchment area. With an appropriate flood management strategy 30 hours in advance, the reduction of peak discharge could have been 15% without releasing water by gate operation and 28% with gate operation during the flood in September 1993. An additional reduction of 7% of the peak discharge would have been obtained during the flood in October 2000 with preventive operations 34 hours in advance.

6.10 The Tennessee Valley River system in the USA

6.10.1 Introduction

The Tennessee Valley River is 1,600 km-long, with an area of more than 100,000 km^2. It has abundant precipitation of up to 1,320mm per year. For the use, conservation, and development of water resources related to the Tennessee River, the TVA operates a system of dams and reservoirs with associated facilities – its water control system. TVA uses this system to manage the water resources for the purposes of navigation, flood control, power production and, consistent with those purposes, for a wide range of other public benefits.

TVA maintains 29 conventional hydroelectric dams throughout the Tennessee River system and one pumped-storage facility for the production of electricity. The total number of regulated dams maintained by TVA River Operations has risen to 87, with the addition of saddle dams, dikes and non-power dams. In addition, four Alcoa dams on the Little Tennessee River and eight U.S. Army Corps of Engineers (USACE) dams on the Cumberland River contribute to the TVA power system.

TVA began automating its hydroelectric system in 1998. The program was completed in 2005, allowing all TVA conventional hydroelectric plants to be controlled and monitored from a command centre in Chattanooga. An ongoing hydro modernization program, scheduled for completion around 2015, will result in an additional 360 megawatts available from existing hydro units.

6.10.2 Background and water control system overview

This chapter describes the seasonal patterns of rainfall and runoff in the Tennessee Valley watershed and the specific components of the TVA water control system.

6.10.2.1 Rainfall and runoff

Rainfall, runoff, and topography in the Tennessee Valley watershed strongly influence the original location, design, and operating characteristics of TVA reservoirs and the water control system. The locations and storage volumes of reservoirs reflect the variation in rainfall and runoff in the region. Rainfall and runoff continue to control when and where water flows into the reservoirs; and runoff exerts a strong influence on the annual, seasonal, and weekly patterns of reservoir operations.

Mean total annual rainfall is 52 inches per year throughout the TVA system, but rainfall varies considerably from year to year and at different locations in the system. About 40 percent of rainfall in the drainage area of the Tennessee River system becomes runoff. Substantial variation in the annual amount of rainfall affects the degree to which objectives of the water control system can be achieved.

6.10.2.2 Structure of the Water Control System

The water control system is composed of dams and reservoirs, tail waters, navigation locks, and hydropower generation facilities, as described in the following sections.

(1)Dams and Reservoirs

The 35 projects that comprise the water control system include nine main stem reservoirs and 26 tributary reservoirs. Each TVA project typically falls into one of four general categories that are closely related to its characteristics (e.g., location and size), primary function (e.g., navigation, storage for flood control, or power generation), and operation. These categories include main stem storage projects, main stem run-of-river projects, tributary storage projects, and tributary run-of-river projects.

(2)Tailwater

Tailwater is a widely used term that generally refers to the portion of a river below a dam that extends downstream to the upper portion of the next reservoir pool in the system.

(3)Navigation Locks

The TVA reservoir system also includes 15 navigation locks located at 10 dams. Operated by the USACE, the locks provide an 800-mile commercial navigation channel. TVA operates the reservoir system to maintain a minimum 11-foot depth in the navigation channel along this navigable waterway.

(4) Hydropower Generation Facilities

Hydropower generation facilities are incorporated into 29 of the project dams. Although these facilities initially provided base load power, they now generate electricity primarily during periods of peak power demand. Depending on annual runoff, the hydropower facilities provide from 10 to 15 percent of TVA’s average power requirements.

6.10.3 Water control system

This section describes how the water control system is operated to optimize public benefits while observing physical, operational, and other constraints.

6.10.3.1 Flows through the Water Control System

Water stored in the tributary reservoirs is released downstream to the larger Tennessee River main stem projects and eventually flows into the Ohio River, and finally the Mississippi. Water is released from the projects to provide flows to maintain minimum navigational depth, re-establish flood storage volume in the reservoirs, generate power as it passes through the system, supply cooling water to the coal and nuclear power plants, and maintains water quality and aquatic habitat.

6.10.3.2 Balancing operating objectives

The TVA reservoir system is not operated to maximize a single benefit to the exclusion of others. The system is operated to achieve a number of objectives and to provide multiple public benefits. Some operating objectives are complementary; others require trade-offs, especially in periods of limited water.

6.10.3.3 Reservoir operations policy

TVA's reservoir operations policy establishes a balance of operating objectives. It guides system-wide decisions about how much water is stored in specific reservoirs, how the water is released, and the timing of those releases. The policy helps TVA in managing its reservoir system to fulfil its statutorily prescribed operating objectives and to provide other benefits.

The reservoir operations policy is composed of guidelines that describe how the reservoirs should be operated given the rainfall and runoff and the operating objectives. These guidelines include:

(1)Reservoir operating guidelines

Control the amount of water in each reservoir, the reservoir pool elevations, and the flow of water from one reservoir to another; these guidelines are implemented through guide curves for each reservoir.

(2)Water release guideline

Control the release of water needed for reservoir system and project minimum flows, including flows for special operations.

(3)Other guidelines and operational constraints

Include procedures and limitations set for hydropower generation, response to drought conditions, scheduled maintenance for power generation facilities, power system alerts, dam safety, security threats, and environmental emergencies.

(4) Reservoir guide curves

Guide curves are line graphs showing the planned reservoir levels throughout the year. They also depict the storage allocated for flood control, operating zones and, in some reservoirs, the volume of water available for discretionary uses.

6.10.4 System monitoring and decision support

To ensure the efficient operation of its complex reservoir system, TVA uses a variety of data collection, computerized reporting, and decision support systems.

6.10.4.1 River Forecast Center (RFC) mission

The TVA's RFC is staffed around the clock, 365 days a year. River schedulers continually monitor weather conditions and water quality data, as well as water availability and demand, with the goal of routing water through the river system to provide the most public value given changing weather conditions and water needs. The RFC responsibilities include:

- Issuing forecasts of reservoir levels;
- Scheduling water releases at TVA dams;
- Providing hourly generation schedules for TVA hydroelectric projects, eight projects operated by the U.S. Army Corps of Engineers on the Cumberland River system, and four reservoirs that make up the Brookfield Renewable Energy Smoky Mountain Hydro project;
- Providing special notifications to the public during flood events;
- Evaluating cooling water needs for TVA coal-fired and nuclear plants;
- Monitoring water quality conditions below TVA dams so that aeration equipment can be turned on when needed to maintain adequate dissolved-oxygen concentrations;
- Serving as the main point of contact in the event of a river system emergency.

6.10.4.2 RFC challenges

While the RFC System continues to operate as a functional river forecasting system capable of developing a daily water schedule, it is an aging system that is in need of modernization. The RFC System is poorly suited to meet the intense demands currently placed on the Tennessee River network. Some of the consequences of this include:

- System failure risk due to thinness of support knowledge and lack of documentation;
- Inflexibility due to custom connections between components;
- Outmoded tools due to cost of keeping current with custom software;

- Waste of forecaster focus due to use of too many interfaces;
- Outmoded customer products due to inability to quickly tailor reports.

6.10.4.3 The RFC modernization project

TVA is addressing this need through the RFC Modernization Project. Throughout 2012, RFC staff partnered with Riverside Technology to evaluate alternatives for a new platform and trial the chosen platform. Delft-FEWS (or simply, FEWS is an open data handling platform initially developed as a hydrological forecasting and warning system) was chosen as the best available alternative and a pilot project was performed to convert the rainfall processing portion of the RFC into FEWS.

Other river management agencies have recently made significant advances developing functional and robust software platforms to support the water management mission. Thus modernization of the RFC System is an entirely realistic, achievable and timely objective for the RFC.

Appendix I: Abbreviations

AFC: Automatic Frequency Control

AVC: Automatic Voltage Control

CLDC: Central Load Dispatching Center

CTG: China Three Gorges Corporation

ELD: Economic Load Dispatching

EDF: Electricité de France

EMS: Energy Management System

GIS: Geographic Information System

HPP: Hydropower Plant

ICOLD: International Commission on Large Dams

KEPCO: The Kansai Electric Power Co., Inc.

LDCC: Local Load Dispatching and Control Center

RDS: Reservoir Dispatching System

RFC: River Forecast Centre

SCADA: Supervisory Control and Data Acquisition

TVA: the Tennessee Valley Authority

TSO: Transmission System Operator

TGP: China Three Gorges Project

USA: The United States of America

USACE: the U.S. Army Corps of Engineers

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