THE INTERNATIONAL ENERGY AGENCY TECHNOLOGY COLLABORATION PROGRAMME ON HYDROPOWER

IEA Hydropower

Management Models for Hydropower Cascade Reservoirs

Main Report

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IEA Hydro Annex XIV

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Content

Management Mode Of Cascade Reservoirs

1 Overview of cascade reservoirs

1.1 Overview of the world's major river basins

The large rivers on the earth are mainly distributed in Asia, Africa, North America, South America and Europe. Asia and South America are the continents with the largest rivers in the world. Brazil in South America is the country with the most large rivers in the world which is located in the tropical area with abundant rainfall. There are 9 large rivers with an annual runoff of more than 200 billion m^3. Australia has the fewest large rivers in the world, the Murray-Darling River, with a drainage area of 1.06 million km^2 and an annual runoff of 22.7 billion m^3, is the largest river in Australian continent. With 6,650 km calculated by length, the Nile River flows through 10 countries and is the longest river in the world. According to the basin area, the Amazon basin in South America covers an area of 7.05 million km2, making it the world's largest river. According to the amount of water,the Amazon River has an annual runoff of 693.8 billion m^3, making it the world's largest river.

Chart 1 World rivers sorted by river length

No.	River Name	Location	Length/km	Water Area/Million km2
1	The Nile	Africa	6650	335
2	Amazon River	South America	6437	705
3	the Yangtse River	china	6300	181
4	Mississippi River	North America	6020	322
5	The Yellow River	China	5464	75
6	The Congo River	Africa	4700	346
7	Mekong River	Asia	4500	80
8	the Heilongjiang River	Asia	4410	186

9	The Lena	Asia	4260	249
10	Niger River	Afica	4180	189

China's rivers are characterized by a large number of rivers, abundant water, diverse water systems and abundant resources. It is customary to refer to the Songhua River, Liaohe River, Haihe River, Yellow River, Huaihe River, Yangtze River and Pearl River as the seven major rivers in China. Among the longest rivers in the world, the Yangtze River and the Yellow River are ranked third and fifth respectively.

1.1.1 The Nile

The Nile is the longest river in the world. It originates from the western mountains of Lake Victoria and flows through Tanzania, Burundi, Rwanda, Uganda, Sudan, and Egypt, and finally flows into the Mediterranean Sea from south to north. The river has a total length of 6,650 km and a drainage area of 3.35 million km^2. It runs through the northeastern part of Africa and has a drainage area equivalent to one-tenth of the entire African continent. The latitude of Nile River Basin spans 35 degrees, and there is a huge difference between the north and south climate, showing a distinct latitude and zonality. From Nimule to the north, the rainy season is shortened and the rainfall is decreasing. The rainy season in southern Sudan occurs from April to October, while in the north central it occurs from July to August. Due to the uplift of the terrain, the climate has a vertical spectrum and has a distinct dry and wet season in the Ethiopian plateau in the southeastern part of the basin. In summer, the low-pressure belt is over North Africa and the Arabian Peninsula, the trade winds of the South Indian Ocean and the humid hot air of the Gulf of Guinea merge into a strong southwesterly airflow, which rises along the plateau and forms a “rainy period” from July to September. In winter, there is a dry northeast wind from the southwest Asian continent prevailing over the plateau, forming a dry season from October to February. The annual average rainfall of the plateau is 1000-2000 mm, which is the most important rainfall center in the Nile Basin. In the south of the basin, the annual average rainfall is 1200-1300 mm, the season distribution is relatively uniform, there is no obvious dry season, and the relative humidity is about 70%, which is another rainfall center in the Nile River Basin.

Of the total annual runoff in the Nile Valley, 60% comes from the Blue Nile, 32% from the White Nile, and 8% from the Atbara. However, there are big changes between the flood period and the dry season. During the flood period, the Blue Nile accounted for 68%, the White Nile accounted for 10%, and the Atbara River accounted for 22%. In the dry season, the Blue Nile decreased to 17%, the White Nile rose to 83%, while the Atbara River was cut off at this time. However, the proportion and variation of the proportion of these rivers in the Nile River are closely related to the precipitation and seasonal distribution of the river basins. With the alternating climate in the upper reaches of the basin, water is beginning to rise in the Nile River Basin in northern Sudan from May, generally reaching the highest water level in August, and then the water level is gradually decreasing. Influenced by seasonal rainstorms on the Ethiopian plateau, the duration of flooding and flooding in the Nile River Basin are quite different.

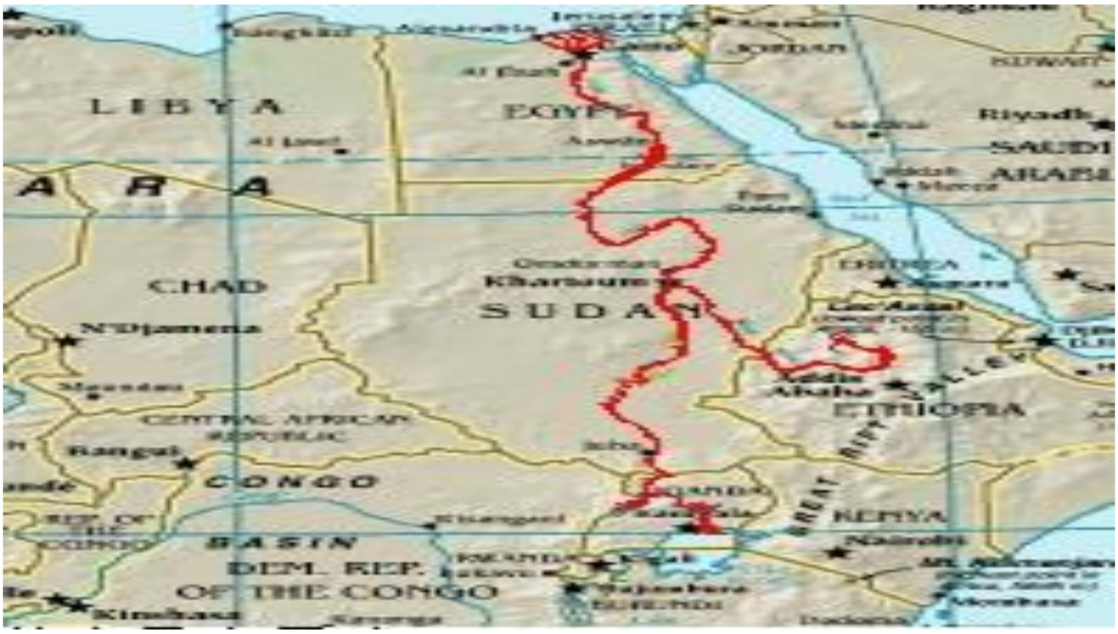

Figure 1 Drainage of The Nile

1.1.2 Amazon River

The Amazon River originates from the middle of the Andes Mountains in South America, the top of Misami Snow Peak on the eastern side of Koropna, Peru, and finally flows into the Atlantic Ocean. It is the second longest river in the world with a length of 6437 km. Located in the north of South America, the Amazon River is the largest river and has the most tributary river in the basin. It traverses around the South America and has more than 10,000 tributaries on the way, distributed over large areas of South America. It flows through Peru, Brazil, Bolivia, Ecuador, Colombia and Venezuela, with a drainage area of 7.05 million km^2, accounting for 40% of the total area of South America. The mainstream flows reach 5.6 million km^2 cross the largest plain in the world (Amazonian plains). The average annual flow of the basin is 220,000 m^3/s, and the annual average runoff is 6.9 trillion m^3, which is equivalent to 1/6 of the total water flowing into the ocean by the world's rivers.

The Amazon basin starts from Brancuku, Brazil, the source of the Madeira River in southern Bolivia, from the Paute River in Cuenca, Ecuador in the west, to the Mararu Bay in Brazil in the east. The entire basin has a latitude of 25°, a longitude of 31°30', a estuary of 240 km, and a flooding period of 280,000 m^3/s. The amount of water is so large that the seawater within 160 km from the shore becomes fresh water.

Located near the equator, the Amazon River is located in the tropical rain forest. It is controlled by the low equatorial zone. The climate is warm, humid and rainy. The precipitation is above 2000 mm. There are dry and wet seasons. Most of the rain comes from the wet season. The water-filled winds from the Atlantic Ocean across the South America, and the eastern slopes of the Andes are forced to rise, bringing heavy rains, forming into such a vast Amazonian river system flowing to the east from the Andes. Over the lowlands, large areas of convective storms produce large amounts of precipitation. According to different rainfall conditions, the Amazon region can be divided into three types of climate: the first one occurs in the western estuary of the Amazon and the western part of the basin, the annual average precipitation exceeds 2000mm, and the annual rainfall distribution is very uniform; in some years, the precipitation can exceed the normal precipitation. The amount is doubled, and in other years it can be long and dry. The second type, which includes most of the Amazon areas, has a particularly small amount of precipitation in a quarter, but it has not been severe enough to affect plant growth. The third type includes areas along the southern edge of the Amazon basin, where the climate gradually changes to the mid-western climate of Brazil, with a more pronounced dry season in the southern hemisphere winter.

The vast Amazonian plains are spread with tropical rain forests and vegetation, there are large gaps when the rivers flow through the mountains and plains, in addition, the water amounts are very large, so that water resources are abundant. The unique tropical rainforest climate, with abundant precipitation throughout the year, makes the water level change small and has no obvious flood season. The Amazon River has a large flow; the maximum flow is 225,000 m^3/s; the minimum flow is 90,000 m^3/s, which occur in May-June and November-December respectively. The average flow is 175,000 m^3/s, which four times compare to the flow of Congo River and ten times compare to the flow of Mississippi River. The Amazon River has an annual seawater intake of 5.4 trillion m^3, accounting for 20% of the total sea runoff in the world. If it is spread into a 10 m thick water layer, its area is equivalent to the area of the North Sea (575,000 km^2). Because the basin is located in the tropics, the river does not freeze, there is no icing period, and there is no icing phenomenon.

The Amazon River has a huge amount of sediment, with an average annual sediment load of 1 billion tons, which are mainly silt and clay. The sediment concentration has obvious seasonal changes. The average maximum sediment concentration in the wet season is 125 mg/L, while the dry season is 22 mg/L. The coarse material is deposited in the downstream reaches and forms a series of sand islands. The Marajo Island between the Amazon estuary and the Pala River estuary is the largest among them.

Figure 2 Drainage of The Amazon

1.1.3 Mississippi River

The Mississippi River is the longest river basin in North America with the largest basin area and has the largest amount of water, located in the south-central North America.

The Mississippi River originates from the Missouri River which has the largest tributary to the eastern Rocky Mountains, and flows from north to south from Lake Itasca, Minnesota, through Minnesota, Wisconsin, Iowa, Illinois, Missouri, Kentucky, Tennessee, Arkansas, Mississippi and Louis. And flow into the Gulf of Mexico near New Orleans, Louisiana. With a total length of 6020 km, it is the forth longest river compared with the Nile River in Africa, the Amazon River in South America and the Yangtze River

in China. The basin covers a large area in the east and central regions, including 31 states in the United States and two provinces in Canada. The drainage area is 3.22 million km^2, accounting for 41 % of the US domestic area. The annual average flow rate near the estuary reached 18,800 m^3/s, and the average annual runoff of the estuary was 598 billion m^3. The average annual sediment transport is 312 million tons. The Mississippi River Basin has significant climate differences. The average monthly temperature in winter is 13 °C in the southern subtropical region of Louisiana. In northern Minnesota, the average temperature in January is between -13 °C and -3 °C. The average temperature in July is between 18 and 29 ° C. The average monthly temperature in summer is 28 °C in Louisiana and 21 °C in Minnesota.

The eastern half of the Mississippi River Basin is humid, and the precipitation in the basin gradually increases from west to east. The Mississippi River Basin is vast, and the geographical conditions and climate differences of each sub-basin are large, so the hydrological characteristics of each section of the river have certain differences. The right bank of the main stream is headed by the Missouri River. It has a large length, a small amount of water, and obvious seasonal changes. The left bank is headed by the Ohio River, with a small length, large water volume, and moderate seasonal changes. The upstream latitude is slightly higher, mainly due to spring snowmelt and rainwater supply. The highest water level in the whole year appeared in April. In June, the highest water level occurred due to the increase of precipitation. The flood period is from March to July, and December is the dry season. The flow rate is 2,900 m^3/s; the water is frozen and the sediment content is small in winter. The average annual flow in the middle reaches is 5800 m^3/s. The flood season is from March to August, the highest water level occurs in June, and the dry season is in December. After the downstream flowing from the Ohio River, the water volume increased greatly, the annual average runoff reached 13,400 m³/s, the flood period is from January to June, the highest water level is in April, and the dry season is in October.

The sediment of the Mississippi River is mainly derived from its largest tributary, the Missouri River. The Missouri River has a rush of water, and the water has a large amount of sediment, especially during the flood season. It not only vents floods to the clear Mississippi River but also imports a large amount of sediment. The sediment content of the Missouri River is second to none in the dry and tributary of the Mississippi River Basin. The annual average sediment concentration is more than 310 million tons, accounting for about 75% of the sediment volume of the entire Mississippi River entering the ocean each year.

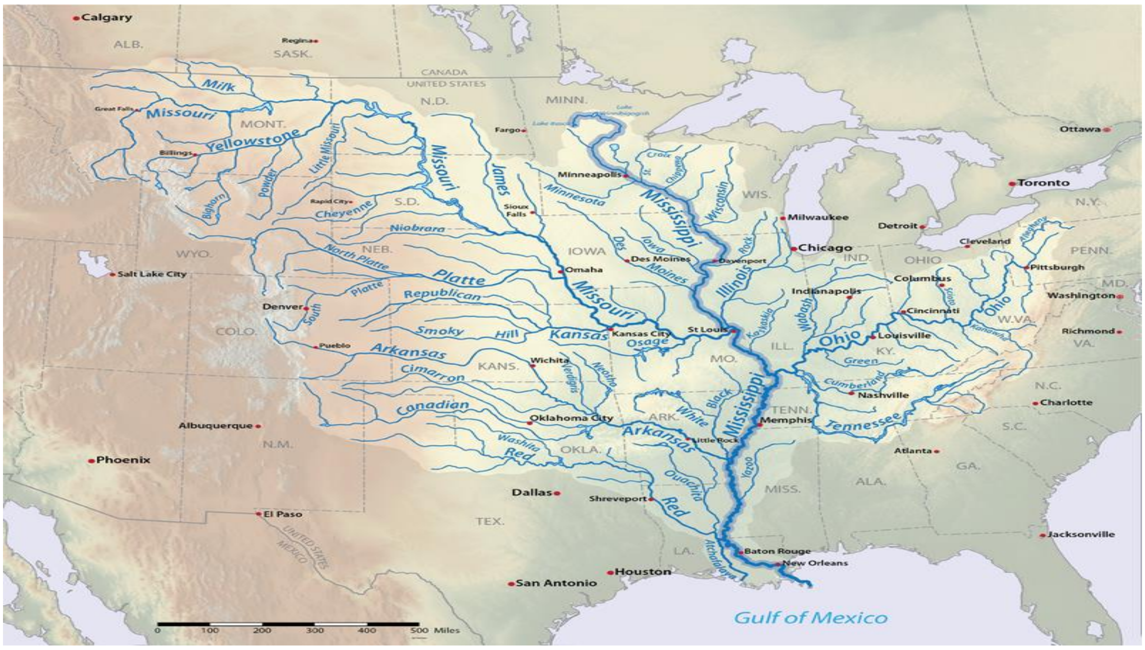

Figure 3 Drainage of The Mississippi River

1.1.4 Volga River

The Volga River is the largest river in Europe and the longest inland river in the world. It originated in the Valdai hill in the northwestern part of the Russian Federation. It twisted from north to south and flows through the central part of the Russian plain into the Caspian Sea. From the Erzhev, not far from the river source, the total drop is only 190 m in the river section of more than 3,000 km. Therefore, the water flow rate of the Volga River is slow, and the sandbank, shoal, oxbow lake and waste river channel are widely distributed. So the Volga River is a typical plain river.

The Volga River has a total length of 3,530 km, a drainage area of 1.38 million km^2, an average flow of 8,000 m^3/s, and an annual runoff of 254 billion m^3. The river network is very developed with over 200 main tributaries. The largest tributaries are the Oka River and the Kama River. From the source to the Oka River mouth is the upper reaches of the Volga River, this section is 1327 km long; from the Oka River mouth to the Kama River mouth is the middle of the Volga River, the length is 511 km long; below the Kama River mouth is the lower reaches of the Volga River, the length of the river section is 1850 km. There are many tributaries of the Volga River and the river network is dense. It connects the Baltic Sea through the Volga-Baltic Canal, connects the White Sea through the North Dvina River, and communicates with the Azov Sea and the Black Sea through the Volga-Don Canal and injects into the Caspian Sea. Therefore, there is a reputation for "five seas navigation".

Most of the Volga River Basin has a continental climate. The upper and middle reaches of the basin and the lower right bank are forest climates; the lower left bank is a grassland climate and a semi-desert climate; the Caspian lowlands are desert climates.

The water supply of the Volga River comes from snow melting from the mountains, accounting for 60% of the annual displacement, 30% of the groundwater, and 10% of the rain. The largest amount of annual runoff in the Volga River occurs in the spring.

The climate of the Volga Basin varies greatly from north to south. From the source to the Kama estuary is a mild climate zone, especially in winter, cold, snowy, warm and humid in summer. From the Kama River to the Wowa Mountain, the summer is hot and dry, and the winter is cold, but there is very little snowfall. As the river progresses to the south and east, the temperature increases and the precipitation decreases.

Figure 4　Drainage of The Volga River

1.1.5 The Yangtze River

The total length of the Yangtze River is more than 6,300 km, the drainage area is about 1.81 million km^2, and the annual average amount of water that into the sea is about 960 billion m^3. It is the largest river in China, the longest river in Asia and the third longest river in the world. The Yangtze River derived from the "roof of the world" - the southwest side of the Ladandong Snow Mountain Group in the middle section of the Tanggula Mountains in the Qinghai-Tibet Plateau. The main stream of the Yangtze River runs from west to east and traverses the central part of China.

The upper reaches of the Yangtze River are mountain plateaus, and the intensity of winter wind is weaker than that of the middle and lower reaches; the Yunnan-Guizhou Plateau is mainly affected by the southwest monsoon. The Jiangyuan area has a high terrain and is winter all year round. The annual average temperature is below zero. The temperature will be higher than zero in May-September. Frost and snow can also occur in midsummer. It has low temperature, low humidity, less precipitation and more

sunshine. The dry and wet seasons in the Jinsha River area are distinct. The winter is controlled by dry heating flow from India and northern Pakistan. The humidity is low and the precipitation is low. The average relative humidity in January is less than 50%, and the precipitation is mostly less than 5mm.In summer, the humidity is high affected by the southwest monsoon from the Bay of Bengal. The average relative humidity in July can reach 70%-80%. The precipitation in May-October can account for about 90% of the year. The Jinsha River and the tributary Yalong River have "Three-dimensional climate" features of "one mountain, different climates". The middle and lower reaches of the Yangtze River are mostly hills and plains. The four seasons are distinct. The winter is often invaded by cold waves. The weather is cold. The summer is controlled by the western Pacific subtropical high. The winter and summer are slightly longer, and the spring and autumn are shorter.

The average annual precipitation in the Yangtze River Basin is 1067 mm, and the regional distribution of annual precipitation is extremely uneven. The general trend is from southeast to northwest. The mountainous area is more than plain, and the windward slope is more than the leeward slope. The rainy season in the Yangtze River Basin is concentrated from May to October. The time of heavy rain is generally higher in the middle and lower reaches than in the upper reaches, and the south of the Yangtze River is earlier than Jiangbei.

The main sand producing areas in the upper reaches of the Yangtze River are the Jinsha River and the Jialing River. Due to the construction of reservoirs in the basin, the development of water and soil conservation in the basin and the changes in climatic conditions, some new changes have taken place in terms of the water and sediment characteristics of the basin. Since the 1990s, the runoff in the upper reaches of the Yangtze River has not changed much, the sediment transport has decreased significantly, and the trend of sand reduction has continued. The distribution law of runoff has not changed much during the year, and the sediment transport in the flood season is more concentrated.

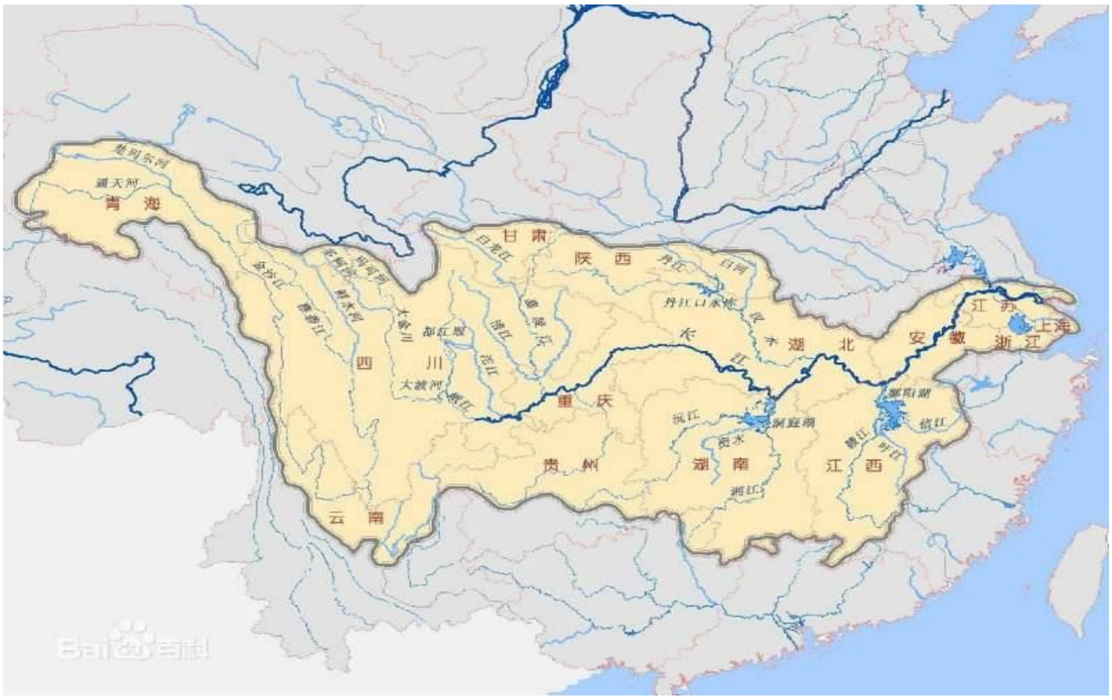

Figure 5 Drainage of The Yangtze River

1.1.6 The Yellow River

The Yellow River derives from the northern foothills of Bayan Kala Mountain in Qinghai Province, China, and flows through Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, Shandong and other nine provinces (districts), and finally flows into Bohai Sea in Yingli County, Shandong Province. The main stream is 5464 km. Yellow River is the second longest river in China and the fifth longest river in the world. The drainage area is 752,400 km^2, and the average annual runoff is 58 billion m^3.

The Yellow River Basin has a vast territory, numerous mountain ranges, and a wide gap between east and west. There are obvious geographical differences between the various regions. The situation affected by atmospheric circulation and monsoon circulation is more complicated because the basin is in the mid-latitude zone. Therefore, the climate difference in different regions of the basin is significant, and the annual and seasonal changes of climate elements are distinct. The Yellow River Basin has sufficient sunshine, strong solar radiation, low humidity and large evaporation. There are many hail, sandstorms and sands, and hail is one of the major catastrophic weather in the Yellow River Basin. Sandstorms are mainly caused by strong winds and are closely related to local (or nearby) geological conditions and vegetation conditions.

The annual runoff in the Yellow River Basin is mainly replenished by atmospheric precipitation. Due to the influence of the monsoon, the seasonal variation of river runoff in the Yellow River Basin is very large. The river water is soaring in summer and autumn so it is easy to flood. The distribution of runoff is uneven during the year, the amount of water is scarce in winter and spring, 60%~80% of the annual precipitation is concentrated in July-October, and most of them form in heavy rains. Some tributaries have more disparity in the distribution of runoff during flood season and non-flood period. Some streams are basically cut off in spring.

The Yellow River is famous for its sediments. The terrain is broken, the vegetation coverage is low in Loess Plateau. Under the impact of heavy rain, strong soil erosion occurs, causing floods in the middle reaches and carrying a lot of sediment. For the past many years (1952~2015), the average sediment load was 978 million tons, and the average sediment concentration was 29.1 kg/m^3.

The Yellow River has a large amount of sediment and high sediment concentration. It is unique in the world's sandy rivers. The majority of the Yellow River's average annual sediment transport volume comes from the middle reaches, 90% of which comes from the flood season, and the flood season is mainly concentrated from several high-sand floods.

In recent years, the amount of sediment transported by the Yellow River has been

drastically reduced. Owing to the concentration of both runoff and sediment, the annual sediment transport was nearly 1.6 billion tonsof the Yellow River Shaoguan Station in the 1970s, which is currently reduced to about 200 million tons. Most importantly, it is the result of combined effects of human activities and climate changes.

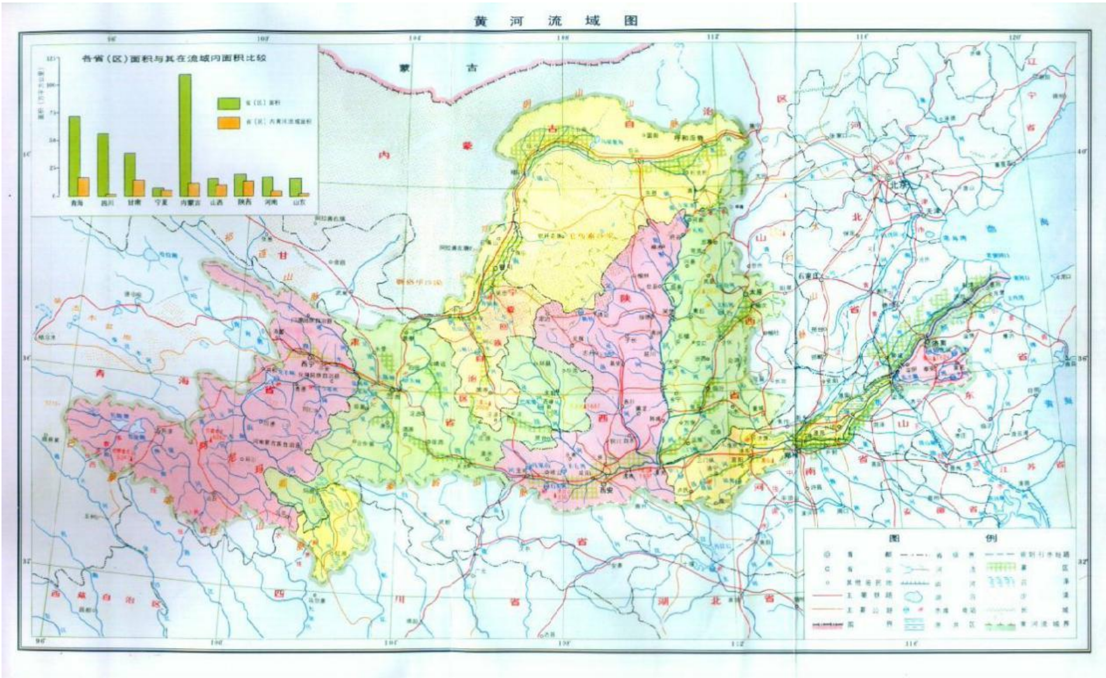

Figure 6 Drainage of The Yellow River

1.2 Overview of typical watershed cascade hydropower development

River basins are the birthplace of human civilization. Ancient Egyptian civilization originated in the Nile Valley. Cuban civilization originated from the Euphrates and Tigris. Ancient Indian civilization originated from the Indus and Ganges, while Chinese civilization originated in the Yellow River and the Yangtze River. The reason why the four major civilizations originated in the Great River Basin is because the basin provides the most basic fertile alluvial plains and favorable irrigation conditions for human survival and reproduction. It has greatly promoted agricultural development at the beginning of human development and created great ancient countries and civilization.

The importance of the basin to humans is self-evident, and its history along with

human development can be divided into three stages.。

The first stage is the development stage of agricultural civilization (also known as yellow civilization). During the period, the use of the basin is mainly. In order to meet the production needs of the agricultural society, water is concentrated in agricultural irrigation, domestic water use and transportation.

The second stage is the development stage of industrial civilization (also known as black civilization). The industrial revolution has greatly promoted the development of productive forces. The traditional agricultural society has gradually been replaced by industrial society. People's eyes have begun to focus on the full use of water resources in the basin. In order to meet the energy demand of industrial development and the rapidly growing urban population demand, the basin has to be over-loaded. Water transport logistics, large-scale water conservancy and hydropower dams and port industrial production have become important missions of the river, which is a distinctive feature of river basin development during this period. At the same time, a series of watersheds environmental and ecological issues are becoming increasingly prominent. Industrial construction and urban development pose great challenges to watershed resources. Water supply is difficult to meet water demand, water use gap is expanding; watershed ecological functions are drastically reduced, pollution is frequent, and the contradiction between people and river basins is prominent. Watershed development encounters bottlenecks and challenges.

The third stage is the development stage of modern civilization (also known as green civilization or ecological civilization) in the middle and late 20th century. Faced with the crisis caused by excessive development of the basin, people began to reflect and re-locate the relationship between humans and watersheds. People realize that it is obviously not advisable to blindly request and ignore the ecological balance. The

over-exploitation of natural laws will not only hinder the normal operation of the basin economy, but will even bring devastating disasters to the healthy development of the entire basin. At this point, the basin development path began to shift from focusing on human needs to the overall balance and harmonious development of the basin. Take the Colorado Basin in the United States as an example. Under the leadership of the federal government basin management agencies, cross-regional and inter-departmental cooperation mechanisms have gradually formed. The Water Quality and Environmental Protection Act has passed the camera, and all stakeholders have worked together and actively participated in river basin governance and sustainable development.

1.2.1 The development process of cascade hydropower

Humans first used hydropower to generate electricity around 1880. At that time, the Selmez sugar factory in France, the Lower House chemical factory in the United Kingdom, and the Korah mine in the United States established small-scale hydropower plants, mainly for driving by self-contained power. Around 1882, there were hydropower plants specialized in power supplying in the United States, Britain, France and other countries. Among them, the Abel hydropower station (10.5 kW installed) created by Edison in Wisconsin, USA is more famous. It is called the official representative of the birth of hydropower station. Since then, hydropower technology has spread around globally. Germany invented the first three-phase hydropower system in 1891, and in 1895 Australia built the first hydropower station in the southern hemisphere. In 1895, the Niagara Hydroelectric Power Station in New York, USA, installed power of 147,000 kilowatts, becoming the largest hydropower station in the world at that time.

In 1905, China built the Guishan Hydropower Station on the Xindianxi tributary

near Taipei, with an installed capacity of 600kilowatt. Since then, hydropower technology has rapidly spread to mainland China. The Yunnan Shilongba Hydropower Station started construction in August 1908 and generated power in May 1912, becoming the first hydropower station in mainland China. The initial installed capacity of the Shilongba Hydropower Station is 480 kW, and the current installed capacity has been expanded to 6,000 kW and is still in operating.

In the first 40 years of hydropower development, although the scale of the hydropower station has expanded rapidly and the installed capacity has increased significantly. However, all countries are in a state of single target, isolated power station development and independent management. In 1933, the United States first proposed the development of multi-objective cascade development in the development plan of the Tennessee River Basin and implemented it. Since then, the Cumberland River, the Missouri River, the Columbia River, the Colorado River, and the Arkansas River have been developed in accordance with the development of the Tennessee River. At the same time, the Soviet Union completed the cascade development plan for the Volga River in 1931-1934 and put it into practice. The second 40 years of hydropower development is an era of rapid development of cascade. Most of the developed countries have developed water energy as the focus of their national energy construction during this period.

Hydropower construction in developed countries has been moving towards a steady development since the 1970s, while some developing countries in Latin America began the climax of hydropower construction in the 1960s. In the last 30 years, Brazil and China have gradually developed into world leaders in the hydropower industry. The Itaipu Hydropower Station, built jointly by Brazil and Paraguay, started construction in 1975. The first unit was built in 1983. It was completed in 1991 with a total installed capacity of 14 million kilowatts. It is the second largest hydropower station in the world today. At present, judging by the installed capacity, the world's largest hydropower station is China's Three Gorges Hydropower Station. The power station started construction in 1994. The first unit was used for power generation in 2003. In 2012, all units were put into operation, with a total installed capacity of 22.5 million kilowatts.

The construction of hydropower projects has a history of more than 100 years. During this period, the attitude and demand of the society for hydropower projects have been constantly changing. The hydropower discipline itself has made considerable progress, which has a great impact on the planning, construction and operation of hydropower projects.

The first generation of the original hydropower station consisted of wooden water wheels, mainly used to provide mechanical kinetic energy. The first small single-function hydropower station was built around 1880, and the hydropower project that was subsequently built has more and more functions to make full use of the dam for irrigation, power generation, water supply and flood control. With the advancement of hydropower technology and the growth of power demand, the scale of hydropower projects is also expanding. The Great Coulee Project in the United States built in the mid-1930s was a milestone in hydropower development. Although the main purpose of the project was irrigation, a turbine group was installed to increase the economic benefits of the project. The modern milestone hydropower development project includes the Itaipu project in cooperation with Brazil-Paraguay and the Three Gorges Project in China.

After the Second World War, the pace of hydropower construction continued to accelerate, initially in developed countries and China. In the following 10-15 years, developing countries also accelerated the pace of hydropower construction. At present, most of the world's hydropower projects were built between 1955 and 1985. Subsequently, due to economic, environmental and social impacts, hydropower project construction activities have slowed significantly.

1.2.2 Cascade hydropower development and management model

Water resources have watershed characteristics, and the implementation of river basin development, utilization, treatment, protection, etc., is not only in line with the natural attributes of water resources, but also conducive to the efficient allocation and sustainable use of water resources, and promote the comprehensive development in economic and social of the river basin. In the process of hydropower development, countries pay more attention to the unified development and protection of river basins, set up river basin management institutions, pay attention to environmental protection, strengthen legislation and public participation. However, due to different national conditions, the hydropower development and management models have different focuses. The development of hydropower in the developed countries is higher, paying more attention to the impact on the ecological environment of the river basin during the development of hydropower, and formulating strict laws and regulations. The development speed of hydropower is relatively slow. In some developing countries, it is still in the stage of hydropower development, and the development speed is still in the acceleration, the hydropower development model is still in the stage of continuous development and improvement.

Hydropower development in developed countries in Europe and America is relatively early, and its hydropower management is relatively mature. However, different countries are affected by comprehensive factors such as geography, climate, politics and economy. Hydropower development and management have distinct characteristics. Here use Norway and the United States as examples.

Among the countries with rich water resources in the world, Norweigan hydropower companies have done a very prominent job in hydraulic development and operation management, and have accumulated rich experience. In terms of natural geography, Norway has a long and narrow terrain and many fjords along the coast. There are many locations with superior terrain to build reservoirs and regulate water storage. Within a short distance, high drop can be formed and the terrain conditions are superior. In terms of hydrometeorology, the Norwegian territory faces the Atlantic Ocean. Due to the influence of the humid air current, the rainfall in summer and autumn is not small, the snowfall in winter, the most rain and snow, the average annual precipitation can exceed 2400mm, and the water resources are very abundant. In terms of hydropower immigration, Norway is sparsely populated, and hydropower construction and various infrastructure constructions have fewer problems such as immigration and relocation, and the cost is much smaller. When planning the development of hydropower, Norway pays great attention to environmental protection, and minimizing the damage to the natural ecology, citing the glacial lakes on the plateau as much as possible, and refraining to build large dams along the river. In terms of underground engineering, Norway uses local good geological conditions to build underground works, namely tunnels and underground powerhouses. The total length of underground waterways in the country is more than 4,000km, and the underground powerhouses are more than 250, ranking first in the world. For hydropower development, Norway passed legislation in 1917 to clearly define water resources management responsibilities and powers. Government departments, water resources management associations, and power generation companies all perform their duties.At the same time, the law establishes a hydropower development permit system to ensure the state's ownership and development control of water resources, and maximize the use of water resources; For the development of watersheds, the implementation of unified planning of the entire basin has ensured the interests of all parties.

The hydropower management model of the Tennessee River in the United States is a successful example of integrated river basin development. Located in the southeastern United States, the Tennessee River is a secondary tributary of the Mississippi River, with a length of 1050km, a drainage area of 105,000 km2, and a land span of seven states. Originating in Virginia, it flows westward into the Ohio River, a tributary of the Mississippi River. The rainfall is abundant and the climate is mild. The annual precipitation is between 1100 and 1800mm. The average annual precipitation is 1320mm, and the terrain is undulating and the river bed is larger. Water resources are abundant. In order to comprehensively develop and manage the natural resources in the Tennessee Valley, the US Congress passed the Tennessee Valley Management Act in 1993 to establish the Tennessee Valley Authority (TVA). TVA is authorized to plan, develop, utilize and manage the natural resources of the Tennessee Valley in accordance with the law. In accordance with the guiding ideology of "Flood Prevention, Dredging Shipping, Power Generation, Controlling Erosion, Greening, Promoting and Encouraging the Use of Chemical Fertilizers, and Developing the Economy", TVA carried out unified planning for the whole basin and formulated a reasonable watershed development and construction procedure. TVA has a high level of internal coordination and clear division of labor.

At present, China's hydropower development is in the midst of a rapid development. China's hydropower resources are more concentrated in the main stream of large rivers. It is easy to establish a hydropower base to carry out strategic centralized development, which is conducive to the realization of river basins, cascades and rolling development, and is conducive to the construction of large-scale hydropower bases, which is conducive to giving full play to the scale benefits of water resources for Implementation of "West-to-East Power Transmission". The "watershed, cascade, rolling, integrated" hydropower development model that conforms to the laws of natural and social development has become the mainstream of hydropower development models for a long period of time, and has been increasingly valued and favored by governments, investors and owners at all levels.

The rolling development of water domain is based on the existing hydropower station as the mother body. The benefit of the parent power station is used to develop other power stations in the basin step by step. The comprehensive benefits of the related industries in the catchment basin are formed by the hydropower benefit as the leader to enhance the self-development of the enterprise. So as to achieve both development and protection, and achieve sustainable development of watershed resources.

Cascade rolling development of water domains requires overall planning of hydropower resources in the basin. According to the supply and demand situation of the power market, the law of hydropower construction and its economic rationality, the development plans for the near, medium and long term are formulated and arranged one by one to achieve a foothold. The power station ensures that a batch is being built, a batch is prepared, and a batch is reserved. It is conducive to ensuring the rational and sustainable development of the river basin resources, and has the development advantages of promoting the regional economy and the comprehensive optimization of water resources and resource sharing among the cascade hydropower stations.

1.2.3 Status of cascade hydropower development

The theoretical total amount of hydropower resources in the world is 43.6 trillion kW·h/year, the technology developable capacity is 15.8 trillion kW·h/year, and the economic developable amount is about 9.5 trillion kW·h/year. The distribution and development of world water resources are quite different. Asia's hydropower resources are the most abundant, accounting for about 40% of the theoretical reserves of global hydropower resources. Its developed hydropower resources account for about 21.1% of the technology developable and 35.2% of the economically exploitable. The development and utilization of hydropower resources in Europe and North America is relatively high, and the economic development degree is over 68%, while the technical development degree of African hydropower resources is only 7.7% and the economic development degree is only 12.3%. Compared with 2007, the global hydropower economic development rate has increased by 5 percentage points. The growth comes from Asia and Africa, but the overall pattern of global hydropower development has not changed.

Chart 2 World Hydropower Development Status

Area	Theoretical reserves of water energy	Technological Developable Quantity	Economic Developable Quantity	Hydropower installation	Generation capacity	Degree of Technological Development	Economic Development Degree
	One hundred million kW•h/year	One hundred million kW•h/year	One hundred million kW•h/year	Ten thousand kW	One hundred million kW•h/year	%	%
Africa	44315	15847	9963	2794	1225	7.7	12.3
Asia	199099	80423	48187	50965	16941	21.1	35.2
Oceania	6580	1850	887	1338	374	20.2	42.1
Euro	31291	12027	8453	18698	5768	48	68.2
North America	76001	19852	10512	17340	7082	35.7	67.4
South America	78884	28034	16768	14785	6758	24.1	40.3
World	436170	158030	94770	105920	38149	24.1	40.3
China	60830	25000	17530	28000	9116	36.5	52

Note: The data in the table comes from the <<World Atlas & Industrial Guide>>. There are 183 countries and regions with water energy information records, and the collected information is updated to 2013.

In 2018, the global installed capacity of hydropower is 21.8GW, and the total installed capacity of the world has reached 1,292GW. In 2018, the hydropower project reached a record 4,200 TWh. From the perspective of world hydropower development, East Asia and the Pacific region is the region with the highest annual growth rate of hydropower installed capacity; hydropower is the single largest source of renewable electricity in Europe; Africa is one of the regions with the greatest potential for hydropower development, and the installed capacity of new projects It is growing steadily; hydropower growth in North and Central America is relatively modest compared to other regions, but concerns about pumped storage projects are increasing.

China once again became the country with the largest installed capacity of hydropower in 2018. A total of 8.5 GW was put into operation, followed by Brazil (3.9 GW), Pakistan (2.5 GW), Turkey (1.1 GW) and Angola (0.7 GW). In 2018, Brazil's 1.1 GW Belo Monte integrated project in the northeast of the country was put into operation and has now surpassed the United States to become the second largest hydropower producer with installed capacity. However, China's growth rate is also slowing down. In 2017, China's new hydropower installed capacity was 9.1GW, and in 2016, new hydropower installed capacity was 11.7GW, compared with 19.4 GW in 2015. The drivers of hydropower growth are not only due to the general increase in electricity demand, but also because of the reliable, clean and affordable electricity sources that countries seek to achieve the carbon reduction targets set out in the Paris Agreement. The development of pumped storage means that hydropower is increasingly recognized for its role in supporting energy systems, especially its role in balancing unstable energy sources such as wind and solar.

The preparatory preparation for hydropower projects is receiving more and more attention. Hydropower risk management measures are being established to ensure that hydropower projects are constructed in suitable locations in a suitable way and achieve comprehensive benefits. Pumped storage systems are continuing to grow, and pumped storage not only provides energy storage, but also provides grid stabilization services. In 2018, the global newly added pumped storage capacity is 7.3 GW, bringing the total capacity of pumped storage in the world to 160.3 GW. In addition, innovative projects for renewable energy provide stable power to the grid. The concept of "Global Energy Internet" is one of the latest trends. The scale of regional interconnection and cross-continental interconnection enables renewable energy technologies to rapidly develop to meet global energy needs. As more and more hydropower assets have reached life expectancy, asset management is becoming a challenge in the hydropower industry. Digital hydropower stations, control systems and surrounding networks are emerging trends in optimizing and upgrading hydropower assets, and intelligent modernization and asset digitization continue to emerge. Climate change has both positive and negative impacts on the hydropower industry. Financing institutions aim to address climate-related risks through project planning and operations.

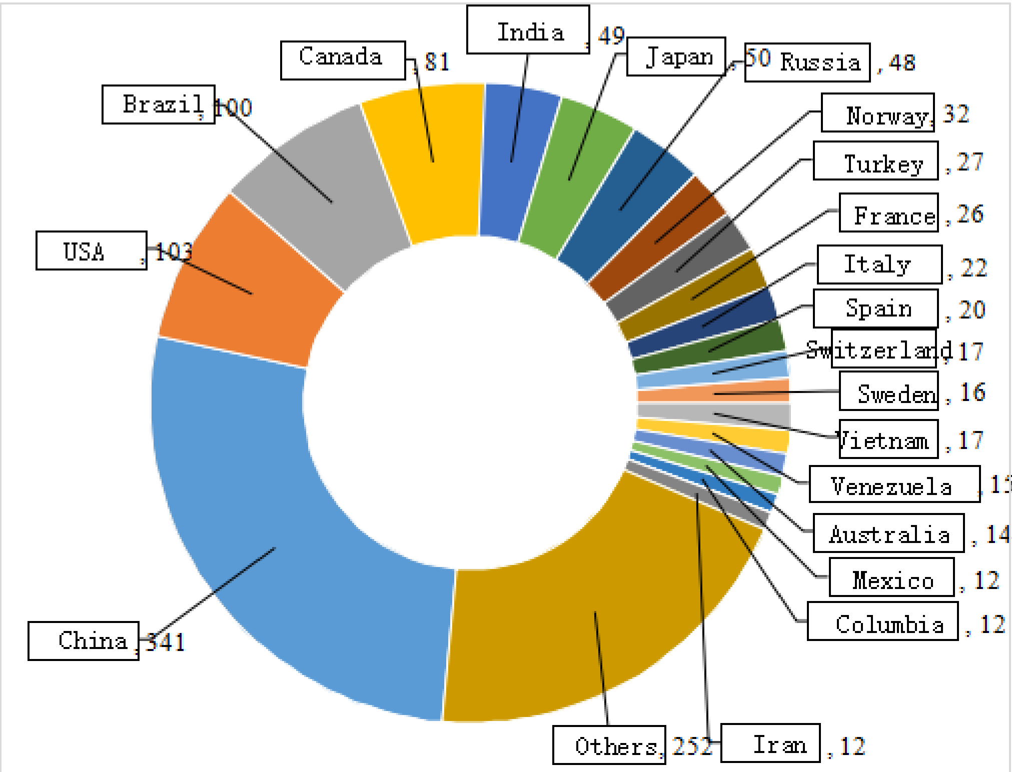

Figure 7 Global total installed capacity (GW) of hydropower by the end of 2017 (including pumping)

Human resources management has undergone supply management, technical water-saving management and structural water-saving management, and is moving towards social management. The river basin management system in the 21st century tends to be perfect, but it is still developing. International water resources development and protection also take the basin as a natural unit, and has experienced a transition path from one-way regional governance to integrated river basin management. Especially, the advocacy of integrated watershed management makes the legislative basis of watershed management related to ecology, management, economics, even philosophy and sociology. Among them, the concept of ecological sustainable protection, public participation and other concepts play a more important role in international watershed management.

The hydropower resources of China's rivers are 676 million kW, and the annual power generation is 592 billion kW·h. The installed capacity of hydropower resources is 378 million kW, and the annual power generation is 192 billion kW·h. Whether it is the reserves of hydropower resources or the hydropower resources that may be developed, China ranks first in the world. China's hydropower resources are abundant but the distribution is uneven. The total amount of developable hydropower in the Northeast, North China, and East China regions accounts for only 6% of the national total, the Central South region accounts for 15.5%, the Northwest Region accounts for 9.9%, and the Southwest Region accounts for the most, accounting for 67.8% of the country.

Since the reform and opening up, with the rapid growth of power demand and the continuous advancement of power system reform, the pace of China's hydropower development has accelerated significantly. Since 2003, China's hydropower has increased its annual scale by more than 10 million kW; in the 10 years from 2000 to 2010, it has surpassed the total of 50 years since the founding of the People's Republic of China. By the end of 2018, China's hydropower installed capacity was 350 million kW. The annual variation of China's hydropower installed capacity is shown in Figure 8.

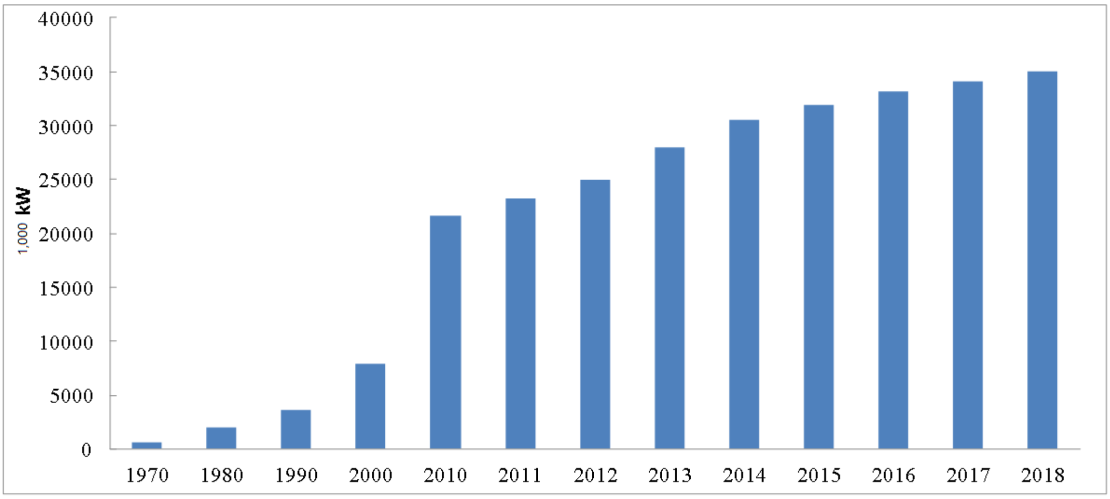

Figure 8 Interannual variation chart of installed capacity of hydropower plants in China

China's hydropower resources have the characteristics of local river sections or regional resources in geographical distribution, which is conducive to the formation of large-scale hydropower bases. China's hydropower resources are mainly distributed in the Yangtze River, the Yellow River, the Pearl River, the southwestern international rivers, the Yarlung Zangbo River and other major rivers in Tibet. The theoretical water energy reserves of the above-mentioned water systems account for 88.5% of the country's total, and the annual power generation of possible development resources accounts for 91.7% of the country. The distribution of water resources in China's river water resources is shown in Table 3. The possible development resources of these nine rivers account for 70.3% of the country. China has planned 13 hydropower bases: Jinsha River Hydropower Base, Yalong River Hydropower Base, Dadu River Hydropower Base, Wujiang Hydropower Base, Yangtze River Upper Hydropower Base, Nanpanjiang Hongshui River Hydropower Base, Lancang River Main Stream Hydropower Base, and Yellow River Upstream Hydropower Base The Yellow River Middle Reach Hydropower Base, Xiangxi Hydropower Base, Nujiang Hydropower Base, Fujian-Zhejiang-Sui Hydropower Base and Northeast Hydropower Base.

1.2.4 Prospects of Cascade hydropower development

Hydropower has been around for more than a century and has become one of the world's largest sources of clean and renewable electricity. In recent years, taking into account the impact of climate change on the limited resources of the earth, there are more and more concerns about environmental protection, and hydropower does have such problems. For example, the barrier lake may damage the growth environment of wild animals and plants. The dam may affect natural fish passages, hydropower operation may increase siltation, change water temperature and reduce dissolved oxygen levels. However, to some extent, these problems can be minimized by building artificial fish passes, dredging sludge, and fine-tuning hydropower operations management.On the plus side, hydropower is not polluted by burning minerals or fossil fuels, its source of electricity (flowing water) is clean, continuously renewable, and through snow and rainfall during the year or longer. cycle. Hydropower can also provide a range of additional benefits. For example, the Three Gorges Dam is not only an important flood control project in China, it also improves the natural waterway and increases the convenience of shipping. From a comprehensive perspective, hydropower is currently playing an active and beneficial role in various countries in the world. However, in the future, the development direction and prospects of hydropower will need to be explored in many aspects.

Hydropower is a reliable and effective renewable energy source. China is currently the world's largest producer of hydropower, and as one of the world's largest emitters of carbon dioxide, hydropower is an important clean energy source for China and plays a very important role in reducing emissions of polluting gases.

However, hydropower is not only widely used in China. According to statistics, hydropower stations all over the world produce about 16% of the total electricity, and hydropower generation in more than 60 countries exceeds half of the total. Although Norway is the largest oil and gas producer in Northern Europe, 90% of its power production comes from hydropower; more than 50% of energy-rich Canada, Brazil and Venezuela's electricity production comes from hydropower.

Potential for future development of hydropower. Hydropower is still one of the most mature and available renewable energy sources to date, and many countries build hydroelectric plants on natural rivers.

From a regional perspective, Africa is the region with the greatest potential for hydropower development. About 65% of the African population lives in areas or watersheds where hydropower can be developed. Currently, some African countries have begun to use hydropower as their main source of electricity, but there are still many Hydropower resources have not been developed and utilized, and hydropower has great potential for development in Africa.

From a global perspective, the technological potential of hydropower development around the world is far greater than actual production: the percentage of undeveloped potential hydropower capacity is 71% in Europe, 75% in North America, 79% in South America, 95% in Africa, and 95% in the Middle East. %, the Asia Pacific region is 82%. However, Western countries' policy constraints on hydropower development, third world economic development constraints, and lack of transmission systems have led to the concentration of most of the hydropower resources that can be developed and utilized in the Asia-Pacific region. In addition, hydropower potential has been tapped in some countries, and the growth space is small. For example, Switzerland has developed about 88% and Mexico has developed about 80%.

Comparison of hydropower and thermal power, nuclear power and wind power.

Compared with thermal power, hydropower eliminates pollutant emissions from fossil fuel combustion (including sulfur dioxide, nitrogen monoxide, carbon monoxide, dust and mercury), avoiding the hazards of coal mining and the indirect effects of coal emissions.

Compared with nuclear power, hydropower construction needs to change the large-scale environment, while the nuclear power plant has a small footprint, and the cost of immigration for hydropower is also very high. For example, in 1949, the United States purchased 94% of arable land for Aboriginal people for the construction of the Garrison Dam for $7.5 million. Although hydropower costs are higher, nuclear power is less flexible than hydropower. The cost of nuclear power is mainly due to its high infrastructure cost, so the cost per unit of energy increases significantly with the decrease of production. Therefore, nuclear power is mainly used for base load. In contrast, hydropower can provide peak power at a lower cost. Therefore, hydropower is often used to supplement nuclear or other sources for peak shaving, etc. In some countries, the ratio of hydropower and nuclear power is close to 50:50, including

Switzerland, Sweden, Ukraine and Finland.

Hydropower is compared to wind power. Wind can be seasonally predicted, but the actual wind cycle can be broken down into daily. The maximum wind power capacity has little to do with the daily peak power consumption. Wind power may peak on nights that do not require electricity, or disappear completely during the day when electricity demand is highest, and sometimes only low winds for days or weeks. Therefore, a hydropower station capable of storing water energy and converting it into electrical energy in time is very useful for balancing the power generation of the grid. When the wind power reaches its peak, it can be offset by the minimum hydropower, and the minimum wind energy can be offset by the maximum hydropower. In this way, easily adjustable hydroelectric characteristics are used to compensate for the intermittent nature of wind energy. Conversely, in some cases, wind can be used as spare water for later use in the dry season.

Future roadmap for hydropower. The US Department of Energy has highlighted five “action areas” that contribute to the vision of hydropower, namely: 1) Technological advancement: The development of innovative technologies will help reduce costs and increase electricity production efficiency and environmental benefits. 2) Sustainable development and operations: This includes a combination of environmental, social and economic factors to ensure the sustainable development of hydropower. 3) Increasing revenue and adjusting market structure: In view of the numerous energy production and grid support services provided by hydropower, appropriate compensation and incentives for new and existing hydropower are needed. 4) Optimize the regulatory process: This includes sharing watershed related data, sharing hydropower science management and scientific and technological progress, improving process efficiency and reducing risk and cost. 5) Strengthen cooperation, education and publicity: Different hydropower groups should actively share practical experience in maintaining, operating and building facilities, formulate professional curriculum plans, and strive to train new hydropower professionals to open the next hydropower era.

1.3 Overview of current status management of watershed cascade reservoir

International river basin management attaches great importance to the uniformity of river basins. In order to strengthen the unified management of river basins, many countries have established institutions related to river basin management. In the United States, Europe countries along the Rhine River, Australia and other countries established their river basin management agencies earlier, and their operating mechanism and system are relatively complete, with remarkable results.

At present, the comprehensive development and unified management of water resources by basin has been accepted and recommended by many international organizations, forming a trend. All world contries have established a basin water resources management system based on their own national conditions. Although the national river basin management model each equipped with its own characteristics, it shows common characteristics in integrated river basin management and has the following development trends: (1) The development and management of river basins develops from a single goal to a multi-objective, integrated development and management. (2) Gradually establishing and improving the management system combined with the unified management of the river basin and the administrative regional management, and separating the resource management from the development and utilization. (3) The prerequisite for achieving integrated management of river basin management is capacity building. (4) While giving the river basin management institutions a large administrative authority, they also gave corresponding autonomy. (5) The implementation of comprehensive watershed development and management must have the support of the state in policy. (6) A good watershed planning is the basis for integrated river basin management.

River basin management organizations can be divided into two categories, one is a watershed management organization established to solve the overall and comprehensive problems, such as the French River Basin Management Committee, the Spanish Basin Hydrographic Commission; one is to solve some special problems. The United States is a decentralized management of water resources. There is no unified water management agency at the central level, and currently three large water management agencies are set up to solve a specific problem, namely the Bureau of Reclamation, the Army Corps of Engineers and the Tennessee Valley, and the focus of management of each institution are different.

Due to the different historical and cultural traditions, political and economic systems, and specific river basins in different countries, there are both centralized and unified modes of cooperation in the organization of river basins. In general, although there is no optimal standard model for river basin management systems in various countries, there are also convergence trends in some aspects. The types of watershed management organizations can be divided into the following categories: (1) International treaty types, such as the European Union Water Resources Management, the Protection of the Rhine International Commission, and the Itaipu Water Management Committee. (2) Government-type institutions, one is a unified watershed management organization directly under the central government, such as the US Tennessee Valley Authority, and the other is a watershed management organization directly affiliated with different government management entities, such as the

Delaware River Basin Commission. (3) Institution-type management organizations with administrative management responsibilities. Such watershed management organizations are generally national-level watershed management organizations with basin organizations as the main body. China's hydropower development started late. With China's rapid growth in energy demand, hydropower development has developed rapidly. At present, the middle and upper reaches of the Yangtze River, the upper reaches of the Yellow River, the middle and lower reaches of the Jinsha River, the Minjiang River, the Nujiang River, the Yalong River, the Dadu River, the Hongshui River and other large hydropower development companies have been formed, and Watershed cascade scheduling or central control center have been established. The development of small and medium-sized water and current fields is showing a rapid development trend. The cascaded reservoirs in the river basin are mainly subordinate to different main bodies. At present, the dispatching operation management mode combining the special situation unified scheduling and the general situation decentralized scheduling is implemented, and the river basin unified dispatching is implemented on the flood control dispatching and emergency water quantity dispatching, and each reservoir management is implemented through unit decentralized scheduling in the operation management. How to efficiently manage the cascaded reservoirs in the basin and improve the comprehensive benefits of the cascaded reservoirs in the basin has become the top priority in the management of watershed cascade reservoir. In the process of implementing reservoir management, we can learn from the management experience of various river basins (reservoirs) and use the legal system, administration, economy, science and technology and other means to conduct comprehensive management according to law.

1.3.1 Watershed cascade reservoir management system

1）Management agency

In China, river basin cascade reservoir management institutions include administrative agencies and operational management agencies. The cascade reservoirs are mostly subordinate to different main bodies. At present, the dispatching operation management mode combining the special situation unified scheduling and the general situation decentralized scheduling is implemented, and the river basin unified dispatching is implemented on the flood control dispatching and emergency water quantity dispatching, and each reservoir management unit is implemented through decentralized scheduling in the operation management.

The administrative management of the reservoir is generally based on the hierarchical management of major functions such as water conservancy, power generation and water transport. In the flood control dispatching and emergency water dispatching, the water administrative department of the State Council, the river basin management agency, and the local water administrative departments at all levels shall implement the unified dispatch of the river basin, and in accordance with relevant laws and regulations, on the basis of meeting the needs of the reservoir for economic and social development. According to the safety requirements of the project, the public, and the environment, the reservoir shall be supervised and managed. The operation management organization, that is, the reservoir management unit established by the reservoir owner (legal person) is responsible for the implementation of engineering maintenance, execution of dispatching instructions and daily dispatch management.

2）Multi-party communication and coordination mechanism

At present, the National Defense and Water Resources Department of China has vigorously promoted the establishment and improvement of the unified dispatching system and mechanism of reservoirs from the national level and the river basin level.

Based on the laws, regulations, the existing flood control and drought-resistance command system, the National Defense General is the highest dispatching command and management organization. The flood control is the basin dispatching command center, and the provincial defense is responsible for the unified dispatching and commanding system of the reservoir group according to the jurisdiction. Coordinated consideration of flood control, water supply, power generation, shipping, ecological and other aspects, breaking the boundaries of industry sectors and the operation of a single reservoir alone, strengthening unified command and unified dispatch. Basin prevention Council has established a dispatching and consultation mechanism with relevant provincial and municipal anti-finger, reservoir management units, power grid companies, shipping management departments, etc, which is responsible for organizing, directing, coordinating and managing major problems encountered in the process in the unified dispatching of river basin reservoirs, In addition, with the reservoir management unit as the center, a coordination mechanism with the power grid company and the shipping department was established to coordinate the comprehensive utilization of the reservoir. Because there are many aspects involved and coordination is difficult, the multilateral communication and coordination mechanism for reservoir group scheduling is still being explored and improved.

3） Information sharing mechanism

Now, due to the accelerated pace of reservoir construction, the number of reservoirs is increasing, and the hydrology and interests between reservoirs are becoming more and more closely linked. In order to improving the forecasting accuracy of the cascade reservoirs, extending the forecasting period, reduce the management cost, making full use of the adjustment and compensation capacity of the reservoir group, and improving the comprehensive benefits of the cascade reservoirs, it is necessary to share the dispatching operation information of the reservoirs. It is absolutely necessary to establish a river basin management committee with each reservoir management unit as the main body, which coordinates and balances the interests of all parties and mobilize the regional polarity by multi-level, multi-sector coordination mechanism, interest compensation mechanism, information sharing and release mechanism.

The existing information sharing mechanism is mainly government-led and enterprise-executed, that is, the enterprise shares the operational information of the managed reservoirs according to the information sharing regulations formulated by the government, and accepts the shared information of all enterprises in the platform. At present, part of the operational information of some river basin reservoirs has been shared within a certain range, but the content is limited. The next step is to build an efficient and stable information sharing platform to strengthen information disclosure and share content.

According to the "13th Five-Year Plan" for hydropower development, China will promote the hydropower construction marketization, establish a coordination mechanism gradually for river basin development and operation management, and promote the establishment of a unified water price model and operation management mechanism for the basin in the next step.

Different from the current situation of multi-owners in cascade management of river basins in China, foreign river basins are generally managed by a single owner, such as the Rhone River Basin in France and the Tennessee Valley in the United States, which avoids problems of communication and coordination caused by the multi-head management, insufficient information sharing and the imperfect of benefits sharing mechanisms. From the scheduling management mode of major foreign hydropower companies, the resource dispatching management of hydropower production presents the trend of "basin-cross-basin-cross-large areas".

1.3.2 Management responsibility and authority division of cascade reservoirs in river basin

In China, the administrative responsibility for water conservancy, power generation, water transport, etc. of the cascade reservoirs in the basin is divided by the main functions of the reservoir group, which are respectively responsible by the relevant national ministries and commissions (the Ministry of Water Resources, the National Energy Administration, the Ministry of Transport, etc.), and the provinces (municipalities) are responsible for their respective regional management of the corresponding scope; State Grid and China Southern Power Grid are responsible for power dispatching and safety of hydropower stations in their respective regions. The watershed management institutions set up by the Ministry of Water Resources of the State Council in important rivers; the flood control and drought relief command institutions include the important river basins established by governments at all levels will be in line with the power grid, transportation, land and resources, fishery, and environmental departments to give instructions for flood control, water supply, ecology, shipping, emergency dispatch, etc and supervise implementation in accordance with the principle of hierarchical responsibility . Meanwhile, The Ministry of Water Resources is also responsible for drafting laws and regulations, rules and technical standards for the management of cascade reservoirs and supervising their implementation.

The reservoir operation management unit exercises the functions of dispatching, management and coordination in the aspects of reservoir dispatching, power generation dispatching, reservoir hub operation management and shipping coordination, uniformly accepting and executing the dispatching instructions of the administrative units with jurisdiction, and participating coordination and formulation of relevant professional dispatching schemes. With the continuous development of cascade rolling development of large and medium-sized river basin hydropower plants across the country, hydropower development companies in various river basins have successively established watershed cascade dispatching agencies and carry out scheduling management to pursue the largest overall comprehensive benefits of cascade hubs under the premise of meeting the grid requirements.

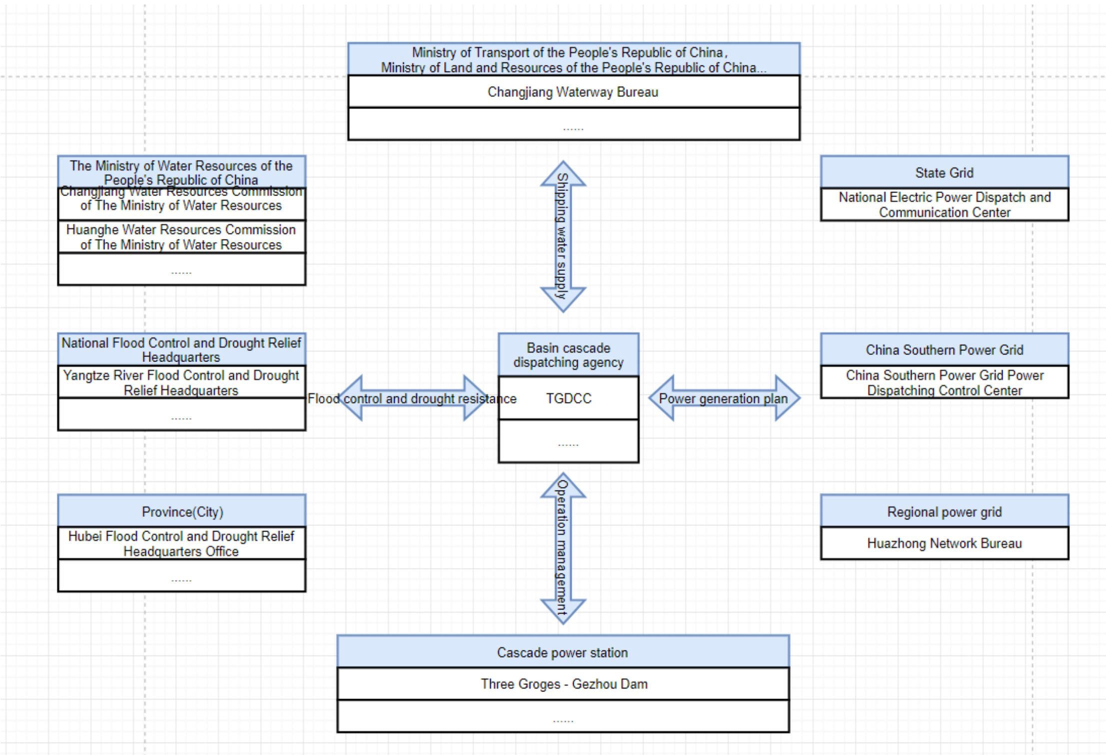

Figure 9 Reservoir group dispatching responsibility division map (taking the Three Gorges ladder as an example)

1.3.3 Technical support for river basin cascade reservoir scheduling decision

The Decision Support System (DSS) is an interactive computer system that supports decision-making activities through the combination of modern computer technology, simulation technology and information technology, and based on decision-related data, knowledge and models. The dispatch decision support system is an application system platform that specifically implements the forecasting and dispatching scheme of the cascade reservoir group and provides technical support for the decision-making and management departments. In the past ten years, the decision-making technology of cascaded reservoirs in the basin has also been gradually paid attention to, and the goals and scope of research and application are also increasing. The decision-making process of reservoir scheduling will also be gradually changed from traditional static figures and charts to dynamic simulations, previews, etc. The direction is developing, and it is required to realize human-computer interaction and provide an expert consultation platform to better realize the exchange of decision-making opinions, and form a complete solution from power station data entry to scheduling decision generation. Each business function module requires componentization and convenient transplantation.

The cascade hydropower stations in the river basin realize the unified centralized dispatching, operation and management of the cascade reservoirs through automation. The completion of the reservoir dispatching automation system centered on the cascade watershed mechanism enables the cascaded power plant operation management unit to grasp the rainwater information and the sudden flood situation of the entire cascade watershed in a timely and comprehensive manner, and make full use of the reservoir characteristics of the cascade hydropower stations on this basis. Considering the comprehensive needs of power generation, flood control, shipping, irrigation, etc., scientific and rational planning and scheduling can greatly explore the potential huge comprehensive benefits of cascade hydropower stations. On this basis, the scheduling decision support system is constructed to provide the functions of programming, scheduling, and decision making. From a technical point of view, with the continuous development of water regime measurement technology, computer application technology, communication technology and industrial control technology, as well as computer information processing and transmission, decision support system (DSS) and geographic information system (GIS) technology With the rapid development, the centralized control and automation of cascade power stations in various countries are getting higher and higher. All the work of cascade hydropower stations in the basin can be completed remotely in a centralized control center, and computer control is fully realized. The technical conditions for constructing decision support systems for cascade hydropower stations are becoming more mature. At present, the basins for the automatic dispatching system of cascade hydropower stations in China have the main stream of the upper reaches of the Yangtze River with the Three Gorges as the core, the Wujiang River Basin, the Lancang River Basin, and the Dadu River Basin, which have played a important role in the dispatching automation of the cascades and the safe and economic operation of the cascade hydropower stations.

The development of modern science and technology provides advanced means for basin (river) management. Some developed countries have entered the stage of network technology and simulation technology in river basin (river) management. High-tech means and technologies such as remote sensing (RS), data collection system (DCS), global positioning system (GPS), geographic information system (GIS), computer network and multimedia technology, and modern communication are widely used in water resources utilization, flood control and pollution. In the fields of prevention, water quality and quantity of water and desertification monitoring, the management of river basins (rivers) has entered the digital age, sharing data resources and making the management of river basins (rivers) more scientific.

In the past half century, the research and application of decision support systems has been very active, new concepts and new systems emerge in an endless stream, and water resources management decision support systems, the US Army Corps of Engineers (USACE), the French Electric Power Company (EDF), Quebec Hydropower, Canada The company (Hydro Quebec), the Danish Institute of Water Resources (DHI), and the Georgia Institute of Technology (GT) have successively developed different reservoir group joint scheduling models and engineering application systems. In recent years, with the rapid development of distributed architecture and cloud computing technology, the research of water resources management decision support system has turned more specialized, customized and efficient. The most representative research is model-driven based on cloud architecture platform (Model-driven) decision support system research. The model-driven decision support system focuses on various models and implements the main analysis functions of the system to provide decision support information.

1.3.4 River Basin Cascade Reservoir Management Problems and Deficiencies

Since the cascade reservoirs involve various regions and departments, the interests are very complicated. Countries are constantly looking for suitable models. The general trend is to emphasize the management system that is based on river basins and combined with national and local administrative supervision and coordination. At present, the problems and deficiencies in the management of cascaded reservoirs in the basin are as follows:

1）The basin reservoir group involves many operational management units and different stakeholders. In addition to the joint flood control, the power generation dispatching of each reservoir management unit is basically independent. This is not conducive to the comprehensive utilization of water resources and the overall benefits, but also to the protection of the upstream and downstream ecological environment of the dry tributaries.

2）In the management of reservoirs, it is necessary to coordinate the contradiction between the single reservoir dispatching target and the watershed dispatching target, the contradiction between ESC and water regulation, the contradiction between daily dispatch and emergency dispatch, the contradiction between domestic water and ecological water use, upper, middle and lower reaches reservoirs. Coordinate interests between different regions and different departments. At present, there is a lack of targeted and applicable joint management system, coordination mechanism, and supporting management methods, legal guarantees and compensation policy measures.

3）The operation and dispatch of the reservoir pays too much attention to economic and social benefits, lacks consideration of the ecological environment, and focuses on solving the problems of regional flood control, irrigation, power generation and shipping by engineering means. It is less considered for ecological environmental protection and is not conducive to river ecological health and Continue to develop.

4）Watershed cascade joint dispatching requirements Fully utilize the cascade compensation benefits of each cascade reservoir group, try to ensure that the reservoirs in the cascade cascades maintain high head operation, achieve the purpose of reducing water consumption and improving water utilization efficiency, and make the water resources of the basin fully available use. If each reservoir in the basin cascades is considered to be in the water storage and power generation production, it will not only cause some reservoirs to be in the low water head for a long time, but also may cause unnecessary water to be abandoned in some reservoirs, or flood peaks may occur, which seriously affects the watershed. Power generation benefits and flood control scheduling. Therefore, when carrying out reservoir dispatching work, the cascade reservoirs should be considered in a coordinated manner, and the peak-blocking and peak-breaking of the upstream reservoir or the leading reservoir should be used to realize the joint flood control and the beneficial dispatch of the cascade reservoirs in the basin. In the implementation of joint dispatch, the interests of various entities should be fully coordinated and a benefit compensation mechanism should be established.

5）The relationship between cascade hydropower station scheduling and power grid dispatch management, the establishment of cascade dispatching mechanism is a challenge to the current power grid dispatch management regulations, and the safety of power system is also crucial. Therefore, how to establish the relationship between cascade dispatch and grid dispatching the management relationship and clarification of their respective responsibilities and objectives in the operation of the power system are the most critical issues that need to be studied and resolved.

6）The sharing of cascade information resources in the basin, the cascade joint scheduling of the basin must be based on sufficient information such as cascade water conditions, comprehensive operational requirements, and unit maintenance plans. At present, the actual situation in most river basins in China is that the number of hydrological telemetry stations in the river basin is small, the coverage is limited, and there are still sites for repeated construction among different owners; in addition, the information collection and the caliber are inconsistent, and the main body of each cascade power station Different, mutual information cannot be used efficiently.

References:

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2 Management Model of Cascade Reservoirs

According to the distribution of cascade hydropower plants, cascade reservoirs can be divided into tandem reservoirs, parallel reservoirs and mixed cascade reservoirs.

1）Cascade (tandem) hydropower station group. This is a group of hydropower stations that are located in the upper and lower reaches of the same river. Under the operation of the same grid operation, there are not only electrical connections, but also runoff links and hydraulic connections. The runoff contact is reflected in the discharge of the upstream hydropower station as a component of the reservoir flow of the next-level hydropower station. The hydraulic linkage is mainly reflected in the utilization of the cascade head and the influence of the water level of the lower-level reservoir of the cascade hydropower station on the working head of the upper hydropower station.

2）Parallel hydropower stations. This is a group of hydropower stations located on different rivers or on different tributaries of the same river. There is no hydraulic connection between hydropower stations, but between the parallel hydropower stations on different tributaries of the same river, if it is necessary to jointly guarantee the tasks of some downstream water conservancy departments, such as flood control requirements, there are often water conservancy links.

3）Mixed hybrid hydropower station group. This is a more general form of hydropower station clustered in series and parallel on the same river and on different rivers. Some of these hydropower stations have hydraulic connections and some have electrical connections.

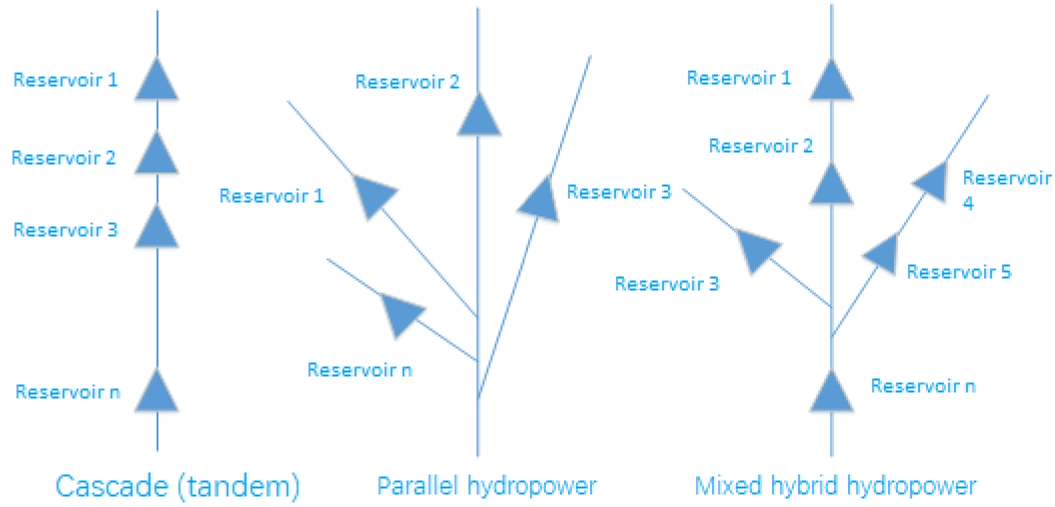

Figure 10 Reservoir group dispatching responsibility division map (taking the Three Gorges ladder as an example)

At present, there are more single tandem reservoirs and mixed reservoirs. The management models of two types of cascade reservoirs have their own characteristics in management system, coordination mechanism, information sharing and benefit distribution.

2.1 Management Mode of Tandem Reservoirs

The single tandem cascade reservoirs are distributed on the same river, and there are close hydraulic connections and runoff links between adjacent reservoirs. Due to the complexity of the river system, it is impossible for the river system to have only the main stream, so a single tandem cascade reservoir group does not exist in the strict sense. The single tandem cascade reservoirs described in this chapter are broadly defined as the case where large reservoirs are only distributed in the main stream and the tributaries are not large reservoirs (hydropower stations). In China, there are many single tandem cascade reservoirs in the broad sense, such as the Wujiang River Basin and the Yalong River Basin. In other countries, there are fewer large-scale hydropower projects in a single basin, and there is a nice distinction between the main stream reservoirs and the tributary reservoirs, and typical cases are few. Therefore, this chapter mainly deals with this type of reservoir group management model with a single tandem cascade reservoir group in China.

2.1.1 Dispatching and Operation Responsibility of Reservoir Group

2.1.1.1 Administration Management

According to its major functions like water conservancy, power generation, shipping and so on, the administration management of tandem reservoirs is regulated at different levels in general. As the dispatching objectives are relatively single or integrated into the entire basin, except for controlling reservoirs, the flood control and water resources management of other cascade reservoirs are generally in the charge of provincial or municipal flood control and drought relief agencies, power dispatching and safety are also generally in the charge of regional or provincial power grid. In accordance with the principle of grading management, the flood control and drought relief agencies would in conjunction with the departments like power grid, transportation, land resources, fishery and environment department, issue instructions such as flood control, water supply, ecology, shipping and emergency dispatching of cascade reservoirs, and monitor the implementation. The ministry of water resources is also responsible for the draft, supervision and implementation of laws, regulations and technical standards for cascade reservoirs.

2.1.1.2 Operation Management

The operation management department of tandem reservoirs is responsible for dispatching, management and coordination in the aspect of reservoir dispatching, power dispatching, reservoir operation management and shipping coordination. The operation management department accept and execute the dispatching instructions from the administrative unit with jurisdiction, also participate in the coordination and preparing of the relevant professional dispatching programs. With the continuous development and construction of large or medium-sized cascade hydropower stations, hydropower development companies in various river basins have successively established watershed cascade dispatching agencies to pursue the largest overall comprehensive benefits of cascade hubs. Under the safety requirement of the power grid, each cascade dispatching agency is responsible for the operation dispatching management of their own cascade reservoirs (hydropower stations).

The cascade reservoirs in Wujiang River Basin are typical tributary tandem reservoirs. They belongs to the first batch of cascades which implement rolling development and joint dispatching. The main targets of cascade integrated dispatching are flood control, power generation, shipping and ecology, etc. The Yangtze River

Flood Control and Drought Relief Headquarters is responsible for its administration management, the flood control and drought relief headquarters of Guizhou Province is responsible for flood dispatch, the power dispatching agency of Guizhou Province is responsible for power dispatch, and Guizhou Wujiang Hydropower Development Co., Ltd. is responsible for the operation management. Wujiang River cascade is the first river basin cascade which is developed and managed by the same one company. In May 2005, Wujiang Company set up the remote centralized control center. In 2009, the company achieve the centralized dispatching of all mainstream reservoirs, remote monitoring and control of hydropower units. The main function of the centralized control center is remote control of the cascade hydropower generating units, optimal operation of cascade hydropower station, it is also responsible for centralized dispatching and management of cascade reservoirs to protect the comprehensive benefits of reservoirs.

2.1.2 Dispatching and Coordination Mechanism of Reservoirs

In the dispatching management, the tandem reservoirs follow the principles below:

Principle of giving priority to the overall situation and the public interest. In the coordination of flood control, drought resistance, power generation, irrigation, water supply, shipping and ecology, priority should be given to the public and overall interests, the local interests are subject to the overall interests, and the interests of individual reservoirs are subject to the overall interests of the cascade reservoirs.

Principle of maximum benefit. On the premise of ensuring the realization of the public welfare dispatching goal, we should fully consider and keep the realization of the benefit target of each reservoir as far as possible. Social and economic efficiency should also be taken into account in public service scheduling, and the effect of public service dispatch should be comprehensively evaluated. It is necessary to set up the adjustment conditions for the joint public welfare dispatching, and only when the comprehensive benefit of the joint operation is obviously greater than the single operation of the reservoir, can the joint operation be started.

Principle of information sharing. The hydraulic connection between the adjacent reservoirs of single tandem reservoir group is extremely close, and the construction of reasonable, scientific, efficient and stable information sharing mechanism will help to improve the overall coordination of the operation of single cascade reservoir group. Improve the comprehensive benefits of cascade reservoirs.

Principle of risk sharing. The joint operation of reservoirs can bring huge comprehensive benefits, and it may also make some reservoirs bear more social responsibility or bear part of the benefit loss. In the process of coordination, the principle of benefit sharing and risk sharing should be adhered to ensure that all stakeholders participating in the joint regulation of reservoirs share the benefits of the joint regulation of reservoirs and take risks together. For example, in the process of joint operation, some controlled reservoirs with strong regulating capacity can achieve greater efficiency in flood control, power generation and water supply in downstream areas or reservoirs by adjusting storage and drainage schemes. Due to the change of operation rules, the benefit reservoir or the benefit area should be given some economic compensation to the responsible reservoir or benefit damaged reservoir.

2.1.3 Information Sharing mechanism between cascade reservoirs

At present, the typical tandem power stations in the single series watershed in China include those in Wujiang River Basin, Jialing River Basin, Yalong River Basin, Dadu River Basin, Jinsha River Basin and so on. Among these typical cascade power stations, the main development bodies of some river basins are relatively uniform. For example, the Yalong River Basin, Yalong River Basin Hydropower Development Company has relatively complete operation and management authority over the cascade hydropower stations in the basin. The unified management and dispatch of cascade power stations in Yalong River basin are realized by establishing the cascade central control center. In some river basins, the main bodies of cascade hydropower stations are different, and the operation and management units are diversified. For example, in the Wujiang River Basin, Guizhou Wujiang Hydropower Development Co., Ltd. (referred to as Wujiang Company) acts as the owner of ten power stations, like Puding, Hongjiadu, Yinzidu, Suofengying, are responsible for the operation and management of the ten cascade power stations in the river basin. Wujiang Company has established the remote centralized control center of the hydropower stations to carry out the unified management and dispatch of the ten cascaded power stations. While, the last two power stations in the Wujiang River Basin,Peng Shui and Yinpan Power Station is developed by Datang Electric Power Company, and Datang International Power Generation Co., Ltd. is responsible for the operation and management of these two power stations.

In the practical management of cascade hydropower stations, the cascade hydropower stations with unified operation and management units carry out unified information collection and dispatch coordination through the centralized control center, and the information communication among the cascade power stations is smooth, so that the cascade power stations can be operated in a more efficient way. Give full play to the comprehensive benefits of cascade power stations.

For cascade hydropower stations with multiple operating departments, the downstream power station's dispatching decision is highly dependent on the flow information provided by upstream power stations, and the importance of information sharing is prominent. The information sharing of cascade power stations is generally carried out through the following ways:

1) The watershed management organization builds the information sharing platform. For example, in the upper reaches of the Yangtze River, the Yangtze River Commission has set up a platform for information sharing of reservoirs in the upper reaches of the Yangtze River, which includes the shared information of water regime and water level of 28 reservoirs. In the actual dispatching process, the downstream cascade power station can query the upstream cascade power station storage and discharge information through the information sharing platform.

2) Meteorological department. The operation management department of power station signs an agreement with the department with meteorological forecast qualification to obtain the relevant regional meteorological forecast information.

3) Hydrological department. The operation and management departments of cascade hydropower stations in the lower reaches of the basin build their own hydrologic station networks or sign long-term agreements with local hydrological authorities to obtain hydrological station data of hydrological departments.

4) Communication and coordination between departments. In practical dispatching, the operation and management departments of upstream and downstream cascade power stations, as the direct stakeholders, often exchange and

share information through communication and coordination among departments.

5) Power system planning information sharing. The Southern Power Grid provides a platform for the sharing of planning information for hydropower stations within its jurisdiction, and the power stations can obtain the power generation planning information of the cascade power stations in the basin through the power grid system.

6）Construction of communication platform between owners. On December 12, 2002, with the approval of the China Hydropower Engineering Society, the cascade dispatching and control committee initiated by 25 power generation companies and research institutes was formally established in Beijing. The establishment of the Institute provides a platform for the exchange and sharing of information, experience and technology for promoting the construction of cascade dispatching and control institutions in Chinese watershed power generation companies.

The information sharing of cascade hydropower stations in a single series river basin is usually combined by the above six modes. Taking the Wujiang River Basin as an example, Pengshui and Yinpan, two hydropower stations operated and managed by the centralized control center of Datang Chongqing Branch, are located at the last two stages of the cascade hydropower stations in the Wujiang River basin, and their operation is affected by the regulation and storage of the upstream hydropower stations (the operation and management of the Wujiang centralized control center). In order to make efficient use of water resources, the centralized control center of Datang Chongqing Branch has set up a more sufficient information sharing mechanism with the upstream. First is to obtain the information by automatic hydrological forecasting, such as the hourly water level, the discharge of the reservoir, the area rainfall of the reservoir and so on in the power station above Goupitan, and for the station below the Goupitan,it also includes the information of the interval rainfall station in addition to the water level of the power station. Second is the reservoir operation information, the Wujiang centralized control center regularly sends the week and month power generation plan of Shatuo power station to the Datang Chongqing branch centralized control center. Third is the daily communication, upstream and downstream centralized control center has established the water situation sharing communication group, Since 2012, the State Energy Administration of Central China Administration has organized a coordination committee for the joint optimal dispatching of Wujiang cascade power stations every year, which further promotes the information sharing and scheduling coordination mechanism.

At present, the information sharing mode of single cascade reservoirs in China is mature, which can effectively serve the comprehensive utilization needs of cascade reservoirs in river basin, such as electricity production, flood control operation, water resources dispatching and so on. However, the shared information is generally confined to the category of real-time hydrological information, and the frequency of sharing is low. As the key production information of power station, the power generation planning information is highly private. Unless the power grid system constructs the relevant information transmission channel, the generation plan is often not transmitted as a shared information. The real-time hydrologic information provides a certain reference for the decision making of downstream cascade power stations, and improves the whole dispatching level and efficiency of cascade hydropower stations in the multi-unit environment. But the real-time hydrologic information limits the forecast period of the downstream cascade power station, and hinders the downstream cascade power station to make the optimal dispatching decision in the longer dispatching period. Further opening the information sharing, constructing a more stable and smooth information transmission channel, combining with the actual situation of cascade power station dispatching, expanding the type of information sharing and improving the quality of shared information, is of great significance for the joint dispatch of cascade hydropower stations in the river basin.

2.1.4 Benefit sharing Mechanism of Cascade Reservoirs

There are many stakeholders involved in the actual operation and dispatch of cascade hydropower stations in river basins, mainly involves the functional stakeholders derived from the comprehensive utilization requirements and the owners' stakeholders caused by the operation management authority.

1)The functional stakeholders

With the gradual development of economy and society, the comprehensive utilization requirements of cascade hydropower stations are getting higher and higher. In addition to flood control, power generation, shipping and other conventional requirements like the ecological dispatching, water environmental protection and other needs have gradually been taken seriously. The stakeholders mainly refer to the power grid system, water dispatching facilities and reservoir operation departments. The main interests of the power grid system are the requirements of the high generation guarantee rate, good regulation, power generation stability and bearing more ancillary services tasks. The interests of water dispatching facilities are the requirements of the water safety (flood control, water supply, irrigation, shipping and ecological environment protection) of cascade reservoirs within the cascade (or region). Then the interests of reservoirs operation departments are the requirements of the maximum operation benefits (like power generation benefit) of reservoirs under the premise of the reservoirs security.

In the dispatching regulations of hydropower stations, the overall regulation and coordination of the interests of all parties has been carried out in accordance with the comprehensive utilization requirements, and the priority of various needs has been stipulated. In the actual dispatching process, when the interests of several parties are in conflict, the relevant management agency shall coordinate and deal with it in accordance with the relevant laws and the requirements of the dispatching regulations. Taking the middle reaches of the Jinsha River as an example, the main targets of six power stations in the middle reaches of the Jinsha River are power generation and flood control. These six hydropower stations are all included in the scope of flood control and unified water dispatch for the upper and middle reaches of the Yangtze River. During the flood season, when floods happened, the cascade reservoirs in the middle reaches of the Jinsha River will conduct joint flood control operations in accordance with the Yangtze River Flood Control and Drought Relief Headquarters to reduce output and block floods. This is in contradiction with the huge power demand of power grid system in the summer. Power grid side, operation management side, and other comprehensive utilization needs institutions under the premise of the requirements of flood control, coordinated cascade operation mode, taking into account all aspects of demand.

2)The owners' stakeholders

The operation management department diversifies the single cascade reservoirs from the management level. The parties have their own positions in the dispatching decision, and aim at maximizing the benefit of owner party. This is contradictory with the extremely close hydraulic connection of cascade hydropower stations. In the actual dispatching process, it often through the construction of the multi-party coordination mechanism of competent departments and the owners to deal with the conflict of the interests. In China,the distribution of benefits is still in the early stage of exploration.

2.2 The management model of mixed or cross regional cascade reservoirs

2.2.1 The allocation of responsibility in reservoir group operation and management

The mixed or trans regional cascade reservoir group (hereinafter referred to as " mixed reservoir group") is a series of tandem and parallel reservoirs. Generally, the mixed reservoir group is developed by multiple owners. For example, in China, the operation and management mode of combining unified dispatch under special conditions with decentralized dispatch under general conditions is implemented. Unified river basin dispatch is implemented in flood control and emergency water quantity dispatch, whereas decentralized dispatch of each owner is implemented in reservoir operation and management. The unified dispatch is in the charge of administrative agencies, including the water administrative department of the State Council, river basin management agencies and local water administrative departments at all levels. According to relevant laws and regulations, on the basis of meeting the needs of economic and social development for the reservoir, and in accordance with the safety requirements of the project, the public and the environment, the administrative agencies supervise and manage the reservoirs. All administrative agencies are equipped with flood control and Drought Relief Commanding organs to organize flood control work and issue dispatch instructions during flood season. Decentralized dispatch is the responsibility of the operation and management agency, set up by the reservoir owner (legal person), to implement project maintenance, execute dispatch instructions and daily dispatch management. Refer to Figure 2-2 for the responsibilities of reservoir group dispatch and management.

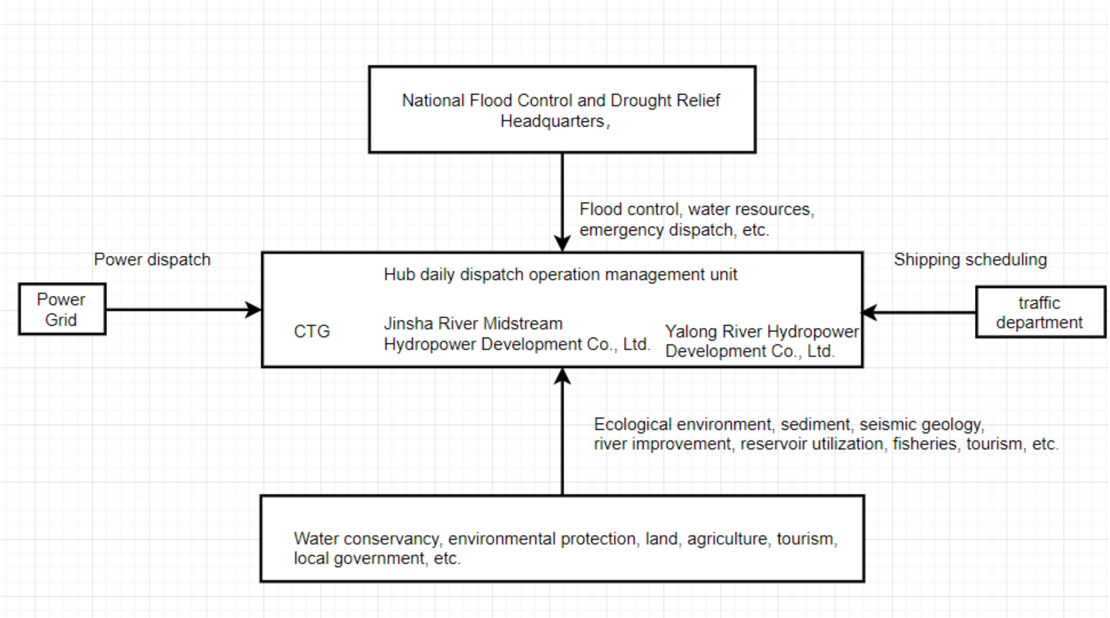

Figure 2-2 Reservoir group dispatch responsibility division map (taking the Three Gorges Corporation as an example)

The mixed reservoir group in upper reaches of Yangtze River is the most typical and complex reservoir group in China, among which 21 large-scale reservoirs have initially implemented joint operation. The 21-reservoir group includes Liyuan, AHai, Jinanqiao ,Longkaikou, Ludila, Guanyinyan, Xiluodu, and Xiangjiaba in Jinsha river, Jinping and Ertan in Yalong River, Zipingpu and Pubugou in Minjiang river, Bikou, Baozhusi, Tingzikou and Caojie in Jialing river, Goupitan, Silin, Shatuo and Pengshui in Wujiang river; Three Gorges on the main stream of Yangtze River,etc. The reservoir group in the upper reaches of the Yangtze River crosses Yunnan, Sichuan, Guizhou, Hubei, Gansu, Chongqing and other provinces (cities). The joint operation aims at coordinating the flood control and water volume regulation relationship between the rivers where the reservoirs (including hydropower stations and navigation power hubs) are located, and the middle and lower reaches of the Yangtze River. In case of large flood, the reservoir group can play an important role in flood control of the Yangtze River Basin. When comes to late flood season or after it, an orderly and gradual water storage plan will be carried out to improve the overall storage rate of the reservoir group, while minimizing the adverse effects of centralized water storage on the lower reaches of the reservoir, as well as the middle and lower reaches of the Yangtze River.

Moreover, joint operation can effectively cope with such emergencies as water shortage, water pollution, water safety accidents, wading project accidents, etc., and greatly mitigate the losses caused by disasters.

The mixed reservoir group dispatch on the upstream of the Yangtze river is classified managed by State Flood control and Drought relief Headquarters (hereinafter referred to briefly as "SFDH"), Yangtze River Flood control and Drought relief Headquarters (hereinafter referred to briefly as "YRFDH"), Provincial (municipal) Flood control and Drought relief Headquarters (hereinafter referred to briefly as "PFDH"), Reservoir management agency, etc.. The former three are administrative units, being in charge of flood control, and are superior organizations of reservoir management agency. The Reservoir management agency include a dozen different proprietors ,such as China Three Gorges Corporation, Jinsha River middle reaches Hydropower Development Co., Ltd., DaDu River Hydropower Development Co.,Ltd., Yalong River Hydropower Development Co.,Ltd., Guizhou Wujiang Hydropower Development Co.,Ltd., etc.. As to the reservoir with comprehensive utilization tasks, its management department consists of power grid dispatch department, shipping department, environmental protection department ,who proposed the demand of power generation, shipping, ecological water supply ,etc.. Among them, the power grid dispatch department is the superior power generation dispatching organization of the Reservoir management agency.

When a heavy flood occurs in flood season or a severe drought occurs in a drought year in middle-lower reaches of Yangtze River, the joint dispatch is operated by YRFDH for the full use of flood control capacity of the controlled reservoir group and the emergency replenishment caused by the water shortage. PFDH and Reservoir management agency do the dispatching at other times, according to the requirements of the comprehensive utilization of the project and the demand of the power system, to realize the maximum benefits of power generation of the project.

The specific dispatching authority is as follows:

1) When the water level of the reservoir is not higher than the limited water level of flood control, and it does not need to undertake the flood control task in flood season, or when the relevant parties have no special requirements for the discharge of the

reservoir in other seasons, the reservoir is managed by the reservoir management agency. Whereas when the reservoir undertake the task of flood control, the reservoir management agency operates the reservoir according to the approved dispatching plan or dispatching instructions.

2) When the influence scope of flood control only relates to the province (city) where the reservoir is located, the PFDH takes the responsible of reservoir dispatching and reports the dispatch process to the YRFDH for the record.

3) When the Three Gorges reservoir needs the cooperation of upstream reservoirs for flood control or the flood control dispatch may affect two provincial-level administrative region, the reservoir should be dispatched by the YRFDH.

4) The SFDH is responsible for the organization, coordination, guidance and supervision of joint dispatch of the reservoir group.

5) The water storage dispatch in late flood season is the responsibility of the flood control and drought relief command organization. The reservoir management agencies compile annual water storage plans according to the situation of flood control, the rainfall prediction and the impounding scheme of reservoir group mentioned above, and implement the plans after the approval of YRFDH. But the annual water storage plan of Three Gorges reservoir must be approved by SFDH in particular.

6) The emergency dispatching plan should be proposed by reservoir management agency and implemented after being approved by the flood control and drought relief command organization with dispatch authority.

7) The power generation plan should be proposed by the reservoir management agency and implemented after being approved by the power grid dispatch department.

2.2.2 Multilateral communication and coordination mechanism of reservoir group dispatch

In the reservoir group dispatch, it is essential to coordinate the contradiction between the dispatch objective of a single reservoir and reservoir group of a river basin, between the power dispatch and water dispatch, between the normal dispatch and emergency dispatch, between the domestic water usage and ecological water usage, between the interests among different regions or the departments on the upstream, midstream and downstream reservoirs. Therefore, how to balance the interests of all parties and mobilize their enthusiasm has become particularly important. In order to ensure the smooth implementation of the joint dispatch, a good coordination mechanism and platform are needed.

At present, the SFDH and the Ministry of Water Resources are vigorously promoting the establishment and improvement of reservoir group dispatch mechanism from the national and watershed level. According to laws and regulations, based on the existed flood control and drought relief command system, a unified dispatch command system is established, of which the SFDH is the highest dispatch management institution, while the watershed Flood Control Headquarters are the watershed dispatch center and the PFDH take their responsibility in accordance with the jurisdiction. Considering the demand of flood control, water supply, power generation, shipping, ecology, etc., this system breaks the boundaries among departments, changes the single reservoir dispatch situation and strengthens the unified command and unified dispatch. The watershed Flood Control Headquarter unites some of the provincial flood control headquarters, the reservoir management departments, the power grid corporations, the shipping management departments and so on, to establish a dispatching coordination mechanism, which is not only responsible for the organization, command, coordination and management of reservoir group dispatch, but also coordinates and solves the contradictions. In addition, with the reservoir management departments as the main organizer, a coordination mechanism has been established by combining the power grid corporations and the shipping departments, to coordinate the comprehensive utilization of the reservoir.

However, reservoir group have various owners and their management is mostly decentralized, each party' s interests are concerned in the implementation of joint dispatch, as well as the coordination problems between public welfare dispatch objectives (such as flood control, emergency water supply, ecology etc.) and power dispatch. At present, the targeted and applicable coordination mechanism, supporting management measures, legal protection and compensation measures are still deficient, multilateral communication and coordination mechanism of reservoir group is still in continuous exploration and improvement.

In terms of dispatch coordination of the reservoir group in the upper reaches of the

Yangtze River, for the smooth implementation of flood control, drought control and emergency dispatch, and in order to define the dispatch objectives, contents, conditions, subjects, supervision of the dispatch process, the division of responsibilities and rights of the parties involved, multilateral communication and coordination mechanism of reservoir group dispatch is established by the departments of water conservancy, electric power, transportation and reservoir management, it has a good effect on the coordination and guidance for the major issues during unified dispatch process. In the future, it is necessary to bring more water related departments into the coordination mechanism, so as to increase the relevant powers, balance the needs and strengthen the coordination effects.

The centralized control center of Wujiang company and Qianyuan company have implemented multi-objective dispatch management of multi-objectives collaborative optimization since 2013.

Through the multi-objectives collaborative optimization management of the two-level power dispatch organizations (Southern Power Dispatching Center and Guizhou Dispatching Center), three flood control and drought relief command organizations (Changjiang Water Resources Commission of the Ministry of Water Resources, Pearl River Water Resources Commission of the Ministry of Water Resources and Guizhou Provincial Hydrographic Bureau), Wujiang company and Qianyuan company, taking advantage of the differences in basin characteristics and the scope and authority of dispatch agencies to ensure safety and overall consideration, the goal of "balanced and complementary in dry season and risk coordination in flood season" for Wujiang and Beipanjiang rivers is established, and the utilization efficiency of water resources is improved through inter basin joint dispatch, so as to ensure the maximum overall benefit of Hydropower of Huadian enterprises in Guizhou.

2.2.3 The information sharing mechanism in cross-region, upstream and downstream reservoir group

Cross-region, mixed reservoirs are generally located in large watershed with developed water systems and complex runoff characteristics. The reservoirs undertake the functions of flood control, power generation, navigation, irrigation and so on. Take the upper reaches of the Yangtze River as an example, there are 4 tributaries whose watershed area is more than 80000 km^2, each of them has a large annual runoff above 49 billion m^3, there are 285 large sized reservoirs (whose total capacity are more than 100 million m^3), most of them undertake the comprehensive utilization functions. In order to improve the inflow prediction accuracy, extend the forecast period, reduce the cost of management, and give full play to the compensation ability and improve the comprehensive benefits, it is essential to share the dispatch information of the mixed reservoirs.

Cross-region, mixed reservoirs belong to various owners, located in different regions, and their hydraulic and power connections are less close than tandem reservoirs. Therefore, part of the mixed reservoirs, especially the reservoirs in the upstream of the watershed, their owners are not active in the promotion of information sharing; on the other hand, the information sharing mechanism of reservoir group is still not so perfect. All these factors affect the development of information sharing to a certain extent.

At present, under the promotion of government departments, some achievements have been gained in the reservoir group information sharing in some watersheds. For example, from the beginning of 2014, the Yangtze River Flood Control Headquarter organized the construction of the reservoir group information sharing system for the reservoirs in the upper reaches of the Yangtze River, and issued *the Regulation of Information Sharing about the Large Sized Reservoirs in the Yangtze River (Trial*). Now, the information sharing system has been put into trial operation, 21 large sized reservoirs were involved, and realized the basic information sharing of reservoir dispatch, which plays an important role in flood control, water compensate and other aspects. However, as to the accomplishment of overall information sharing in reservoir group and the optimal allocation of resources, there is still a long way to go, so it is necessary to combine the current situation of reservoir group development and management, and base on the existing information sharing mechanism, so as to establish a comprehensive, open, mutual information sharing model.

2.2.3.1 Government—leader，enterprise—executor

As the cascade reservoir have multiple owners who pay different degrees of attention to the information sharing system. Also, some electricity enterprises located in the upstream resist the information sharing of reservoir operation for their own benefits. Therefore, information sharing will meet great resistance and cannot be fully realized if the sharing work is only promoted by enterprises. But the government, who has no private interests, can promote the work of information sharing in reservoir group operation with administrative measures, to achieve watershed comprehensive benefits. According to the information sharing rules set by the government, the hydropower enterprise shares the reservoir operation information of their own and accepts the operation information from the other enterprises. The government and the hydropower enterprises co-construction the information sharing platform, on which they could uploaded and query the information about flood control, navigation, reservoir operation, rainfall, electricity and other related data timely.

2.2.3.2 Information disclosure, Comprehensive sharing

At present, relying on the effects of YRFDH and the support of companies, some reservoir group operation information in the upper reaches of Yangtze River has been shared to a certain extent. But the information sharing is not comprehensive, and only include information such as reservoirs real-time water level, reservoir inflow and reservoir outflow. Furthermore, the information which has greater influence on forecast and dispatching of cascade reservoirs, such as flood forecast, runoff, scheduling plan, etc., has not been shared. Therefore, in order to give full play to the basin comprehensive benefits of cascade reservoirs, it is necessary to expand the scope of information sharing and achieve the overall sharing of information.

2.2.3.3 Platform co-construction and costs sharing

In order to guarantee the timely and accurate transmission of the information to each participating enterprise, the government and enterprises should co-construct an information sharing platform, which can help them get the reservoir scheduling information. Due to the government (mainly social benefits) and all enterprises that participate in information sharing can obtain benefits from the platform, it is reasonable to share the costs of platform construction according to the amount of information and benefits that these platform builders obtain. Considering that the government mainly obtain social benefits instead of economic benefits, the platform construction cost is mainly borne by the enterprises.

2.2.4 The benefits sharing in cross-region, upstream and downstream reservoir group

Reservoir group belong to various owners, and is managed dispersedly. Joint dispatch will definitely change the ways of reservoir operation. Involving the interests of all parties, joint dispatch is also related to the coordination of interests among flood control, power generation, navigation, water supply, ecology and other scheduling objectives. At present, the coordination and compensation in multi-owner and multi-objective are still being researched. The supporting management measures and coordination mechanisms are needed urgently to match the multi-developer model.

Reservoir group operation will increase social and economic benefits. The social benefits have been directly shared by the public and don't need to be redistributed. Whereas the economic benefits are mainly obtained from power generation by information sharing and joint dispatching in reservoir group. Admitting that joint dispatch could increase the total electricity generation in the whole basin, but the power generation in certain parts of reservoir group will be affected. Therefore, the allocation of additional benefits should follow the "sharing resources and sharing interests" principle. In the distribution of additional power generation benefits, the certain parts of reservoir group mentioned above should be given priority to make up their reduced benefits. And then the remaining additional benefits should be distributed to hydropower stations according to the amount of their contributions to the joint dispatch, so as to achieve economic benefits sharing. The specific distribution of benefits is as follows:

1) Estimation of additional benefits: First of all, calculating the power generation revenue of each hydropower when it is operated independently. Furthermore, according to the " retreat more fill less " principle and based on the calculated income , if the actual generating income of individual hydropower station in joint operation is higher than the calculated income, the higher part of income is taken as the additional benefits; Whereas if the actual income is lower than the calculated income, the loss should be compensated from the additional benefits, making the actual income equal with the profit on a separate operation. Then the residual benefit is the additional benefit of reservoir group operation.

2) Allocation of additional benefits: Based on the principle of “sharing interests”, the additional benefits should be allocated according to the proportion of the individual reservoir regulation capacity to the total reservoir regulation capacity, the proportion of individual power generation capacity in design to the total design capacity in multi-hydropower station, the proportion of the generating capacity in individual station to the total power generation in multi-hydropower station, and the proportion of installed capacity in individual power station to the total installed capacity in multi-hydropower station.

2.2.5 The mixed or cross-region cascade reservoirs management mode in the worldwide

At present, the management mode of mixed or cross regional cascade reservoirs in foreign countries is generally different from the management mode of multiple owners in China, who are responsible for their own reservoirs. Foreign river basins are generally operated and managed by a single owner, which avoids the problems of difficult communication and coordination, inadequate information sharing and imperfect benefit sharing mechanism brought by China's multi management. For example, in France, except for the relatively independent pilot project of power station construction and production management in the Rhone River Basin, the other power plants are under unified operation and management by region. The United States has established a special basin management agency to manage the cascade reservoirs in the basin. For example, in Tennessee basin, through the establishment of the Basin Management Bureau, 50 reservoirs in 7 southeast states are managed. In Canada, Quebec hydropower company is responsible for the unified operation and management of multi basin cascade reservoirs, including the St. Lawrence River, Lagrange River, St. Morris River and other 8 major water systems, with a total of 51 hydropower stations. From the dispatch management mode of major foreign hydropower companies, the development trend of hydropower resources dispatching management is "basin to cross basin to cross large area".

2.3 Comprehensive utilization and sustainable development of cascaded reservoirs in the basin

With the development of economy and society, the development and utilization of water resources by human beings has gradually shifted from the water conservancy project with a single target in some areas to the comprehensive utilization of water resources in the basin, and gradually form the reservoir groups, the basin control and the integrated functions. However, the adverse effects of the reservoir's dispatching and application on the ecology and the environment cannot be ignored. In the process of dispatching, it can be rationally discharged according to the actual conditions of each reservoir. Ecological base flow (minimum or suitable ecological water demand), use appropriate scheduling methods to control eutrophication of water, prevent physical and chemical properties of water and "water blooms", avoid salty tides in the estuary, etc., in order to reduce or eliminate the adverse affect on the ecological ecology in the downstream of the reservoir. From the perspective of river ecosystem protection, the comprehensive utilization of cascade reservoirs will not only improve the overall utilization efficiency of the cascade reservoirs in the basin, but also promote the sustainable development of ecology and environment. In the process of comprehensive development and utilization of river basins, the social, economic and environmental are considered together, and maximizing the benefits of these three factors has become the trend of the times.

2.3.1 Comprehensive utilization tasks and requirements

According to its dispatching objectives, reservoir dispatching can be divided into beneficial dispatching and flood control dispatching. Beneficial dispatch generally includes power generation dispatching, irrigation dispatching, industrial and urban water supply, shipping requirements for reservoir dispatching. Its main task is to use the reservoir's water storage regulation capacity to redistribute the river's natural incoming water to meet the various water requirements of water departments. The basic task of flood control dispatching is to adjust the flood according to the downstream flood control needs under the premise of ensuring the safety of the dam; the reservoir and the downstream river dyke and the flood control system of the sub-stagnation and flood detention area are used together to give full play to the flood control effect of the reservoir.

When the reservoir shoulders many tasks, such as power generation, flood control, irrigation, water supply and shipping, it should follow the principle of comprehensive utilization, comprehensively coordinate and meet the needs of various sectors of the national economy, thus effectively improving the comprehensive utilization efficiency of the reservoir. Since the introduction of the principle of multi-objective development of rivers in the 1930s, comprehensive utilization has almost become the fundamental guiding principle for river development in any country in the world. With the gradual development and utilization of water resources in the basin and changes in regional economic development requirements, sometimes the main objectives of development will also change. However, the principles of comprehensive utilization are always consistent. The main objectives and comprehensive utilization of river development in some countries in the world are shown in Chart 3.

Chart 3 Utilization target of typical river in the world

River name	geographical location	comprehensive target
Columbia River	North America	Power generation, flood control, irrigation, shipping, fishing, over-wood
Tennessee River	Southeastern United States	Power generation, shipping, flood control, agriculture, fisheries, tourism
Colorado River	Southwestern United States, northwestern Mexico	Irrigation, power generation, water supply, flood control
Volga	Southwestern Russia	Shipping, power generation, irrigation, tourism
Yenisei	North Asia	Power generation, shipping
Parana	Between Uruguay and Argentina	Power generation, flood control, shipping
Danube	Europe	Shipping, power generation, flood control, irrigation
Rhone	Switzerland, France	Power generation, shipping, irrigation, tourism
Ligenchuan River	Japan	Flood control, power generation, irrigation
Yangtze	China	Flood control, power generation, shipping, water supply, fisheries
Yellow River	China	Flood control, power generation, irrigation, fisheries, anti-fl

1) The scheduling method of combining flood control and profitability. For

reservoirs that undertake flood control and profit-making tasks, the reservoir's flood control capacity and benefit storage capacity should be combined as much as possible to maximize the overall benefits.

For example, the Colorado River Mead Reservoir (Hoover Dam), as a control project for the basin, Its first development goal is river water regulation, improving shipping and flood control; the second is irrigation, living and commercial water supply; Third is hydroelectric power, which can completely control the flood above the dam site to prevent frequent flooding in the downstream; it can guarantee the irrigation of 7 000 hm2 land in the desert area of California and Arizona. Southern California is a semi-arid area with an annual rainfall of only 380mm.The Mead Reservoir can supply water to cities such as Los Angeles through the aqueduct on the right bank of the Lower Parker Reservoir, and can also irrigate the arid areas such as the Valley through the water diversion channel of the Imperial Dam Reservoir. In addition, In some low-lying areas of the Colorado River, river water is introduced into these areas to provide protected areas or stagnant areas for local and exotic wildlife to restore the ecological environment that has disappeared since the construction of the Hoover Dam; As well as the operation of the reservoir, it is also trying to protect and restore local fish species and their quantity. In addition, a number of wildlife sanctuaries have been established in downstream of the Colorado River near the reservoir to help fish. In terms of power generation, the Installed capacity of Hoover Power Station is still the highest in the United States, providing electricity to states such as Nevada, Arizona and California. In terms of leisure, the initial construction of the reservoir is an incidental benefit, but today, Lake Mead has become a well-known leisure and scenic spot in the United States. About 12 million people go to the reservoir for swimming, skiing, fishing, etc. during the 12-month open year.

The dispatching task of the Three Gorges-Gezhouba cascade water conservancy project in the Yangtze River Basin of China is to give full play to the comprehensive benefits of flood control, power generation, shipping and water resources utilization under the premise of ensuring project safety. Among them, the dispatching principle of the Three Gorges Water Control Project is that the benefit dispatch obeys the flood control dispatching, the power dispatching and shipping dispatching coordinate with each other and obey the water resources dispatching, coordinate the relationship between the beneficial dispatch and the water environment, water ecological protection and long-term utilization of the reservoir, and improve the water resources benefit of the Three Gorges. The Gezhouba Water Control Project is the shipping counter-regulation hub of the Three Gorges Water Control Project. The dispatching task is to counter-regulate the non-constant flow process of the Three Gorges Water Control Project. The power generation benefits are fully utilized under the conditions of ensuring safe and smooth shipping.

2) The single scheduling target mode is the main mode, taking into account the scheduling mode of other scheduling targets. According to the primary and secondary relationship of the reservoir to undertake the task, the appropriate scheduling method is drawn up.

1) For reservoirs with power generation, the dispatching method can be formulated according to the power generation reservoir.

For example, the six cascade hydropower stations in the middle reaches of the Jinsha River in China are mainly based on power generation dispatching. During the flood season from July to August, the cascade operation of the cascade reservoirs cooperates with the downstream Three Gorges Reservoir to undertake the flood control tasks in the middle and lower reaches of the Yangtze River. For example, in the cascade reservoirs in the upper reaches of the Yellow River in China, except for the Longtouxia Reservoir, which has comprehensive utilization tasks such as flood control, anti-flooding, irrigation, industrial and urban water use, the other reservoirs are mainly based on power generation, and it plays the role of peaking, frequency modulation and accident backup power stations.

2) For reservoirs that rely on flood control or water supply for power generation, the flood control or water supply volume should generally be used to formulate the dispatching mode, and the power generation time and power generation amount should be determined according to the requirements of irrigation or water supply.

For example, the Aswan Reservoir in the Nile River in Egypt mainly uses irrigation requirements as the scheduling principle. In addition, it also needs to consider various requirements such as flood control, power generation, shipping, downstream riverbed erosion, and water quality. From February to September each year, the reservoir is dominated by irrigation water supply. From October to January of the next year, the amount of water required for irrigation is small, but this is the peak season for tourism. In addition, due to the large water surface area, the Aswan Reservoir does not change much of the water level in the reservoir, and the water quality is good, which is suitable for fishery development. In terms of power generation, the power generation of the reservoir accounts for more than half of the total power generation of the entire Egyptian power system. The contribution to meeting the increased demand for electricity in Egypt is significant.

The Danjiangkou Reservoir, the mid-line hub of the South-to-North Water Diversion Project of China, is mainly responsible for flood control, to ensure that in the event of a 100-year flood, the dikes of Hanjiang River are safe. In terms of benefit dispatch, water supply is its primary task, followed by power generation dispatch.

3) Other comprehensive utilization tasks are unified scheduling methods. When the reservoir is also responsible for one or more tasks of anti-icing, shipping, aquaculture, improvement of downstream water quality, tourism, etc., when formulating the scheduling method, they should also consider their requirements for water level, flow rate and discharge process. In the coordination, we must take the principle of the overall benefit of the national economy as the best. For example, the Columbia River in the United States has built 29 major reservoirs that provide flood control, irrigation, fish migration, habitat for fish and wild species, power generation, shipping, and recreation. The role of flood control in the Volga River Basin is not very important in its comprehensive utilization planning, but fisheries occupy is an extremely important position in Russia, and the fishing volume accounts for about 50% of the country. In addition, water supply, power generation, shipping, and tourism are also the comprehensive utilization of the Volga River.

2.3.2 Comprehensive utilization scheduling management and implementation

Reservoir dispatch management is a scientific management method for rationally dispatching and utilizing reservoirs to achieve maximum comprehensive benefits under the premise of ensuring reservoir safety, and is the central link of reservoir management. With the rapid development of the economy, the society put forward higher requirements for water resources. The management of reservoir dispatching is not only related to the performance of reservoirs and the interests of various water departments, but also related to the safety of the reservoir and the major problems of the safety and property of the upper and lower reaches. Therefore, reservoir dispatch management not only needs to deal with the relationship between flood control and profit, but also needs to coordinate the water demand of various departments, properly arrange the relationship between storage and discharge, and optimize the allocation of water resources.

French reservoir management is recognized as one of the successful models in the world. France divides the country into six major river basins according to the water system, and establishes basin committees and basin water resources bureaus (also known as water bureaus) in each basin to plan and manage water resources in a unified manner, and to realize efficient development and utilization of water resources in the basin under the premise of protecting the environment. The reservoir management agencies in France are divided into national, river basin, regional and local levels. In addition, there are international institutions established specifically for international river or water affairs.

National level - Ministry of the Environment

The Ministry of environment plays a major role in reservoir management in France.The Ministry of Environment has a Water Resources Division, which is responsible for supervising the implementation of water regulations and water policies, analyzing and monitoring water pollution, and formulating national standards related to water. The Ministry of the Environment has a dispatched agency in the relevant area - the Environment Department, which mainly implements relevant national laws and regulations and the European Community's guidelines on water, supervises reservoir management and public utilities, and cooperates with the Water Affairs Bureau to formulate water resources management and development plans. Also they provide advices on water environment issues.

Basin level

France's Water Law of 1964 clearly designated the country into six major river basins and established six river basin water bureaus. However, the original system has not been reformed. Although the newly-built six major river basin water bureaus have no administrative management powers, such as issuing water and drainage permits, neither do they construct, manage or operate any water projects. However, as a watershed committee composed of representatives of water users, local governments, and central government departments involved in water resources utilization, the executive agency of the Water Council——the Watershed Water Authorit. There are three main functions: first, the development of watershed planning; second, watershed levy and financial support for water resources development and utilization and protection and management units in the basin; third, water information collection and release. The Water Affairs Bureau consists of: integrated management, fees, water quality, water resources development, planning, financial management, information and foreign affairs.

River basin committee

The French River Basin Commission is equivalent to a water conservancy "parliament" at the basin level and is a "parliamentary" form of democratic management of water resources. It is to enable all kinds of users to participate in the decision-making process of water resources development and utilization, in order to increase the democratic and legality of decision-making. Its role is to provide an authoritative advisory opinion on the long-term planning and development and utilization guidelines and charging plans of the watersheds formulated by the Water Affairs Bureau. The River Basin Committee is a very important organization. It also adopts the "three-three system" organization, consisting of more than 100 people, one third of which are representatives of users and professional associations, and one third is representatives of local authorities (mayor elections) Generated), the remaining one third is assigned by the representative of the relevant government department. Its role is to advise the Water Authority on planning, cost collection and water regulations.

Regional level (each region consists of 2 to 5 provinces) water management agencies mainly include regional chiefs, regional water technology committees, and regional board of directors. Its functions are to participate in the formulation and implementation of small watershed development plans in its jurisdiction, to promote and coordinate research work, and to supervise and approve project implementation.

For example, the French Seine River Basin has the Una River Reservoir, the Seine River Reservoir, the Marne River Reservoir and the Obe River Reservoir. The governing agency is the Inter-provincial Reservoir Administration of the Seine River Basin in France.

The Seine River Basin Interprovincial Reservoir Authority is a financially independent public agency under the direct direction of the French International Water Authority. It was established in 1969 and covers jurisdictions in Paris, Upper Seine, Seine Saint-Denis and the Marne Valley .The agency manages four reservoirs: the main task of the agency is to regulate and protect the Paris region from the floods of the Seine and Marne rivers by using the four reservoirs in the Seine Valley.The specific scheduling method is: when the rivers of the Seine and Marne rivers are at a high water level, the reservoir is used to intercept water from the river to reduce the flood peaks; in the low water level, water is discharged from the reservoir to the river to keep the water level of the Seine and the Marne is in the normal range. The Provincial Reservoir Administration shall arrange the storage and water supply dispatching of the reservoir in accordance with the principle of solidarity and mutual assistance among the provinces in the basin, and protect the natural ecological environment of the reservoir area.

1）Water supply dispatch

The groundwater resources in the Paris region are poor. After the Seine and Marne reservoirs are treated by the water plant, they will be responsible for two-thirds of the drinking water supply in the region. The Paris region is short of water for one month each year, and half of the Seine River runoff from September to October, and even three-quarters of it is dependent on the reservoir's water supply.Every year from July to October, and sometimes from June to December, the Seine and Marne River reservoirs supply water to the Seine and Marne to improve the aquatic environment and ensure the supply of drinking water. The four reservoirs provide more than 1 billion m^3 of water per year to the Paris region, ensuring that the Seine River around Paris is kept within normal limits throughout the year, ensuring the use of water for residents of the Parisian city of the Seine Valley.

2）Tourism of Reservoir area

The completion of the reservoir in the Seine River Basin not only hasn'tadversely affected the ecological environment, but also greatly promoted the economic development of various industries in Paris, and also brought considerable income to the tourism industry.

The four reservoir areas under the jurisdiction of the Interprovincial Reservoir Authority of the Seine River Basin are now important scenic spots in France and Europe and are listed as internationally important wetlands suitable for water bird survival. The reservoir management agency has taken various measures to create favorable conditions for the survival and reproduction of waterfowl. In addition, the reservoir management agency has also worked with local forestry authorities to contribute to greening in the upper reaches of the Seine. They harmonize water conservancy facilities with the environment and reduce the environmental impact of the facilities. This approach embodies the policy of sustainable development of reservoir management institutions, fully respects the ecological balance, and regards construction, management and the environment as an organic whole. Each of the four reservoirs in the Seine Valley seems to have entered the national nature reserve. The grass and trees there are completely in a natural state, and they are in a very harmonious atmosphere with the water conservancy project, and the disturbance and damage to the environment caused by the construction and management facilities are not seen. In particular, local governments have played a key role in ensuring the natural harmony of the reservoir environment and have oversight functions for the impact of project management on the natural environment.

In recent years, China's reservoir dispatching work and technology have made certain progress, especially since the implementation of the cascaded rolling development in the basin, a cascade dispatching mechanism has been established to optimize the power generation of hydropower stations by controlling and adjustment under the premise of ensuring the safe operation of the hydropower station and the safety of the power grid. In the aspect of flood control and dispatching, the National Flood Control and Drought Relief Headquarters organizes, coordinates, directs and supervises the flood control and drought relief work throughout the country. The

National Flood Control and Drought Relief Headquarters set up the Office of the National Flood Control and Drought Relief Headquarters in the Ministry of Water Resources. It is responsible for implementing flood control and drought relief and emergency water dispatching for important rivers and lakes and important water conservancy projects, and preparing national flood control and drought relief emergency plans and organizing implementation. At the local level, local governments (provinces, cities, and counties) set up flood control and drought relief headquarters offices in the Water Resources Department (bureau) to take charge of flood control and drought relief in their administrative areas, and implement the executive head responsibility system for flood control and drought relief.

In addition, at the state level, the State Council's water conservancy department has formulated corresponding laws and regulations for reservoir dispatch management to regulate reservoir dispatch management. Local governments have formulated specific implementation measures for reservoir dispatch management in their administrative areas in accordance with state laws and regulations. The reservoir management unit shall formulate the Procedures for the Operation and Control of Reservoir Dispatching and the Application Plan for Annual Dispatch Control to the higher level for approval. After approval by the superior, the two documents shall be used for dispatch management. In the flood season, the reservoir management unit, in addition to the dispatching regulations and control application plan management, must also obey the unified command of the Flood Control and Drought Relief Headquarters to do the flood prevention work of the year. When the disputes between the management units at all levels in the dispatch management of counties, cities and provinces cannot be resolved, they shall be coordinated and resolved by the competent authorities at the higher levels. The flow of the reservoir dispatch management program is shown in Figure 12.

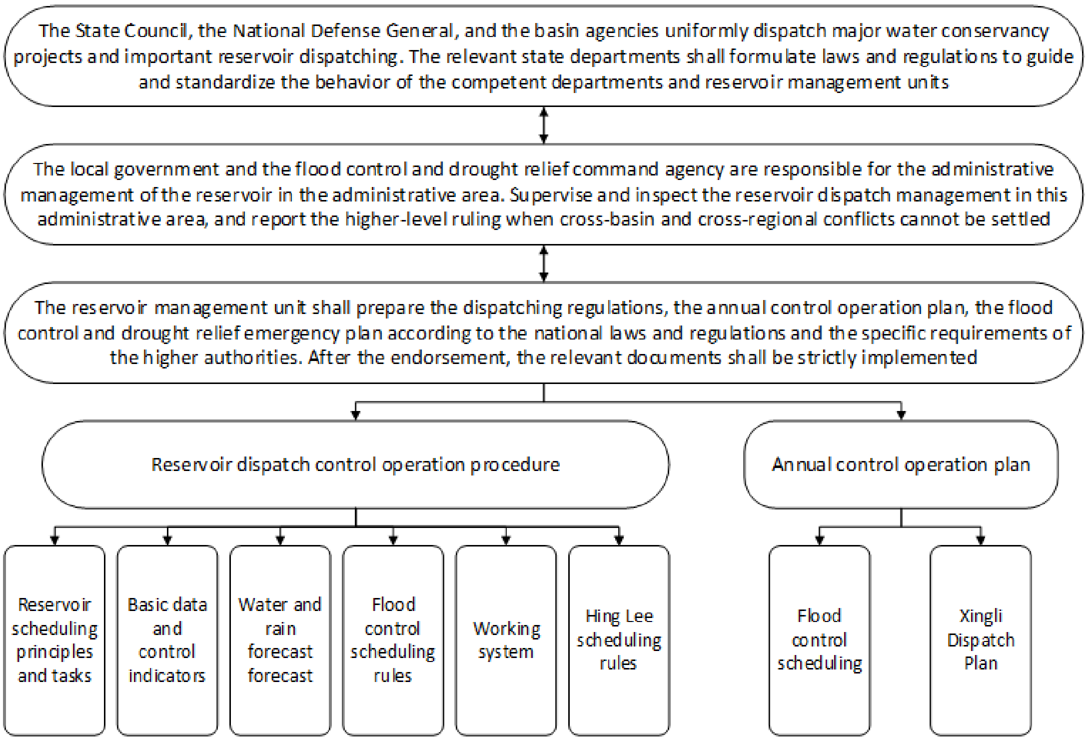

Figure 12 Scheduling manager flow chart

Taking the Yangtze River Basin（China） as an example, at present, there are 40 reservoirs jointly dispatching in the upper and middle reaches of the Yangtze River, with a total storage capacity of about 100 billion m^3, a regulated storage capacity of 57.5 billion m^3, a flood storage capacity of 41.5 billion m^3, and an installed capacity of 83.8 million kilowatts. In the process of joint dispatching of reservoirs in the Yangtze River Basin, the comprehensive benefits of flood control, power generation, shipping, water supply and ecology of the reservoirs have been fully utilized, and the economic and social benefits are very significant.

1) Flood control scheduling

The flood control capacity of the middle and lower reaches of the Yangtze River, especially the Jingjiang section and the vicinity of Chenglingji, has been significantly improved through the joint dispatch of reservoirs. In 2012, it successfully responded to the largest flood since the reservoir was constructed, the peak of the flood was 71200 m^3/s. In the flood season of the Yangtze River in 2017, the National Defense General and the Yangtze River Defense General implemented joint dispatching. The total water retention of the reservoir group in the upper and middle reaches was about 15 billion m^3. The discharge of the Three Gorges Reservoir was the smallest in history, and it played a significant role in flood cutting. It effectively reduces the flood control pressure of the main stream in the Dongting Lake area and the middle and lower reaches of the Yangtze River, and avoids flooding in the Chenglingji area.

2) Power generation scheduling

Under the premise of ensuring flood control safety, the National Defense General and the Yangtze River Defense General make full use of small and medium-sized flood resources and scientifically dispatch the Three Gorges Reservoir. In 2014, the Three Gorges Power Station generated an annual power generation of 98.8 billion kWh, creating a new world of single hydropower stations. Record; On March 1, 2017, the cumulative power generation of the Three Gorges Power Station has exceeded 1 trillion kWh since it was put into operation in July 2003, creating a new record for the cumulative power generation of a single power station in China. According to statistical analysis, from 2009 to 2015, through the optimization of dispatching and joint dispatching, the total power generation capacity of the reservoir was increase by 53.8 billion kWh, and the power generation profit was increase by more than 13 billion yuan, equivalent to saving 13.35 million tons of standard coal and reducing greenhouse gas emissions by 51 million ton.

3) Shipping scheduling

Limited by the traffic flow between the Three Gorges dam and the Gezhouba dam, when the discharge of the Three Gorges Reservoir exceeds 30000 m^3/s, the ship locking phenomenon will occur in the section. In order to evacuate the ship in time, ease the navigation pressure and ensure the safety of the ship, the Yangtze River Anti-General dispatched the Three Gorges Reservoir to reduce the discharge flow. During the dry season, some river sections in the middle and lower reaches of the Yangtze River have insufficient navigation capacity, resulting in backlog of ships. By increasing the outflow of the Three Gorges Reservoir, the shipping depth is increased by 0.5 to 1.0 m, effectively alleviating shipping pressure. In 2014-2016, the freight volume exceeded 100 million tons for three consecutive years. In 2016, the freight traffic volume reached 120 million tons, further expanding the navigation benifit of the Yangtze River Basin.

4) Water supply dispatch

In response to the salt water intrusion in the Yangtze River estuary in February 2014, the Yangtze River Defense General implemented the water dispatching to deal with the salt tides in the Yangtze River estuary for the first time. The outflow increased to 7000 m^3/s, and the downstream water supplement was 17.3 Billion cubic meters, effectively protecting the water security in the Yangtze River estuary. Since 2009, the reservoirs in the upper reaches of the Yangtze River have accumulated supplied water for more than 200 billion m^3 in the middle and lower reaches, effectively alleviating the dry water situation in the middle and lower reaches and ensuring the safety of water supply in the basin.

5) Ecological scheduling

Since 2011, the Three Gorges Reservoir has carried out eight ecological rescue experiments in the Yangtze River Basin, which promotes the breeding of four major fishes for many years. It simulates the natural environment rising water process and promotes the natural reproduction of the four major fish. From late April to early June 2017, the joint ecological dispatch test of Xiluodu-Xiangjiaba-Three Gorges Reservoir was carried out for the first time. The total number of fish eggs in the Yibin section of the upper reaches of the Yangtze River was 0.05 million, and the total number of fish eggs in the Jiangjin section was 106 million. The Yidu section in the middle reaches of the Yangtze River monitored the total number of eggs laid by four major fishes was 1.08 billion, effectively promote the large-scale reproduction of the four major fish.

2.3.3 Emergency dispatch management and implementation

The cascade hydropower reservoir scheduling is a process of scientifically distributing water resources in the basin to realize the comprehensive benefits of hydropower resources. Under normal circumstances, the basin reservoir group scheduling is to make full use of water resources and maximize its economic benefits. Under certain circumstances, when certain unexpected events occur in the basin, the cascaded reservoir group scheduling in the basin can play the emergency function of emergencies. The emergency response capacity of the reservoir is mainly reflected in the adjustable storage capacity of the reservoir. The adjustable storage capacity is large, and the emergency response capacity of the reservoir is large; the adjustable storage capacity is small, and the emergency response capacity of the reservoir is small. From the type of accidents, river basin emergencies can be divided into the following categories:

1) The threats and damages to the water conservancy facilities caused by floods in the basin, such as dam breaks, piping, landslides, flooding dams, etc.;

2) Long-term water supply security threats caused by extreme weather disasters, such as drought, crop irrigation, etc.;

3) Incidents caused by human error in the water system of the river basin, such as water pollution, urban water supply safety, etc.;

4) Sudden accidents caused by accidents or aging of hydropower facilities in the basin, resulting in difficulty in output or difficulty in sending electricity;

5) Safety threats to river basin water conservancy projects caused by natural or human factors, such as earthquakes, terrorist attacks, etc.;

6) Other social and economic needs, such as ecological needs such as water bloom, shipping demand and inter-basin water transfer demand.

2.3.3.1 Water quality emergency dispatch

As an important means to deal with sudden water pollution incidents, water conservancy project dispatching has unique advantages and has been widely used. It is important to increase the discharge flow of reservoirs to alleviate sudden water pollution. If the accident location is closer to the reservoir, emergency dispatching can play a big role.

For example, after the occurrence of the Yiluohe diesel pollution incident in the first tributary of the Yellow River in China in January 2006, the Yellow River Conservancy Commission implemented emergency water volume dispatching, and adopted measures to reduce the discharge flow of the tributary reservoir and increase the discharge flow of the Xiaolangdireservoir, greatly reduced the total amount of pollutants entering the mainstream of the Yellow River, and won time for local government organizations to implement diesel cleaning and disposal of pollution incidents, and also reduced the concentration of pollutants in the mainstream river. In February 2015, due to the tidal phenomenon, the water source of the Yangtze River estuary in Shanghai, China, was invaded by salt tides, which had a great impact on the normal operation of the water sources such as Qingcaosha and Chenhang in the

Yangtze River estuary. At the request of the Shanghai Municipal Government, the Yangtze River Defense General Daily requested the National Defense General to agree that the Three Gorges Reservoir increased the outflow of the reservoir, initiated the "salt tide" emergency dispatch, and accumulated a total of 1.73 billion m^3 of water to the downstream to alleviate the downstream salt tide intrusion.

In some countries in Europe, long-term mechanisms for water quality monitoring and protection have been established. For example, the Rhine River, which supplies 20 million people with drinking water, has been concerned about water quality along the river countries, especially downstream countries. After the Second World War, The industrial recovery, urban renewal, and the water quality of the Rhine began to decline. In the early 1970s, the ecological protection measures lag far behind the speed of economic development, and the Rhine is heavily polluted, known as the "sewer of Europe". An automatic water quality monitoring system and a mobile monitoring station have been established on the Rhine and its tributaries, and advanced monitoring methods are used to monitor the river water. Many chemical substances, suspended sediments, sediments and biological populations in the monitored water bodies, each monitoring station has a water quality warning system, which provides early warning of short-term and sudden pollution accidents through continuous biological monitoring and online chemical monitoring.

2.3.3.2 Water emergency dispatch

Emergency water transfer is based on the premise of not affecting the normal water use of the original users making full use of existing water transfer projects and natural rivers for water transfer. The main scheduling principles include:

1)The water transfer scope is the emergency water transfer between the administrative districts of different prefecture-level cities and different water systems in the province, and the water resources within the administrative areas of different river basins and different prefecture-level municipalities are temporarily transferred from the relatively abundant areas to the shortage areas. To meet the needs of life, production and ecological water.

2)Taking natural water bodies and existing (original) projects as carriers, give full play to the adjustment capabilities of large reservoirs, appropriately add temporary projects and restore, maintain water sources.

3)The priority of water supply is: Mainly for urban water supply, taking into account large-scale irrigation areas and key ecological protection areas.

4)When the emergency water transfer is started, the water adjustment amount is a small value among the adjustable water quantity and the required water adjustment amount. At the same time, it is necessary to scientifically allocate the water use order and water volume of each industry, handle the relationship between the transfer zones, and rationally design the water transfer plan.

Since urban, agricultural, and ecological emergency water transfers have not been initiated at the same time, the urban life and industrial emergency water transfer volume are not simply superimposed. The actual amount of water to be adjusted is reasonably determined based on the amount of water that can be adjusted according to the amount of water that can be adjusted in the region when the emergency water transfer is initiated.

The Australian Snow Mountain Project consists of 16 reservoirs along the route (with a total storage capacity of 8.47 billion m^3 and an effective storage capacity of 6.91 billion m^3) and related buildings. The average annual inland water transport is 1.13 billion m^3. During the drought period, the amount of water discharged by the power station can be adjusted to ensure that the water volume during the most severe drought period is not less than 85% of the average flow rate.

From January to June 2011, the precipitation in the Yangtze River Basin in China was abnormally low, which was nearly 40% less than the average of many years. Among them, the middle and lower reaches of the Yangtze River were less obvious, and the precipitation in Hubei, Hunan and Jiangxi provinces was the lowest in the past 60 years. The water conservancy project is insufficiently stored, and the water level of the dry tributaries is low, resulting in a major drought disaster in the middle and lower reaches of the Yangtze River. In order to cope with the continuous drought in the middle and lower reaches of the Yangtze River and support the drought-resistant drinking water in the middle and lower reaches of the Yangtze River, the Yangtze River Flood Control and Drought Relief Headquarters initiated drought emergency dispatching. The Three Gorges Reservoir increased the discharge flow, and continued to replenish water for 5 billion m^3, with an average downstream replenishment of about 1540 m^3/s to alleviate the drought.

In 2014, the total water coming from the Hanjiang River Basin in China was dry, and the accumulated water in the Danjiangkou Reservoir was 20% less than that in the same period of the previous year. At the same time, since the beginning of the flood, the high temperature, low rainfall and dry weather in Henan Province of the Hanjiang River Basin have continued to occur, and some cities have difficulty in supplying water. In order to meet the urban water demand, the National Defense General decided to implement emergency water diversion from the Danjiangkou Reservoir. The official implementation of emergency water transfer was started from August 7th and finished on September 20. The time was 45 days, and the total amount of emergency water transfer was 50.22 million m^3. Through emergency water transfer, the urban living water is effectively guaranteed, production and ecological water are supplemented, drought conditions are effectively alleviated, and the social benefits of emergency water transfer are very significant.

2.3.3.3 Dam safety emergency dispatch

The safe operation of the dam is the primary condition for the dispatching of the reservoir. Since the early 20th century, the loss of life and property caused by dam accidents is not uncommon. Therefore, ensuring the safe operation of the dam is the core issue after the completion of the project.

In August 2014, a 6.5-magnitude earthquake struck Ludian County, Yunnan Province, China, forming a barrier lake on the Niulan River, a tributary of the Yangtze River. The total volume of the plug body is 10 million m^3, the total storage capacity is about 260 million m^3, and the upstream return water is about 25km. It is a "large-scale dammed lake", and it is difficult to carry out emergency evacuation and disposal. Deze Reservoir and Xiaoyantou Power Station are built in the upper reaches of the barrier lake. The Hongshiyan Power Station is built near the lake, and the ceiling power station and the Huangjiaodian Power Station are built in the lower reaches. There are a large number of market towns in the lower reaches of the barrier lake, the population is dense, and the security risks are very serious. In order to reduce the flood control pressure of the barrier lake, the Yangtze River Flood Control Headquarters has formulated a joint reservoir dispatching plan. The upstream Deze Reservoir will intercept and reduce the flood peaks, reduce the amount of water in the barrier lake; implement strict management of Xiaoyantou Power Station, maintain the balance of inflowand outflow in the case of special water conditions; implement empty space for downstream ceiling power station and Huangjiaoshu Power Station In the case of the reservoir, the water level is reduced to a certain limit water level, and a certain flood peak is blocked when the dam breaks, ensuring the safety of the lives and property of the people in the towns such as the steep beach and the small river along the downstream.

2.3.3.4 Marine emergency dispatch

On the evening of June 1, 2015, the "Oriental Star", a tourist passenger ship that sailed from Nanjing, China to Chongqing, overturned during the journey to the Jianli waters of Hubei Province in the middle reaches of the Yangtze River. After the "Eastern Star" sinking incident, the National Defense General, the Ministry of Water Resources and the Yangtze River Defense General launched an emergency dispatch plan for the Three Gorges Reservoir and carried out emergency dispatch. The discharge flow of the Three Gorges Reservoir was gradually reduced from 17200 m^3/s to 10000 m^3/s, 8000 m^3/s and 7000 m^3/s. Affected by pressure and reduced flow, the Yangtze River from Yijiang to Jianlijiang section quickly stopped rising and turned to falling. At March 2, the water level of Jianli Station rose to 30.05m, and then began to fall back and continue to decrease. According to analysis, if the Three Gorges Reservoir does not reduce leakage, The water level in JianLi station will rise to a maximum of 32m, and the water flow conditions in the shipwreck area will be greatly deteriorated. In the search and salvage stage, the maximum water level of the Shashi and Jianli stations in the section of the shipwreck was 2.80m and 0.80m, respectively, and the flow rate of the shipwreck area also slowed down accordingly. Since then, the Three Gorges Reservoir has maintained a discharge flow of 7000 m^3/s for five days, and the reservoir water level has risen from 145m to 154.06m. On June 4, according to the water coming from the upper reaches of the Yangtze River, the Yangtze River Defence General implemented the joint dispatch of the upstream reservoir group. The Yangtze River tributary Wujiang River Basin, the Goupitan, Shaying and Pengshui Hydropower

Stations timely buffered floods, slowed the water level rise of the Three Gorges Reservoir, and created favorable conditions for the shipwreck rescue.

2.3.4 Sustainable development of cascade reservoirs

With the continuous enhancement of people's environmental awareness, the environmental effects generated in the operation and management of cascade reservoirs in the basin have been paid more and more attention. It is not rational to measure the comprehensive benefits of reservoirs with the greatest economic benefits. It is increasingly important to consider the unification of social, economic and environmental benefits from a macro level. Therefore, in the comprehensive utilization of cascade reservoirs, it is necessary to take into account the following issues:

1) Determine reasonable ecological base flow

The ecological base flow should be determined according to the ecological water demand of the river channel downstream. Ecological water demand refers to the amount of water resources that maintain the objective needs of a certain environmental function or target (status, recovery or development). Determining the ecological water demand is an effective measure to protect the functions of river ecosystems. The determination of river ecological water demand should be determined according to the ecological function requirements, that is, the water demand of the organism itself and the environmental water demand by which the organism depends. River ecological water demand is not only related to the biological population structure in river ecosystems, but also related to regional climate, soil, geology and other environmental conditions. The continuous improvement of water resources development and utilization makes the contradiction between water resources utilization and ecological water use very prominent in the world. However, there is still a lack of perfect and mature methods for the selection of ecological flow. The United States, France, Australia and other countries have carried out many studies on the relationship between fish growth and reproduction and river flow, and proposed the concept and calculation method of the minimum ecological (or biological) flow of rivers, such as wet-week method and river channel flow increase method, Montana law, etc.. For the minimum river ecological water use, some countries simply make mandatory regulations. For example, France requires that the minimum river ecological water flow should not be less than 1/10 of the average annual flow, for rivers with a multi-year average flow greater than 80 m^3/s, the lowest flow rate. The lower limit must also be no less than 1/20 of the average annual flow. According to the region where the river is located, China also proposes different methods for determining the ecological flow of the river. For example, the river ecological ecological base flow in the Yangtze River Basin generally adopts the average flow rate of the most dry rivers with a guaranteed rate of 90% or 95%.

2)Control water eutrophication

For the control of water eutrophication in the local slow-flow area of the reservoir, the speed of water flow in the slow-flow area can be speed up by decreasing the water level of the dam, or by changing the dispatching operation mode of the cascade reservoir, which will increase the flow rate of the water body in the slow-flow area and destroy the eutrophication of the water body. The conditions are formed, or the flow rate of the reservoir water is increased by increasing the discharge flow of the reservoir within a certain period of time, so as to eliminate the eutrophication of the local water body of the reservoir. Water diversion can also be adopted, such as the "Yinjiang Jihan" project in the lower reaches of the Han River in China. By citing the water flow from the Yangtze River to the tributary Han River, the flow of the river is increased, and the eutrophication of the river water body is eliminated. In addition, in low-head or lake-type reservoirs, it is also possible to control the eutrophication of water bodies by adding pipe network facilities. For example, Germany has laid a network of sewer pipes according to the characteristics of its reservoirs, and has achieved certain effects. Switzerland uses deep storms and forced circulation, and Finland uses water to dilute it. Measures such as law to improve the water quality of the reservoir area and control the eutrophication of water bodies.

3)Fully consider the protection of aquatic organisms and fish resources

After the formation of the cascade reservoirs in the basin, on the one hand, some conditions that are conducive to the reproduction of some aquatic organisms are produced, and the types and quantities thereof will increase substantially, and the productivity will increase. On the other hand, the regulation of runoff by cascade reservoirs changes the hydrological situation and physical properties of rivers in the reservoir area and under the dam, and the reproduction of aquatic organisms and the growth, development, reproduction, feeding, and wintering of fish. Different degrees of influence are generated. For these adverse effects, artificial flood peaks, controlled low temperature underwater discharge, and controlled discharge gas supersaturation can be used to reduce or eliminate the effects. The Glen Gorge Dam, built in 1963, is located in the main stream of the Colorado River. After the dam is built, the sediment is deposited in Lake Powell. The river becomes clear, the flow rate is reduced, the water temperature is kept at around 9 °C, and the winter water temperature is increased before the dam. In summer, there has been a significant decline, and such dramatic ecological changes have caused a variety of local fish to become extinct. In order to alleviate the ecological and species damage caused by dam construction, a series of man-made flood tests were carried out to grind sediments, restore sandbars and beaches, and conduct steady low-flow tests in summer to raise the temperature of river water, promote fish growth and achieve good results. In order to avoid damage to the embankment ecological community and protect the surrounding slope and reservoir stability in order to meet the shipping conditions downstream of the dam, the Tucurul hydropower station in Brazil clearly stipulates that the hydropower station operating water level should not exceed 72.00m. In the 1990s, the Roanoke River Management Committee of the United States decided to partially adjust the operation mode of the original reservoir, that is, to control the flow rate before the dam construction during the spawning period of the carp from April 1 to June 25 of each year. Between 25% and 75%, and the rate of change per hour of flow is less than 42 m^3 / s, the number of carp is found to increase significantly.

4)Fully consider the regulation of sediment

The regulation and storage of cascade reservoirs changed the annual runoff distribution of natural rivers and the temporal and spatial distribution of sediments. During the flood season, the flood peaks were reduced, the dry season flow increased, and a large amount of sediment was deposited in the reservoir area. The river channel downstream of the dam will be washed along the way. At the same time, due to the adjustment of the flow process, the amount of sand discharged will decrease, and the river will undergo different adjustments. River bed erosion and river adjustment have a certain degree of impact on flood control and shipping. The river bed is deep, reducing the flood level and increasing the flood discharge capacity of the river channel; the adjustment of the annual inner diameter flow distribution is conducive to the improvement of the ability of discharging flood for shoal channel. However, during the adjustment of the river regime, the safety of the flood control embankment and revetment works may be jeopardized, and local shoal deterioration may occur. The adjustment of sedimentation in the reservoir area and the scouring of the riverbed downstream of the dam, and the resulting problems, are natural phenomena after the construction of the reservoir and cannot be avoided. The impact of sediment erosion on flood control, power generation, shipping, and ecology is an important indicator for verifying the success of the sediment problem in water conservancy projects. The reservoir can reduce the flushing intensity of the downstream river channel by reducing the amount of sedimentation and flow of the outflow stream according to the methods of “clearing and draining the dumping”, adjusting the discharge mode and controlling the discharge flow, and reducing the conventional dispatching situation. The river washes the range and delays its progress to reduce adverse effects. For example, the rivers in the Yangtze River Basin in China are generally large in water and sandy, and the amount of incoming water is concentrated in the flood season. The normal operation of the Three Gorges Reservoir adopts the scheme of 175m~145m～155m. In the flood season, combined with flood control, the reservoir water level is reduced to discharge sand, and non-flooding water storage. Raise the water level to use the “storage clearing and draining” reservoir dispatching method. Through this kind of dispatching measures, the adverse effects caused by sediment erosion and siltation can be greatly reduced, and most of the effective storage capacity of the reservoir is retained for a long time. Giving full play to the comprehensive benefits of the project.

2.3.5 Watershed sustainable development characteristics

Comprehensive analysis of the practice of comprehensive utilization and sustainable development of cascade reservoirs in various countries. Although the national conditions of different countries are not consistent, the natural characteristics of rivers vary widely, but in terms of comprehensive utilization and sustainable development, they clearly show some common features：

1）Establish a watershed management organization with a focus on unified management

The development organization shall be established according to the river basin or river section, and shall be responsible for the planning, development, construction and even operation management of the river basin or the river section. This is the general management mode for cascade development abroad. Of course, for large rivers, such as the Columbia River, the Yangtze River, etc., because of the large cross-region, there is not necessarily a unified development management agency for the whole river, but the planning is carried out by one or two units; The development and construction of a river section or a tributary is also the responsibility of an organization. Some large rivers, although there is no clear unified development and management organization, are often responsible for the development of the cascades of the whole river (or a river section) by one unit (such as the Yenisei River and the Angara River). The United States Tennessee River, the French Luojing River, the Austrian Danube (the Austrian river section), and the unified management of the Lagrande River cascade development in Canada are the most distinctive and representative, as shown in Chart 4. The unification of the development management organization can make the planning, development and economic construction of the river basin or river section reasonable. The unification of development management does not necessarily mean that the investment entity is single. Investment entities can still be diversified, but this only involves the diversification of power plant ownership and interests, and does not contradict management integration.

Chart 4 Typical river basin reservoir management institutions at home and abroad

River name	Watershed Management Institutions	The Nature of Management Institutions
Tennessee River	Tennessee River Basin Authority	A body of government and business directly under the President and the Federal Parliament

Rhone River	Rhone River State-owned Company	State Ownership, Government Supervision and Independent Management
Danube River (Austrian Reach)	Danube Power Company	State Ownership, Government Supervision and Independent Management
Lagrande River	James Bay Energy Development Corporation	The provincial government and private hydropower companies are jointly organized and independently operated
Yangtze River	CYPC	State Ownership, Government Supervision and Independent Management
Yalong River	Yalong River Basin Development Company	State Ownership, Government Supervision and Independent Management

2）Focus on sustainable development

The adverse effects of the dispatching and utilization of cascade river reservoirs on ecology and environment cannot be ignored. Therefore, it is necessary to make overall plans for flood control, benefit and ecological needs, and use advanced dispatching techniques and means to fully utilize the reservoir's flood control, power generation, irrigation, water supply and shipping on the basis of meeting the ecological protection of the downstream and the water environment protection requirements of the reservoir area. Various functions such as tourism ensure that the negative impacts of the reservoir on the downstream ecology of the dam and the water environment in the reservoir area are controlled within an affordable range, and the ecological and environmental systems are gradually restored. According to the current management and dispatching status of the world basin reservoirs, in the existing dispatching mode, according to the actual conditions of each reservoir, it is possible to control the water quantity by using appropriate ecological flow (minimum or suitable ecological water demand) and appropriate scheduling methods. Nutrientization, control of physical and chemical properties of water bodies and the outbreak of "water blooms", control of salty tides in the estuary, etc., in order to reduce or eliminate the adverse effects on the downstream ecology of the reservoir and the water environment of the reservoir area.

2.4 Optimal compensation of cascade hydropower and other energy sources in River Basin

According to the International Renewable Energy Agency (Irena), by the end of

2018, the total installed capacity of renewable energy in the world was 2.351 billion kilowatts, of which the installed capacity of traditional hydropower was 1.293 billion kilowatts, accounting for 55% of the total installed capacity of power generation; the installed capacity of wind power was 564 million kilowatts, accounting for 24% of the total installed capacity of power generation; the installed capacity of solar energy was 486 million kilowatts, accounting for 20.7% of the total installed capacity of power generation. In 2018, the installed capacity of renewable energy in the world increased by 172 million kilowatts, a year-on-year increase of 7.9%. China also continues to lead the world in terms of new capacity, with more than 40% of the world's installed capacity in 2018. The global installed capacity of renewable energy between 2009 and 2018 is shown in Figure 2-5.

With the rapid growth of new energy installation in the world, the energy structure of most countries or regions in the world is changing from single energy mode to multi energy complementary mode. In some developed countries in Europe and the United States, hydropower as the main energy, other energy optimization compensation has become the norm. In China, with the adjustment of power energy structure and the rise of new energy, the joint optimal operation of hydropower and other energy sources will gradually become the mainstream of the industry.

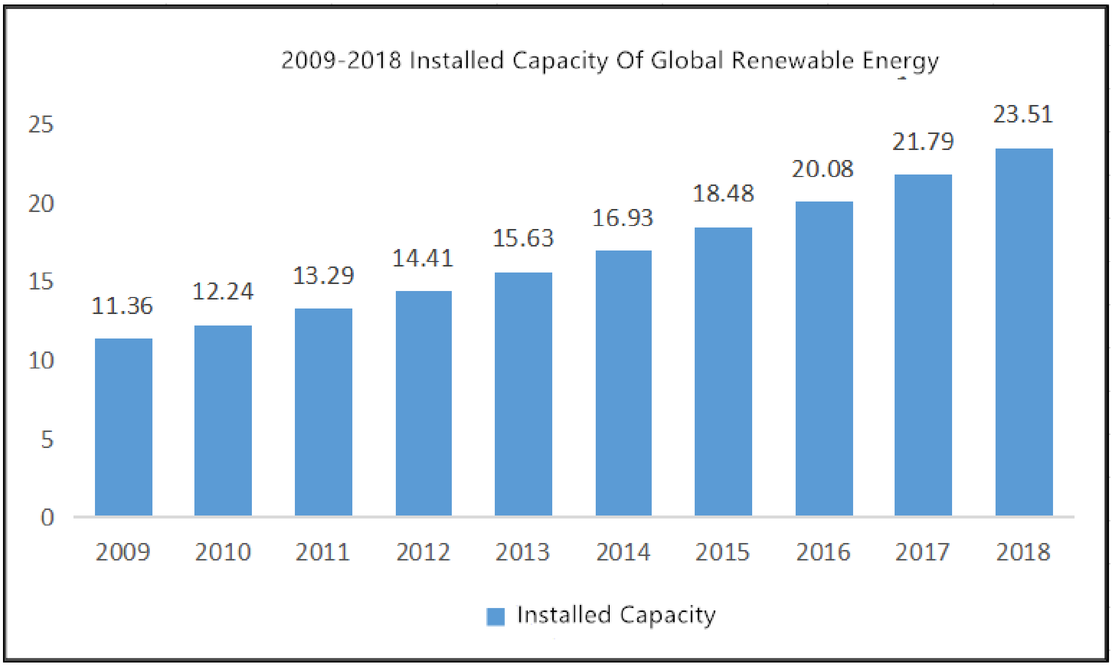

Figure 2-5 Global renewable energy installed capacity in 2009-2018

Note: Date above are coming from the Internet

2.4.1 Complementary management and implementation of water and fire

2.4.1.1 Feasibility analysis

Hydropower has the characteristics of short start-up time, low cost, fast climbing speed, etc. It is an ideal peak regulating power supply in the system. However, the hydropower output is highly uncertain. During the wet season, the risk of water abandonment is high. During the dry season, the water supply station is less likely to develop or not. The hydropower station generally needs to undertake tasks such as flood control and shipping, which limits the water level variation and limits the peak amplitude. Hydropower is located in a remote location and requires long-distance transmission lines to ensure delivery. Compared with hydropower, thermal power units have the characteristics of long start-up time, slow single-unit climbing speed and high marginal cost. For areas with large heating demand, the peaking range of thermal power units is limited to ensure continuous heating. However, due to the large proportion of thermal power in the power supply structure, it has a scale advantage, and the location of thermal power is generally close to the load center. The main peak regulation of the system still relies on thermal power.

In the long term, when it is rainy in summer, thermal power can reduce the load and leave room for hydropower. While in winter, hydropower reduces the output and leaves room for thermal power. In the short-term, the hydropower output has a large change with the upstream water in the flood season, and the total water in the dry season is small, and the output change is also small. According to the weather forecast, the inflow water and the upstream reservoir storage and release water, the thermal power is combined with the hydropower to adjust the output. From a technical point of view, the development of UHV long-distance transmission technology makes hydropower, although remote, but can still establish electrical connection with thermal power in the area near the load center. The development of joint dispatching technology for cascaded reservoirs in the basin has enabled reservoirs in one or more river basins to establish a electricity and hydraulic connection, which reduced the uncertainty of hydropower station output. Hydropower and thermal power have their own advantages and disadvantages, and complementarity is feasible..

2.4.1.2 Hydropower and thermal power complementary mode

The complementarity of hydropower and thermal power is cost-effective from the overall economic benefits, but it is unfair to thermal power and can be compensated economically for thermal power.

When the hydropower output is insufficient, the thermal power will increase the output to meet the load demand, and there is no loss of hydropower, but thermal power may lose money. In this case, the thermal power cannot make its own income to compensate for the hydropower; When the hydropower output is sufficient, the reduction of thermal power output reduces hydropower waste, the marginal cost of excess electricity is zero, but it takes up the power and electricity of thermal power. Therefore, the basic idea of hydropower and thermal power economic compensation is that when hydropower is generated, hydropower generates electricity according to capacity (except for blocked lines), and thermal power is reduced. At the same time, the amount of peak adjustment is increased to make room for hydropower, and the benefits obtained by hydropower are partially compensated for thermal power.

2.4.2 Hydropower and other energy management and implementation

In order to focus on global climate change issues and increase the proportion of non-fossil energy in primary energy consumption, the proportion of renewable energy in the world's future energy structure will increase, and clean energy such as hydropower, wind power, photoelectric power generation, nuclear power will bear the heavy responsibility of the world's energy structure adjustment. Vigorous development of clean energy will become an important measure to promote the energy production and consumption revolution and promote energy transformation.

Energy sources such as water, wind and solar energy have their own advantages and disadvantages, and there is a strong complementary potential. In order to improve energy efficiency, joint optimization of various energy sources is imminent.

2.4.2.1 Joint operation of hydropower and photoelectric power generation

Although solar energy resources are abundant in the world, in view of the fact that photoelectric power generation must have lighting conditions, it has nighttime intermit tentness and a certain degree of randomness. Only by cooperating with other energy storage devices can it make up for the electric energy vacancy caused by the inability of photovoltaic power generation at night to form a stable electric energy output. For photoelectric power plants with a capacity of more than one million kilowatts, at least a large-scale energy storage system with daily regulation and above needs is required for adjustment. At present, large-scale hydropower stations are the only choice.

Chinese Longyangxia Water and Light Complementary Example

China Longyangxia Hydropower Station has a single unit capacity of 320MW, 4 units installed, and grid-connected photoelectric power stations installed at 850MWp. Since the power of the photoelectric power station is sent to the Longyangxia Hydropower Station through the 330kV line, and the five 330kV lines of the Longyangxia Hydropower Station are used to access the grid. The Longyangxia Hydropower Station and the PV Power Station can be seen as one power point from the perspective of the grid system. That is to say, the daily dispatching department issued the overall power generation index for the Longyangxia water and solar hybrid project, and the water and light complementary coordinated operation control system controlled the AGC and AVC of the Longyangxia hydropower station and the photoelectric power station to realize its dispatching target.

A large number of experimental data show that the peaking and frequency regulation performance of the Longyangxia Hydropower Station, which is generally worried, has not been affected, but has been further strengthened. The annual utilization hours of the Longyangxia Hydropower Station transmission line can be increased from 4,621 hours to 5,019 hours. Improve the economic benefits of hydropower stations.

The grid-connected photoelectric power station is connected to the hydropower station, and the hydropower station is connected to the system. On the one hand, it solves the problem of the long-distance access system of the photoelectric power station. On the other hand, it is feasible to adjust the output of the photovoltaic power station through the rapid adjustment ability of the hydropower station, and to reduce the impact of the output of the photovoltaic power station on the system due to changes in weather conditions.

2.4.2.2 Joint optimization operation of hydropower and wind power and photoelectric

Hydropower is a high-quality power source. Wind power and solar photoelectric power generation are both intermittent energy sources. Hydropower, wind power and photoelectric combined operation will help maximize the proportion of renewable energy power grids, reduce wind (light), and benefit the grid system. Smooth and safe operation, while reducing the proportion of fossil energy consumption.

When the coordinated operation of hydropower, wind power and photoelectric power generation is arranged, priority should be given to the dispatching operation of wind power and photoelectric, so that the equivalent load curve is formed on the basis of the system load curve. On the equivalent load curve, optimally arrange the adjustable output part of the hydropower station with a regulated storage capacity for dispatch operation. In this way, hydropower operates at the high-end position and exerts capacity benefits. It not only participates in the regulation of the load, but also participates in the regulation of wind power and photoelectric, that is, the coordinated operation of hydropower and wind/PV power.

Complementary example of "hydropower and wind/PV power" in Yalong River, China

China's Yalong River Basin has unique water, wind and solar resources. Through the complementary of wind power, photoelectric, and hydropower, the comprehensive adjustment capability of the cascade hydropower station and the existing delivery channel are the effective ways to solve the bottleneck of wind power and photoelectric development.

The output of wind power and hydropower showed obvious complementarity during the year. During the dry season, the wind power output is large, and the average wind power output during the flood season only accounts for less than 10% of the installed capacity. The complementary characteristics of the two can be used to bundle the electricity and make full use of the hydropower output channels. Photoelectric has little difference in each month of the year, but it also exhibits certain complementary characteristics with hydropower. The output process of wind, light and water in the

Yalong River Basin is shown in Figure 2-6.

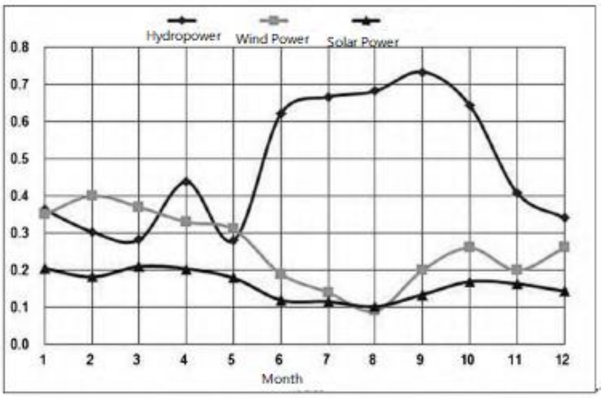

Figure 2-6 The output process of the ‘hydropower and wind/PV power’ in the Yalong River Basin

The daily output of wind power and photoelectrics shows an obvious complementary form. When photovoltaic output is zero, wind power output is at its peak. Wind power and photovoltaic power generation form a relatively unified complementary relationship within the day. This complementarity reflects the complementary advantages of multiple clean energy sources of ‘hydropower and wind/PV power’. The advantages are shown in Figure 2-7.

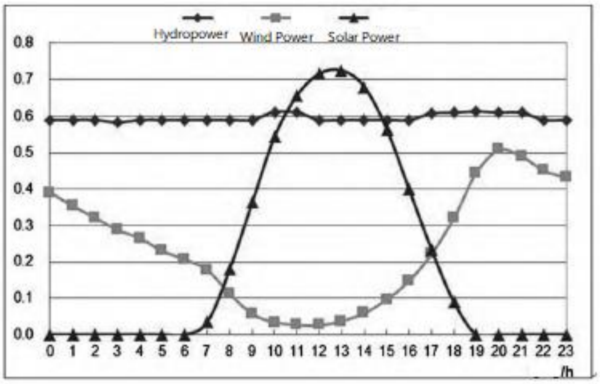

Figure 2-7 In-day output process of scenery water in the Yalong River

According to the preliminary plan, about 80 wind farm sites will be laid along the coast of the Yalong River basin, with an estimated installed capacity of 12.61 million kW; about 25 photovoltaic power generation sites, with an estimated installed capacity of 18.16 million kW. After the regulation of the Lianghekou Hydropower Station Reservoir in 2025, the output process of the downstream cascade hydropower station was optimized. The available passageway in the Yalong River Basin increased to 19.6 million kW. According to the power transmission capacity of the cascade transmission channels in the middle and lower reaches of the Yalong River, the wind/PV power abandonment rate does not exceed 5% of its maximum transmission capacity, the hydropower transmission channels in the middle and lower reaches of the Yalong River can absorb the total installed capacity of wind power and photovoltaic power generation about 13 million kW, reaching 10 million kilowatts or more.

Multi-energy complementary examples of the four Nordic countries

The four Nordic countries (Norway, Sweden, Finland, Denmark) are networked. In Norway, hydropower accounts for 90% of all power sources.In Sweden and Finland, hydropower, thermal power, and nuclear power dominate the power system. As Denmark's terrain is low, thermal and wind power accounts for nearly 100% of the power production. There are many run-of-river hydropower stations in Sweden and other countries. When the flood season comes, there is a large amount of abandoned water. Therefore, when planning the development of small watersheds, Norway fully considers pumped storage and trans-basin water transfer, which is to connect several parallel river waterways into one, to integrate small power stations into larger power stations, and to use natural and superior terrain. The mountain reservoirs are properly arranged to store excess water during the wet season, while the water in the reservoir is released during the dry season, so that the various cascades downstream of the reservoir can generate more electricity during the dry season. Using its geographical advantages, Norway has purchased a large amount of low-cost electricity from neighboring countries during the wet season to pump water to fill large reservoirs on the mountains. In the absence of electricity in neighboring countries during the dry season, Norway puts water in the mountains down to generate electricity and sell them. In this way, the annual net income can reach more than 12 billion US dollars.

One special feature fo the Norwegian hydropower system is the high storage capacity. This is important because there must be a balance between production and consumption The growing share of intermittent production technologies in the Nordic and European power system makes even more vital that there is flexibility available, in order to reduce vulnerability to fluctuations in production between seasons and years.

[Source: energifaktanorge.no]

2.4.3 Hydropower optimization scheduling strategy and implementation in the context of electricity market

In the electricity market, the United States, Canada, New Zealand, Australia, the European Union and other countries already have mature market operation systems (wholesale market, retail market, auxiliary service market) and trading organizations, power regulatory systems and risk management and control measures. China's new round of power market reform has just started, and qualified regions are in the active exploration stage of establishing a medium- and long-term transaction as the mainstay, supplemented by spot transactions, and at the same time advancing the construction of auxiliary service markets.. The final mature China's power system model depends on what kind of energy supply trading mechanism model is needed to ensure reliability, guide the use of electricity and investment, and smoothly transition from long-term capacity incentives to power competition. Achieve short-term and long-term equilibrium.

Most of China's hydropower resources are concentrated in the southwestern region, followed by the central and southern regions, while the economically developed load demand areas are mainly concentrated in the southeastern coastal areas. The large-capacity, long-distance, and high-voltage across the provinces are the main transmission, distribution, Supply and demand mode of hydropower in China. .

In the current hydropower optimization production scheduling, special inter-provincial cross-regional trading rules and regional market trading mechanisms are formulated, and hydropower clean energy consumption is promoted through various mechanisms such as agreement transactions, power generation contract transfers, centralized bidding, listing transactions, and spot transactions. In the cross-provincial transnational transactions between the United States and Canada, in the case of stable power transmission and reception, it is usually carried out by signing a long-term contract; in the case where the receiving side has established a spot market, cross-provincial cross-border power transmission can also directly participate in the end of the power spot market, long-term contracts can be directly converted into CFDs.

In areas with abundant hydropower resources and limited consumption space, using bilateral negotiations, monthly listings, power generation contract transfers, temporary listings and other measures to increase hydropower delivery and consumption. Regarding the consumption of surplus hydropower, the price mechanism of surplus hydropower will be adjusted to enhance the competitiveness of the hydropower market. For example, China's Sichuan Province adjusted the policy of flood/dry season and peak-to-valley electricity prices to promote the consumption of hydropower resources. The Ontario government of Canada introduced a market incentive component in hydropower's power generation revenue by "regulating fixed price + market incentives" to encourage it to adjust power generation based on market price fluctuations. It not only provides a stable return on investment for hydropower, but also reduces the operational risks of hydropower enterprises. It also stimulates hydropower to generate electricity at high prices and fully utilizes its peaking function.

3 Key technologies for cascade dispatching in river basins

The implementation of cascade joint dispatching of river basins needs related key technologies as support, including meteorological forecasting technology, hydrological forecasting technology, joint dispatching key technologies and dispatching decision support systems.

3.1 Weather forecasting technology

The main content of conventional weather forecasts is the forecast of cloudy, sunny, rainy, snowy, maximum and minimum temperatures, wind direction and wind force, and special severe weather in a region or city in the future. The meteorological station accurately forecasts the location and intensity of natural disasters such as cold waves, typhoons, and rainstorms, and directly serves industrial and agricultural production and the lives of the people. Among various meteorological elements, precipitation is the most important factor that affects reservoir operation and efficient use of water resources. Therefore, the meteorological forecast serving the dispatch of river basin reservoirs and reservoir groups focuses more on precipitation forecast, and the most concerned is the reservoir control basin. The total amount of precipitation in the country and its temporal and spatial distribution. In recent decades, meteorological forecasts for river basins have continuously developed from qualitative and descriptive forecasts to digital and grid-based forecasts, and their forecast temporal and spatial resolution and accuracy have been greatly improved..

3.1.1 Classification of watershed precipitation forecast

According to the length of the foreseeable period, the basin precipitation forecast can be divided into the following categories:

1) Short-term near-precipitation forecast: forecast of 0-6h in the future.

2) Short-term precipitation forecast: forecast of 0-3d in the future.

3) Mid-term precipitation forecast: forecast for the next 3-10d. The medium-term precipitation forecast focuses on the forecast of the precipitation process.

4) Extended precipitation forecast: forecast from the 11th to the 30th day in the future. The precipitation forecast in the extended period focuses on two aspects: First, the forecast of precipitation process, including the description of the number of precipitation processes, the occurrence time of precipitation, the intensity of precipitation and the location of the center during the forecast period; the second is the forecast of precipitation trends, including the total precipitation during the forecast period. Description of quantity and distribution.

5) Long-term change trend prediction: monthly and above monthly change trend prediction, mainly including monthly and seasonal change trend prediction. Some large-scale reservoirs or groups of reservoirs focus on the prediction of the evolution trend of the critical period of reservoir operation according to the requirements of reservoir operation.

3.1.2 Development process of drainage area precipitation forecasting technology

Drainage area precipitation forecasting has emerged with scientific hydrology. Accurate watershed meteorological and hydrological forecasts are the key to the rational use of water resources and the full use of comprehensive benefits such as flood control, power generation, and shipping. In China, taking the Yangtze River basin as an example, in recent decades, with the development of hydropower in the upper reaches of the Yangtze River and the Jinsha River, Yalong River, Dadu River, Wujiang River and other river basins, a large-scale reservoir group has formed in the upper reaches of the Yangtze River, serving the reservoirs. The dispatched catchment precipitation forecasting technology is also becoming more mature. The development of watershed precipitation forecasting technology in the industry has roughly gone through four stages:

The first stage: 1950s-1960s, mainly using statistical forecasting methods. The statistical forecast became an independent branch of the forecasting method from the late 1950s to the early 1960s, and it became an important means of forecasting meteorological elements in the late 1960s. The forecast value of the statistical forecast often differs greatly from the actual value. The forecast value is generally biased towards the average value and the amplitude is small.

The second stage: 1970s-1980s, mainly using weather map forecasting methods. Weather forecasters use weather maps to infer changes in the circulation situation and make predictions about precipitation. The method needs to manually draw and analyze the weather map. The forecast is extrapolated and subjective judgment. The details of the evolution of the weather system are difficult to identify, and the timeliness and accuracy of the forecast still cannot meet the needs of reservoir group scheduling.

The third stage: 1990s-2010s, mainly using numerical weather prediction technology. The modern medium-term numerical weather prediction model can provide daily circulation situation and meteorological element forecast in the next 1-10 days. The timeliness and accuracy of watershed precipitation forecasting have been greatly improved by the continuous advancement and wide application of numerical weather prediction technology.

The fourth stage: Since 2010s, Mainly develop and apply grid forecasting technology. Numerical forecast products are an important foundation, but only numerical forecasts are not enough. The China Meteorological Administration has started the construction of a grid weather forecast system in 2013. After several years of development, it has achieved important results in the ways and methods of realizing smart grid forecasting. The core of grid forecasting is objective forecasting technology. Through the application of objective forecasting technology and fusion of subjective forecast corrections, the precipitation forecast of the basin has entered a refined stage in terms of time, space and frequency.

3.1.3 Key technologies and methods for precipitation forecasting

The precipitation forecast of the drainage area mainly focuses on the precipitation trend in the area controlled by the reservoir. After years of development, a seamless drainage area reservoir group precipitation forecasting technology covering time scales from short-term approaching to short-term, extended, monthly, and critical periods (seasons) has been gradually formed.

3.1.3.1 Short-term near-quantitative precipitation forecasting technology

Heavy precipitation is one of the factors that cause flash flood disasters. Early warning and nowcasting are of great significance to disaster prevention and mitigation and reservoir dispatch. At present, the nowcasting method based on radar observation data and the rapid assimilation mesoscale forecasting system are the key technologies that constitute the short-term nowcasting system and the important technical support for the forecast and early warning of meteorological disasters. Because radar extrapolation forecasting and numerical forecasting technologies have their own strengths, it is considered to combine radar echo extrapolation and high-resolution numerical model forecast results through fusion technology to form the optimal forecast of hourly quantitative precipitation, which is a short-term forecast Current main development direction[1].

3.1.3.2 Short-term precipitation forecasting method

In recent years, many studies on global hydrometeorology have pointed out that the integrated forecasting quantitative precipitation forecast technology (Quantitative Precipitation Forecast, QPF) is an important method to improve the accuracy of hydrological forecast-oriented precipitation forecasts in the basin.

Numerical prediction is the technical foundation and development core of QPF. Although precipitation is one of the most difficult variables to forecast in the model, continuous model upgrades (including increasing resolution, improving data assimilation capabilities, and improving numerical techniques and physical processes, etc.) can continuously improve precipitation forecasting skills. At present, there are several commonly used numerical forecast model products in the business: ECMWF, NCEP-GFS, GRAPES, etc. The following briefly introduces several numerical models and their precipitation products:

The NCEP Global Forecast System (GFS) is the basis for the application of NCEP data to forecasting operations. They use the most advanced global data assimilation system and a complete database to perform quality control and assimilation of observational data from various sources to obtain a A complete set of reanalysis data, which not only contains many elements, a wide range, but also extends over a long period of time, and is usually used as a historical fact in scientific research. The spatial resolution of NCEP precipitation data is 0.5°, and the longest forecast time limit is 11 days.

The Global Regional Integrated Assimilation Forecast System (GRAPES) is a new generation of numerical forecast system independently developed by China with the support of the Ministry of Science and Technology and the China Meteorological Administration. By the end of the Tenth Five-Year Plan, the research and development of the GRAPES basic system has been completed, and the GRAPES medium-scale forecast system has been operationalized. The spatial resolution of GRAPES-GFS precipitation data is 0.25°, and the longest forecast period is 10 days. The spatial resolution of GRAPES-MESO precipitation data is 9km, and the longest forecast time limit is 3.5 days.

3.1.3.3 Prediction method of extended period precipitation trend

In the current weather and climate forecasting business, the 10--30d extended-range forecasting is a difficult point in "seamless forecasting". The reason for the difficulty of forecasting is that its forecasting timeliness exceeds the theoretical upper limit of deterministic forecasting (about 2 weeks), and the time scale of forecasting objects is smaller than the monthly and seasonal time scales of climate forecasting. Therefore, extended-period precipitation forecasts usually adopt integrated techniques.

At present, there are three main types of extended-range forecasting methods in the meteorological industry. The first category directly increases the integral length of the meteorological forecast model to develop extended-range forecasts, as well as the interpretation and application of dynamic model products. For example, the CFS (Climate Forecast System) model of the National Environmental Forecast Center of the United States, the European Centre for Medium-Range Weather Forecasts (ECMWF), and the DERF (Dynamic Extended Range Forecast) model of the National Climate Center of China Meteorological Administration. In such methods, the output results of the model are directly applied. In addition, in the past 10 years, data assimilation technology and model performance have been greatly improved, and ensemble forecasting technology has been widely used, which also provides favorable conditions for improving extended-range forecasting skills. Using the method of ensemble forecasting, the inevitable uncertain factors in the numerical model become part of the forecast. Ensemble forecasts can estimate the distribution of forecast errors and the reliability of forecasts to gradually improve the stability of forecasts. The European Centre for Medium-range Weather Forecasts (ECMWF) is leading the world in this aspect, and the forecast timeliness has reached about 15 days.

The second major type of extended-range forecasting method is the physical analysis and statistics method, which uses atmospheric low-frequency signal data to obtain the period and oscillation amplitude of the atmospheric low-frequency signal, and then uses these low-frequency signals to extrapolate to develop extended-range forecasts. Representative methods are Low-frequency weather chart method, low-frequency period extrapolation method, previous climatic feature similar fluctuation extrapolation method, low-frequency intraseasonal oscillation similar extrapolation method in low and middle latitudes, etc.

The third category of methods is the big data forecasting method. Using technologies such as data decomposition, expansion and transformation, some valid data are extracted from scientific big data with high data correlation and multiple data attributes, so that more comprehensive information on mid-latitude atmospheric low-frequency changes can be obtained than in the past sampling analysis, which is extreme weather The extended-range forecast of events from 10 to 30 days provides a better development basis and has broad application prospects.

3.1.3.4 Prospects for meteorological forecasting technology

In recent years, with the advancement of the modernization of weather business, artificial intelligence (AI) technology has been gradually applied in the weather industry. Traditional weather forecasts continue to develop more complex dynamic numerical models in order to forecast the weather more accurately and in advance, while artificial intelligence weather forecasting is based on the forecasting technology driven by big data. In fact, these two methods solve different problems, namely The evolving numerical model system provides higher resolution and more accurate forecast results. However, due to its own shortcomings and the uncertainty of weather forecast, it still cannot meet the different needs of various users. Data-driven methods are used to bridge this gap. Provides very useful tools. In the next 10 years, the integration of numerical forecasts based on physical models and data-driven methods will bring new opportunities to meteorological forecasts, such as applying machine learning to forecasts that are difficult to process with physical models in order to provide more valuable The information helps human beings come up with better decision-making plans when dealing with weather effects.

3.1.4 Application of precipitation forecast in reservoir dispatch at domestic and abroad

Numerical weather forecasting is widely used in reservoir operations abroad. For example, the Norwegian Meteorological Institute (DNMI) has released a quantitative forecast model LAM suitable for the characteristics of Norwegian meteorology, which can issue a grid-based quantitative precipitation forecast with a forecast time limit of 36 hours. Based on the results of the Global Forecast System (GFS), the Iranian Meteorological Organization developed the Regional Numerical Weather Forecast System (RFS) in 2005 and used radar precipitation data to correct the model results. Then the precipitation forecast result is used as the input of the hydrological forecast model and applied to reservoir operation and power market forecasting. Brazilian Hydropower’s weather forecast mainly comes from two models: one is the GEFS (Global Ensemble Forecast System) model data developed by the National Oceanic and Atmospheric Administration (NOAA) for short- and medium-term forecasts within 10 days. The other is the Eta regional mode, which is mainly used for short-term weather forecasts. An intelligent grid forecasting system for the power station control basin has been developed in the section from the lower reaches of the Jinsha River to the Three Gorges in China. There are two main technologies used in this system: one is modeling, which uses the raw data of large-scale models and mesoscale models (wrf-9km, GRAPES-MESO) such as Europe, NCEP, GRAPES-GFS, and Data of different resolutions are bilinearly interpolated to a unified 5km×5km fine grid to generate short- and medium-term (0-10d) objective and refined precipitation grid forecast products. The second is multi-model integration. The Multifactorial Optimal-integration Forecast Approach in fine-Region (MOFAR) for short has been developed. This method is to dynamically test the precipitation products of multiple numerical forecast models. Establish the classification and time-dependent precipitation forecast performance ranking of each district, and then quantify the forecaster's experience, and finally provide the best precipitation forecast product.

The precipitation forecast of the drainage area is highly professional, and it must be closely followed the development of weather forecast while integrating the water regime forecast. Accurate precipitation forecasts are conducive to prolonging the forecast period of flood flow forecasts and improving the accuracy of flood peak flow forecasts. Then, based on the information of water and rain conditions, reservoir operation strategies can be formulated to achieve efficient use of water resources.

3.2 Hydrological forecasting technology

Hydrological forecasting is based on known information to make qualitative or quantitative predictions of hydrological status in a certain period of time in the future [1]. Hydrological forecasting technology is based on the basic laws of hydrology and hydrological model research, combined with the needs of practical production problems, constitutes a specific forecasting method or forecasting scheme to serve the actual production [2]. Hydrological forecasting technology has been widely used in flood control, drought resistance, water resources development and utilization, national economy and national defense, etc., with huge economic benefits and numerous application units.

In reservoir management, hydrological forecasting provides decision-making basis for flood control and optimal utilization of water resources, and there is a certain difference from conventional hydrological forecast (see Chart 5). The most important concern in reservoir management scheduling is the amount of water and water level. Therefore, the main elements of hydrological forecasting are reservoir inflow and flood regulation water level.

Chart 3-1 Comparison of conventional hydrological forecasting and hydrological forecasting based on reservoir management scheduling

No.	Conventional hydrological forecast	Reservoir hydrological forecast
1	River flood forecast	Mainly based on the use of water conservancy projects. The production and convergence of natural watersheds is supplemented.
2	Provide flood warning for flood control departments	Provide flood warning information for flood control departments. Provide decision-making basis for reservoir dispatching and utilization. Forecast pre-storage/pre-discharge to maximize overall benefits.
3	"Flood prevention" forecast. Focus on the flood peak forecast.	"Water resources" forecast. Focus on flood forecasting.

3.2.1 Hydrological forecast classification

According to the forecasted projects, it can be divided into runoff forecast, ice forecast, sand forecast, water quality forecast and typhoon forecast [3]. The reservoir management mainly focuses on runoff forecasting, which is divided into short-term hydrological forecast and medium- and long-term hydrological forecast according to the foreseeable period.

1) Short-term hydrological forecast: The foreseeable period is generally several hours to several days, including rainfall runoff forecast and river section flood forecast. Due to different reservoir scheduling rules, the definition of the forecast period for short-term hydrological forecasts is different. For example, in Brazil, the short-term forecast of the interconnected power system reservoir is the rainfall and runoff forecast within a week; in the French Ariel cascade water resources management, the short-term forecast is the future 24-hour runoff forecast..

2) Medium-term and long-term hydrological forecasting: Usually refers to hydrological forecasts whose forecast period exceeds the maximum confluence time of the basin, such as ten-day, monthly, and annual runoff forecasts, drought and flood trend forecasts, mainly using cause analysis and mathematical statistics. According to the length of the forecast period, it can be divided into: medium-term forecast (3 days-15 days), long-term forecast (15 days-1 year), and ultra-long-term forecast (over 1 year). The length of the forecast period varies with the requirements of reservoir operation.

3.2.2 Hydrological forecasting technology development process

Hydrological forecasting before the 14th century is still in its infancy, only empirical calculations and estimates; from the early 15th century to the mid-20th century, the period has made great progress in concepts, experimental research, and experience-related laws [2], especially Darcy groundwater theory, Mulvaney's torrential rain formula, and GTMcCarthy's Muskingen channel flow calculation method laid the foundation for hydrological forecasting.

In the second half of the 20th century, a new situation emerged in the development of hydrological forecasting technology. With the application and development of computer technology, the acquisition, transmission and processing of hydrological information is more rapid and simple, saving a lot of manpower and time; in addition, the rapid development of communication technology and satellite remote sensing technology enables hydrological forecast data to be monitored and stored. The transmission aspect has been greatly improved, thereby improving the accuracy of the forecast results. In the early 1980s, countries such as the United States, the United Kingdom, and Norway adopted a modified depth sounder to greatly improve the flow measurement accuracy and shorten the flow measurement time of large river floods, especially high-speed floods. At the same time, countries began to study the relationship between rainfall and runoff in different regions, and successfully carried out research and application of watershed hydrological models and forecasting methods with different watershed characteristics. At present, in order to efficiently perform reservoir hydrological forecasting, both hydrological forecasting systems such as data collection and management, meteorological and hydrological coupling, multi-model combination, and forecasting evaluation have been developed and applied to provide decision support for reservoir dispatching, such as the Three Gorges Dispatch and Communication Center. The hydrological forecasting system of the upper reaches of the Yangtze River, the hydrological forecasting subsystem of the Brazilian interconnected power system, and the US RFC system.

3.2.3 Key Technologies and Methods for Hydrological Forecasting

Existing hydrological forecasting methods are divided into parametric and nonparametric methods [4]. Traditional conceptual models, distributed models and mathematical statistical models are mostly parametric models. The recently developed phase space prediction methods based on chaos theory and nonparametric regression methods developed from traditional regression models are nonparametric methods. The classification of hydrological forecasting methods is shown in Figure 3-1.

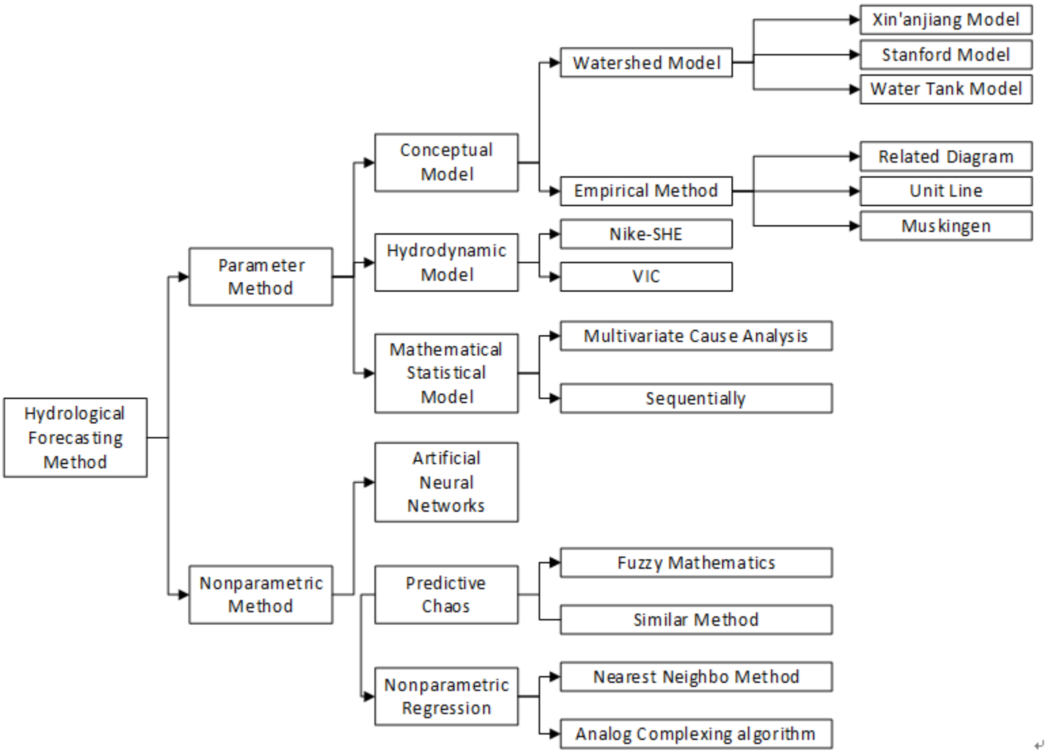

Figure 3-1　Classification of hydrological forecasting methods

3.2.3.1 Short-term hydrological forecasting method

1)Practical hydrological forecasting scheme based on correlation graph method

The practical hydrological forecasting scheme based on the correlation diagram method is summarized and condensed through long-term practical work experience. Its essence is to regard the causes and results of hydrological phenomena as independent variables and dependent variables, and use statistical correlation or other relevant fitting techniques for the measured values. , Find the quantitative relationship between them or directly use the graphic method to find the correlation. This method not only has a certain theoretical basis, but also has a large amount of measured data as the basis, can fully integrate the characteristics of the basin, and generally has high forecast accuracy. Common practical hydrological forecasting schemes based on correlation diagrams include rainfall runoff experience correlation method (API model), upstream

and downstream corresponding water level (flow) method, synthetic flow method, multi-element coaxial correlation method, etc. [5]..

2)Basin hydrological model

The hydrological forecasting model attempts to fundamentally solve the mechanism and law of hydrological phenomena by simulating the internal relationship of the hydrological system, and has made great progress compared with the practical hydrological forecasting scheme based on the correlation graph method.

1) Traditional lumped concept hydrological model

The traditional lumped conceptual hydrological model means that its model has certain physical meaning, but it is not a dynamic equation established completely based on the physical process of rainfall and runoff. It simplifies the rainfall runoff process, so many parameters are empirical parameters and cannot be directly Obtain and homogenize the parameters. Traditional hydrological forecasting models include river basin hydrological models (such as Xin'an River model), river routing hydrology and hydraulics models (such as Muskingen river algorithm, dynamic wave flood evolution model), etc. Traditional hydrological models have been eliminated and screened in practice and become the mainstream of forecasting operations, mainly because their accuracy is reliable and their reliability has withstood decades of forecasting practice; it is convenient for empirical correction. After long-term use, these models are gradually combined with the experience of forecasters. ; Epistemology reflects the macro law of floods.

2) Modern distributed physical hydrological model

The distributed hydrological model with strong physical mechanism is based on the principles of physics and the characteristics of the watershed to derive a set of interrelated mathematical equations describing the process of rainfall runoff, saturated unsaturated zone water flow, and sediment production and transportation. It can also reflect the non-uniformity of parameters. Homogenization is a good description of the temporal and spatial variation characteristics of parameters, such as SWAT in the United States and TOPMODEL in Japan. The distributed physical hydrological model mainly has the following advantages: the model structure is rigorous, the parameter meaning is clear, and conventional theories can be used to describe the process of changing hydrological elements with time and space; the model can be established in areas lacking hydrological data; it can be combined with GIS, RS and other technologies Obtain more detailed basic data that matches the actual situation.

3.2.3.2 Medium and long-term hydrological forecasting methods

1)Traditional medium and long term hydrological prediction method

First method is Hydrological statistics method. The hydrological statistical method is to apply the mathematical statistics theory and method to find the statistical relationship between the forecast object and the forecasting factor or the statistical law of the historical change of the hydrological element from a large amount of historical hydrological data, and establish a forecasting model for forecasting. It is mainly divided into two categories: single factor forecasting and multi-factor comprehensive forecasting. Second method is Genetic analysis method. This method uses many factors such as early atmospheric circulation, early sea temperature characteristics, relative sunspot cycles, changes in the Earth's rotation speed, planets and many other factors to make a qualitative estimate of the later hydrological situation. Linking atmospheric circulation, long-term evolution of astronomical geophysical factors, and the law of succession to the mid- and long-term forecast of hydrological elements is an important way with a physical basis, and it is also the future development direction of medium and long-term hydrological forecast.

2)Modern medium and long-term hydrological prediction methods

Modern methods are divided into two categories. One is to use some modern mathematical methods to forecast, mainly fuzzy mathematics, artificial neural network, grey prediction, hydrological stochastic simulation, etc., and the other is driven by climate dynamics. Dynamic mode method, and extended probability method based on historical rainfall rainfall. The dynamic model method is based on long-term climate prediction, using climate data as the driving data, and conducting medium and long-term forecasts. For example, the 2017 European Central Numerical Forecast indicates that there is no obvious precipitation in the south of the Yellow River in eastern China, and the results of the Japan Climate Center are North China, Huanghuai, Jianghuai and South China have more precipitation; the extended probability method, such as the America ESP, assumes that the historical rainfall process will repeat itself in the future, using the initial conditions of the current forecast day, using the historical rainfall for conditional simulation, with the results of the conditional simulation Statistical analysis is then performed to give a probabilistic forecast.

3.2.3.3 Key technologies for hydrological forecasting

In the past ten years, with the development of science and technology, some high and new technologies have been applied in hydrological forecasting, which has improved the accuracy of forecasting and prolonged the forecast period of forecasting.

1. Model parameter optimization technology. In the calibration of the model parameters, a variety of mathematical automatic optimization methods such as Rosenbroke, simplex and genetic genetic methods are widely used, which improves the automation of parameter recognition and speeds up parameter optimization. At the same time, it is controlled by the objective function and automatically adjusts the optimization search direction to find the optimal range faster.

2. River system forecast. Making full use of the water and rain station network in the basin, and refinement of forecast units can effectively improve forecast accuracy. As the current construction of water conservancy projects has changed the flow generation and convergence of natural river basins, especially the construction of large-scale reservoirs, not only the natural river courses have been changed, but also the regulation of reservoirs has made accurate river system forecasting difficult. Therefore, making full use of the reservoir nodes, understanding the water regulation and storage situation, and grasping the discharge flow is one of the keys to the current river system forecast.

3. Coupling prediction technology of precipitation and flood. Coupling fixed-point, quantitative, and timed precipitation forecasts with flood forecasts can increase the forecast period and improve forecast accuracy. In recent years, the development of numerical weather forecasting technology has provided new ideas for precipitation forecasting, flood forecasting and early warning. Since the Ensemble Prediction System (EPS) can well consider the uncertainty of the model, changes in boundary conditions and data assimilation, ensemble forecasting has been tried to be applied to flood forecasting, early warning, and flood risk assessment.

4. Large-scale meteorological changes. The medium and long-term hydrological change trend is mainly affected by the changes of large-scale hydrometeorological elements, such as changes in ocean factors, especially El Nino, La Nina and other phenomena have a certain control effect on continental hydrometeorology, and the mastery and interpretation of their changing laws will be helpful The accuracy of long-term hydrological forecasts plays an important role.

3.2.3.4 Prospects for hydrological forecasting technology

With climate change and changes in the reservoir operation environment, reservoir operation puts forward higher and higher requirements for hydrological forecasting accuracy and forecast period. Hydrological forecasting is developing towards diversified forecast products, high-precision forecasts with long forecast periods, and probability forecasts with risk identification.

1) Increased forecast demand

From the perspective of forecasting, it is necessary to expand from the Rivers and key areas to digital river basin forecasting in the country; from the forecasting dimension, it needs to expand from the zero-point forecast of the site to the one-dimensional line, two-dimensional surface and three-dimensional body along the river basin. Hydrological forecasting; in terms of forecast content, it is necessary to increase forecasts such as large droughts, mountain torrents, and urban floods; from the perspective of forecasting, from real-time flood forecasting to high-precision medium- and long-term forecasts.

2) Change in forecast results

Deterministic hydrological forecasting will be transformed into probabilistic-based forecasting. Forecasts based on factors (flow, water level, etc.) will be converted into forecasts based on event impact (reservoir scheduling), and flood-based threshold-based forecasts will be converted to risk-based threshold-based forecasts, based on products. The transformation of services into decision support and social service forecasting.

3) Weather forecast

Although there are many numerical forecasting models for precipitation forecasting products such as the European Center, the Japanese Model, the German

Model, and the WRF Model, the complexity of precipitation causes and the experience of interpretation of model products vary from forecasters to short-term forecast precipitation. (1~3 d) Qualitative is more certain, but the medium-term forecast of 4~10 d is dominated by trend, and its accuracy is more difficult to guarantee. The accuracy of precipitation forecast needs to be improved.

4) Hydrological forecast based on drainage area reservoirs

The existing forecasting system and forecasting scheme have been tested in practice for many years and have achieved good results, proving their good technical support for the scientific dispatch and comprehensive management of the basin. However, with the completion of the reservoir group, the original flow production and convergence law of the original river course has been changed, and the hydrological forecasting method of blocking large watersheds still needs to be explored continuously.

3.2.4 Hydrological forecasting ability and level

At present, hydrological forecasting has achieved rapid development in both hardware and software. With the rapid development of computer technology, information technology with computer technology and communication technology as the core technology has been widely used in hydrological forecasting; secondly, the hydrological information flood station network has also been further improved, and major power generation companies will Establish its own dedicated telemetry station network. For example, China Yangtze Power Corporation has established 633 telemetry stations in the drainage area; In addition, the drainage area hydrological model and forecasting technology used in hydrological forecasting have been further developed, and the physicality and technology of the model are advanced. In terms of hydrological forecasting systems, the management agencies of cascade reservoirs in larger river basins in various countries have a set of integrated forecasting systems with more complete functions and high forecast reliability, such as Brazil Interconnection The hydrological forecasting system in the power system, the hydrological forecasting system for the upper reaches of the Yangtze River from the lower reaches of the Jinsha River in China to the Three Gorges cascade reservoirs, and the river forecasting system for the Tennessee Basin in the United States.

The development of precipitation forecasts in the basin has greatly improved the accuracy of hydrological forecasts. At present, the short- and medium-term precipitation forecast in the basin can provide more accurate information on the area of heavy precipitation, the main precipitation period, and the moving path; the monthly precipitation trend forecast in the basin can provide a more accurate overall trend of monthly precipitation. Hydrological forecasting with meteorological and hydrological coupling as the core technology can not only extend the forecast period but also improve forecast accuracy. Now the short and medium-term 3-5d hydrological forecast can accurately forecast, the 6-7d process can be estimated, and the 8-10d can be qualitatively analyzed, which has provided a certain decision-making time and basis for the optimal operation of the reservoir; the long-term runoff trend forecast has been relatively good Accurately provide runoff trends in the next ten, month, and year, and provide important support for long-term reservoir dispatch and power generation plans.

3.3 Key technologies of joint scheduling

3.3.1Overview of joint scheduling

Cascade hydropower stations usually have comprehensive benefits such as flood control, power generation, irrigation, water supply, shipping, ecology, landscape, etc. [1]. Their dispatch has the dual characteristics of water conservancy and electricity. Water conservancy needs to meet the comprehensive utilization of water resources. Electricity requires hydropower stations to provide sustainable clean electricity to meet the energy needs of social and economic development. The two characteristics influence and restrict each other, and have a unity of opposites. There is a close hydraulic connection between the upstream and downstream reservoirs of cascade hydropower stations. The upstream reservoirs play a role of retaining and storing natural water. Especially for large reservoirs with strong regulation capacity, the annual and even inter-annual distribution of inflow and river runoff in the downstream reservoir will change, thus changing the runoff characteristics of the whole basin. The essence of the joint optimization scheduling problem is based on the related theories of operations research and reservoir scheduling [2], abstracting the reservoir scheduling problem as solving the mathematical optimal solution problem with constraints, in order to coordinate the interests and demands of the upstream and downstream water departments in the basin. In order to maximize the comprehensive benefits of cascade reservoirs [3]. The key technologies of joint scheduling mainly include three aspects, as shown in Figure3-2.

The research on hydropower station dispatching technology started earlier. In 1946, American Mase first introduced the concept of optimal dispatching into the field of hydropower station dispatching. The stochastic linear program with recourse was first formulated by Beale (1955) and Dantzig (1955). Many researchers proposed to use Dantzig-Wolfe decomposition (1960) to solve the dual of this problem and others proposed Benders´ decomposition (1962) to the primal problem. In 1962, DoforMa produced a linear programming model with the greatest economic benefit. After Bellman proposed the dynamic programming (DP) method in 1957, DP was widely used in the modeling and solving of hydropower station optimization scheduling. The DP model is not very different in nature. Different dynamic programming models differ mainly in selections of state variables and decision variables , the period length of stages, the continuity and dispersion of state variables and the degree of discretization of decision variables . Although the dynamic programming model can completely preserve the characteristics of the hydropower station optimal scheduling model, the dynamic programming model has the problem of "dimensionality disaster" when solving the optimal scheduling problem of cascade hydropower stations. In addition, some experts pointed out that due to the complexity of hydropower station optimization scheduling problems and the incommensurability between targets, mathematical programming models such as linear programming and dynamic programming models have different degrees of simplification in modeling and solving. Therefore, some experts simulate the optimal operation behavior of hydropower station through simulation technology, and use mathematical description methods to restore the characteristics of optimal operation model of hydropower stations establishing a simulation model of hydropower station optimization scheduling.

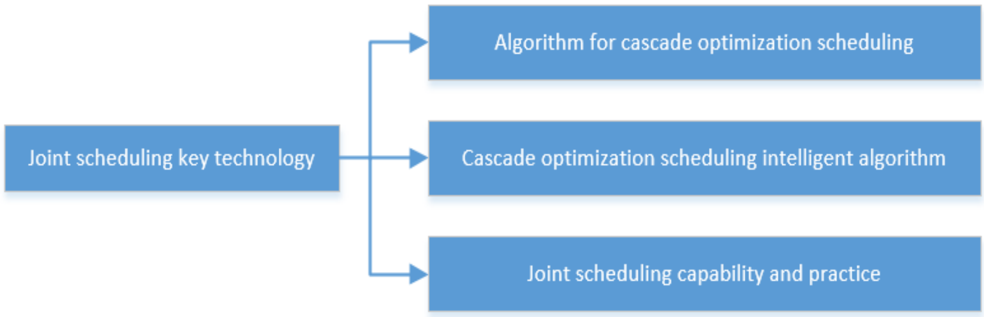

Figure 3-2 The key technologies of joint scheduling

3.3.2 Cascade optimal scheduling algorithm

Relying on the historical hydrological runoff data of the reservoir, the theory of runoff regulation and water energy calculation are used to explore the reservoir dispatching mode, so as to formulate the dispatching rules and guide the operation and management of the reservoir in the form of regular dispatching diagrams or scheduling rules. The traditional conventional scheduling method is intuitive, concise, and easy to use. It focuses on ensuring reliability and has certain physical mechanisms. However, it lacks comprehensive considerations for future future inflow of reservoir and power generation benefits. The scheduling results are conservative, usually feasible solutions rather than optimal, it is difficult to deal with multiple targets, and the joint scheduling problem of constrained and complex river basin reservoirs cannot meet the needs of comprehensive utilization of water resources for social and economic development.Therefore, it is necessary to seek a coordinated and unified scheduling mode among multiple objectives. Based on operational research and reservoir operation theory, the multi-objective optimal operation of cascade reservoirs is abstracted as a mathematical optimization problem with multi-objective and multi constraints. With the help of data processing ability of computer, combined with long-term, medium-term and short-term hydrological forecast results, the optimal operation scheme is found in the solution space satisfying the constraint conditions. Compared with the conventional operation methods, the reservoir inflow forecast, reservoir operation objectives and constraints were taken into account in the optimal operation method , which improves the utilization rate of water energy resources, and has become the main method used in the field of reservoir operation.

3.3.2.1 Linear Programming method

The linear programming method is a mature mathematical method with a wide range of applications. It is mainly used for the optimization problem in which the objective function and the constraint are linear. The calculation is simple and the global optimal solution can be obtained. The establishment of a mathematical model generally has the following steps when solving the practical problems : finding a decision variable according to the purpose; determining the objective function from the functional relationship between the decision variable and the purpose; determining the constraint condition to be satisfied by the decision variable by the constraint condition of the decision variable. Because the target model of flood control scheduling is mostly expressed in a linear way, it can provide a basis for the reasonable scheduling management and operation decision of the dispatching organization. Therefore, linear programming has been widely used in the flood control scheduling problem of reservoirs.

3.3.2.2 Nonlinear programming method

The nonlinear programming method is a mathematical programming in which the constraint condition or the objective function is nonlinear. The objective function and the constraint condition can contain nonlinear expressions. The nonlinear programming method is an important branch of operations research. In the 1970s, nonlinear programming was further developed, and it was widely used in engineering, management, economics and so on, providing a powerful tool for optimizing design. At present, the nonlinear programming method is mostly used to find the optimal point problem of a one-dimensional function in a certain interval, and a large number of multi-dimensional optimization methods rely on a series of one-dimensional optimization. The commonly used one-dimensional optimization method has a golden section method , tangent method and interpolation method. The golden section method is applicable to the unimodal function. The basic idea is to design a column of points in the initial search interval. By comparing the function values one by one, the search interval is gradually narrowed down to obtain an approximate optimal point. The tangent method is also called Newton's method, which is also for the unimodal function, the basic idea of the tangent method is: linearizing the derivative function of the objective function near a guess point, using the zero point of the linear function as a new guess point, and gradually iterating to approximate the most advantage; Interpolation, also known as polynomial approximation, is based on the use of polynomials (usually with quadratic or cubic polynomials) to fit the objective function. In addition, there are Fibonacci method, secant method, rational interpolation method, batch search method, etc. Nonlinear programming method has stronger applicability than linear programming method.

3.3.2.3 Large system method

The large-system method decomposes complex large systems into several relatively independent simple subsystems, first proposed by Dantzig and Wolfe in 1960 to deal with large linear programming problems. In the 1970s, Mesarovic proposed the theory of large-scale hierarchical control. The solution was to first decompose a complex large system into several relatively independent subsystems to locally optimize the subsystem. According to the overall goal of the system, the upper subsystem is used to coordinate the subsystems, and the information exchange between the upper and lower layers is repeated. At the same time as obtaining the extreme value solutions of each subsystem, the overall optimization of the large system is realized. The research on modern practical reservoir dispatching in China began in the 1970s. In the early stage, single-reservoir scheduling was the main one. In the 1980s, multi-objective optimization scheduling of reservoir groups began. A series of theories and methods emerged, including multi-objective and multi-level optimization methods. The target scheduling fuzzy optimization method, etc. The most influential is that the famous scholar Zhang Yongchuan of China has creatively proposed the convex dynamic programming theory and proved the transfer theorem of convexity in recursive calculation, and established the scheduling function and the residual benefit statistical iterative algorithm. It effectively solves the famous problem of dimensionality disaster in multi-database problems.

3.3.2.4 Dynamic Programming method

Dynamic programming was proposed by American mathematician R.E. Bellman et c in the early 1950s to study the optimization problem of multi-stage decision making. Dynamic programming is to transform the multi-stage process problem into a series of single-stage problems. It is an effective method to solve complex nonlinear optimization problems by using the relationship between each stage. Dynamic programming and its improvement method are more optimized,more mature and widely used methods for reservoir scheduling research.

3.3.2.5 Stochastic Dual Dynamic Programming

The stochastic dual dynamic programming (SDDP) is an algorithm for the solution of multistage stochastic optimization problems and was first proposed by Pereira (1989) and Pereira-Pinto (1991). It is based on the approximation of the expected-cost-to-go functions of stochastic dynamic programming by piecewise linear functions. These approximate functions are obtained from the dual solutions of the optimization problem at each stage and can be interpreted as Benders cuts in a stochastic, multistage decomposition algorithm. No state discretization is necessary, and the combinatorial "'explosion" with the number of states (the well known "curse of dimensionality" of dynamic programming) is avoided. The algorithm is also suitable for implementation in parallel processors.

In 1993, the SDDP algorithm was extended to take into account serial correlations of the inflows to reservoirs through auto-regressive periodic models, which allowed to consider the hydrological trend as state variable, Maceira (1993). Consequently, the SDDP method paved the way for considering multiple reservoirs in the long-term scheduling without compromising the computational complexity. This development triggered the development of the SDDP-based NEWAVE model (2008, 2018) by Cepel, the Brazilian Electric Energy Research Center in 1993, that has been used officially since 1998.

3.3.2.6 Progress Optimality method

The Progress Optimality Algorithem(POA) is to transform a complex multi-stage optimization problem into a series of two-stage optimization problems, which was proposed by HR How so n and NGF Sando in 1975. The algorithm decomposes multi-stage problems into multiple two-stage problems. Each time, only the decision of the two stages in the multi-stage decision is optimized, and the last optimization result is used as the initial condition of the next optimization, so that the cycle is repeated step by step until convergence. This method can effectively overcome the "dimension disaster" problem that occurs when the dynamic programming solves the problem [4], and the method does not need to be discrete for the state variables, so that a higher precision solution can be obtained.

3.3.2.7 Discrete differential dynamic programming method

The discrete differential dynamic programming method is based on experience or other methods (such as dynamic programming method) to produce an initial solution that is optimized as much as possible, and then uses the dynamic programming method to search for excellence in the corridor within a certain amplitude of the initial solution:Finding an optimal solution in the channel, then using the optimal solution as the initial solution and iterate iteratively until the convergence accuracy is reached. Since the discrete differential dynamic programming method optimizes in the corridor within a certain amplitude of the given initial solution, the number of discrete points in each iteration calculation is less, thereby greatly reducing the required storage space and computational time, and adapting to large-scale joint optimization scheduling problem of reservoir group [5]. The initial solution is needed for the optimization of the method. It is difficult to choose a reasonable initial solution, and the optimal solution obtained from the initial solution cannot guarantee the global optimal solution. The commonly used method is to select different initial solutions for trial calculation, and compare the trial results to obtain the optimal solution.

3.3.2.8 Extended linear quadratic Gaussian method (ELQG)

"Extended linear quadratic Gaussian (ELQG)" is a very effective method for solving large-scale stochastic dynamic optimization problems. In decision support systems, both long-term and short-term optimization models are solved using ELQG. ELQG was first proposed by Georgakakos and Marks of the Massachusetts Institute of Technology in 1987, and further refined by Georgakakos and Yao, which is a relatively mature and stable method. ELQG is an iterative optimization algorithm that starts with the initial control series {u(k); k = 0, 1, 2, .., N-1} and then gradually finds the improved series until convergence. The ELQG method is characterized by fast calculation speed and no "dimensionality disaster" problem, which is especially suitable for the optimization problem of multi-reservoir systems with uncertain inputs.

3.3.3 Bionics method for cascade optimal dispatch

Modern reservoir operation and decision-making must take power generation, flood control, shipping, ecological and other objectives into account ,which involves both economic benefits and social and environmental benefits .

Due to the defects in traditional optimization methods, such as linear programming, integer programming, nonlinear programming, etc.Some methods can get the global optimal solution, but it takes a long time. Some methods can get the answer quickly, but can not guarantee the global optimal.Some methods are complicated in calculation and need specific expressions, and are only suitable for small-scale optimization problems, so they can not be widely used in engineering practice. At the same time, the modern cascade optimization scheduling problem is becoming more and more complex, It's necessary to achieve multi-objective decision-making under multi-constraints, and quickly and effectively find the best solution, or approximate optimal solution. Biomimetic optimization algorithm provides an effective way to solve multi-objective optimization problems. It is a kind of behavior mode to simulate the structure characteristics, evolution law, thinking mode and foraging process of the natural population. It is also a manifestation of population cooperation mechanism and belongs to the category of swarm intelligence, so it also belongs to intelligent algorithm[6]. According to the mechanism of biological population simulated by bionic optimization algorithm, it can be divided into bionic process algorithm and bionic behavior algorithm. Bionic process algorithm is a kind of optimization algorithm which simulates the evolution process of biological population and develops on the basis of genetic theory. The most representative algorithm is evolutionary algorithm [7] - [9]. Bionic behavior algorithm simulates the social behavior of biological population. The representative algorithms are particle swarm optimization, firefly algorithm, bat algorithm and cuckoo search algorithm.

3.3.3 Practice of cascade joint dispatching in river basins

The cascade optimization of watershed cascades is usually divided into medium and long-term optimal dispatch, short-term optimized dispatch and plant economic operation according to the length of the dispatch period. In the current practice of optimal scheduling, traditional algorithms are widely used, such as dynamic programming and its various improved planning methods. With the enhancement of computer software development capabilities and the improvement of hardware computing efficiency, various intelligent algorithms have been widely used, such as genetic algorithms and neural networks. Through years of operation management, hydropower operation companies all over the world have gained rich practical experience in the cascade optimization of watershed cascades. Through continuous improvement of key technologies for optimization and scheduling, the comprehensive efficiency of cascaded reservoirs in the basin has been improved.

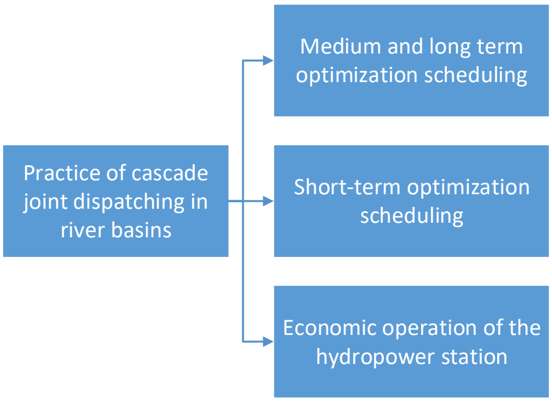

Figure 3-3 Joint scheduling capabilities and practices

1)Medium and long term optimization scheduling

The medium and long-term optimal dispatching of cascade hydropower stations is to formulate optimal operation plans for each power station under different water conditions in the basin. As the overall guidance for the operation of the power station group, it is the basis for the power generation planning and scheduling strategy for the power station to develop annual, monthly, and different periods (falling period, flood season, water storage period, etc.). However, due to the long-term optimization of the medium- and long-term optimization, the impact of the natural water intensive changes and reservoir scheduling capacity is significant, and the randomness and uncertainty of the original information make the medium and long-term optimization scheduling more complicated. Hydropower stations are closely related to multiple water and water control departments, and interact with external factors such as social, economic, and ecological environment, and are subject to internal factors such as the operation of power station units and overhaul of hydraulic structures. These internal and external factors of power station operation have great randomness and uncertainty, such as temporary failure of power station units, temporary work of water discharge buildings, etc, rainfall in the basin has strong uncertainty, and reservoirs are formed through the production and convergence of the reservoirs. The warehousing flow affects the upstream and downstream flood control and irrigation water supply of the reservoir; the load requirements of the power grid are related to the industrial and agricultural production status of the power receiving area, the climatic conditions (cold wave or extreme high temperature), and the requirements of large-scale national activities. With the reform of China's power market, the time-sharing on-grid tariff policy will be gradually implemented and promoted, and will fluctuate according to market conditions and demand for electricity. The implementation of time-sharing electricity price makes it necessary to consider the role of electricity price factor in the process of medium- and long-term optimal dispatching of hydropower stations, and optimize the dispatching operation to maximize the economic benefits of the power station group.

Taking the Three Gorges Group as an example, the Three Gorges Group has put into operation four cascade reservoirs in the upper reaches of the Yangtze River (including the lower reaches of the Jinsha River), from the upstream to the lower, namely Xiluodu, Xiangjiaba, Three Gorges and Gezhouba. Through the establishment of watershed water and rain monitoring system, reservoir dispatching automation system, reservoir group information sharing platform, and disaster early warning mechanism, medium and long-term joint optimization scheduling is implemented. Based on accurate forecasting and forecasting of river basin meteorological and inbound flow, efficient use of water resources has achieved win-win results in flood control, power generation, shipping, water supply, ecology, siltation reduction, and coordination of construction projects.

During the fall-off period, according to the change of the incoming water and the water level of the reservoir, the descending order of the cascade reservoirs is optimized, and the water level is controlled reasonably. At the same time, combined with market consumption, downstream water demand, flood control during flood season, and risk of water abandonment by power station, the water level of each reservoir is further optimized to meet the needs of shipping, ecological water supply, reservoir tailing siltation scheduling test and ecological dispatch test. In the event of a maritime accident, emergency dispatching of emergencies will be carried out, and emergency rescue will be actively coordinated to achieve comprehensive benefits of ecological environment and social economy.

In the flood season, cascade reservoirs jointly implementing joint flood control dispatching, strengthening flood forecasting frequency, improved flood forecasting accuracy, which effectively guarante flood control in the middle and lower reaches of the Yangtze River and the Chuanjiang River. In 2016, the cumulative flood storage reached 8.853 billion m^3. In 2017, a total of three flood control dispatches were implemented, with the maximum reduction of flood peaks of nearly 20,000 m^3/s and the cumulative interception of flood storage of nearly 12.7 billion m^3. By blocking the peaks of floods, the upstream and downstream waters are prevented from overlapping, which effectively alleviates the flood control pressure in the middle and lower reaches. At the same time, the cascade flood control dispatch reduced the duration of the forbidden flight between the Three Gorges and Gezhouba, which improved the navigation capacity of the middle and lower reaches of the Yangtze River. In the flood season of cascade reservoirs, the flood control and power generation dispatching are organically combined through the optimal dispatch of small and medium-sized floods. By the arrangement of water storage work in advance, the water storage and flood season dispatching are closely combined to improve water use efficiency.

During the water storage period, according to the water flow of each reservoir, the consumption of electricity market, the maintenance of power grid equipment and power plant units, the requirements of various water departments, and the needs of ecological environment, the water storage plan at the end of the flood season is optimized, and the water storage process of each reservoir is scientifically arranged. In 2017, the cascade reservoirs ensured downstream water supply demand in the absence of incoming water. Xiluodu and Xiangjiaba use the combined storage capacity to extend the downstream navigation time by about 68 hours. The Three Gorges Reservoir has accumulated 170 days of water replenishment, and the accumulated water supply is 21.8 billion m^3, with an average water depth of 0.7m. It promoted the breeding of the four major fishes and gave full play to the comprehensive benefits of cascade power generation, shipping, water supply and ecological environment.

2)Short-term optimization scheduling

Short-term optimal dispatch refers to the natural water coming in a day and night, and the runoff is redistributed according to the water demand process of the water department. According to the characteristics of China's monsoon climate, the natural inflow water flow during the flood period is large. Hydropower stations can usually generate electricity according to the total installed capacity. The natural water in the non-flood period can be regarded as a uniform flow in the day and night, while the daily demand water in the water sector is uneven. Power generation water, irrigation water consumption, and crop water demand change within a day and night. From the perspective of resource optimization configuration, the short-term optimal operation of hydropower systems is divided into two categories: one is that the total water consumption of the cascade hydropower system is the smallest; the other is that Under the premise of satisfying various constraints, the total power generation of the reservoir group is expected to be the largest during the control period to improve the economic efficiency and operation level of the entire power grid system.In view of the existence of mid- and long-term regulating performance of hydropower stations in hydropower station systems, there is unequal energy storage. Under the market conditions of electricity, due to market competition, there are uncertainties in electricity prices and electricity. Currently, short-term optimal dispatch planning is not only necessary. Consider the effects of cascade propagation time, hydraulic and electrical connections, and consider factors such as bidding and load distribution. In the problem of step load daily distribution, the cascade power station is used as a unified power point. After the power grid releases the 96-step step load in the day, it is uniformly dispatched according to the storage capacity and storage flow of the cascade reservoir, and the load distribution between the plants is the basic operation of the cascade dispatching in the basin. The way is also the basis for making daily plans and real-time operations.Through the optimal allocation of step load, the rice regulating effect of the cascade downstream power station is fully exerted, the load is distributed reasonably among the cascade power stations, and the largest possible economic benefit is obtained, which is the purpose of the cascade optimal dispatching. However, the benefits of cascade hydropower stations cannot be simply regarded as the problem of water quantity and head. It is necessary to consider the utilization of these water

sources in subsequent periods, and consider the time-sharing feed-in tariff, which reflects the time-dependent characteristics of water energy. This is a multidimensional multi-stage nonlinear programming problem. At present, the commonly used optimization scheduling methods are: discrete differential dynamic programming method, genetic algorithm, particle swarm algorithm and so on.

3)Economic operation of the hydropower station

The basic task of the economic operation of the hydropower station is to determine the optimal number, combination and start-stop sequence of the working units in the plant according to the characteristics of the power station and the unit, and to meet the total load or total water consumption, and to realize the optimal load or flow between the units. The purpose is to optimize the operation mode, reduce the production cost of the power station or increase the power generation under the premise of satisfying the safety, reliability and high quality of electric energy production, and has obtained the largest possible economic benefits.The optimization criterion for the economic operation of the hydropower station is: when the load of the power station is given, the water consumption of the power station is required to be the minimum, or when the water consumption of the power station or the flow rate of the incoming water is constant, the power generation is maximized. The former is suitable for hydropower stations with better power plant regulation, and the latter is suitable for hydropower stations with poor regulation capability. The economic operation of the plant includes both space and time. For a certain power generation task, reasonably select the number of units and the number of units, and implement the reasonable distribution of the load between the units in the unit combination. On this basis, consider the connection and influence of the operation modes between the time periods.The optimal operation of the hydropower station in the plant needs to be optimized in both space and time. On the one hand, the production activities are guided in real time in a single time period optimization; on the other hand, the influence of the unit and flow changes over the entire period on the optimization problem is considered. The economic operation in the plant is an important way to improve the efficiency of water energy utilization. In theory, it can be solved by classical methods such as micro-increasing rate method and dynamic programming method.

However, with the increase in the number and type of units, dynamic planning will face problems such as "dimensionality disasters". In order to avoid this problem, some scholars have proposed improved algorithms from different angles, such as two-tier stepwise optimization method, improved mixed integer quadratic programming algorithm, improved dynamic programming method and so on. When the number and type of hydropower units are large, the conventional solution algorithm usually cannot meet the requirements of online practice in production practice for fast solution, calculation accuracy, and stable results. In this case, intelligent algorithms such as immune algorithms, particle swarm optimization, genetic algorithms, and improved genetic algorithms are often used in research, but such algorithms are affected by their own optimization mechanism. There are still some limitations in terms of stability and convergence.

4)Long, medium and short term coupling nesting

Optimal scheduling of cascade reservoirs requires decisions for different lengths of time in the future. The short time scale model provides feedback for long time scale models, and the long time scale model provides control boundaries and constraints for short time scale models. The medium- and long-term scheduling model provides a multi-objective trade-off curve during the planning period, and is gradually implemented according to the runoff forecast information and the optimal operation plan of the reservoir group operating conditions. The short-term model is constrained by the mid- and long-term results, and the long-term average results are distributed to the period of time. Considering the actual demand and forecast deviation, the medium and long-term models need to be updated one by one, and the short-term models need to be updated day by day.Through the initial water level and different levels of forecasting inflow runoff process, the optimal scheduling schemes of different scheduling periods are generated in order, in which the optimized scheduling scheme of the middle and upper model provides the lower level scheduling model with the control water level at the beginning and end of the scheduling period, reflecting the upper layer. The "control" effect of the model on the lower model; then, according to the difference between the actual situation and the expected difference caused by the implementation of the plan, the forecasting inflow process of different levels is updated, and the current water level is taken as the starting water level, and the subsequent remaining period is adjusted. The optimized scheduling scheme reflects the "feedback" of the lower model to the upper model in this process. During the annual dispatch scheme is continuously revised.

3.4 Dispatching decision support system

Decision Support System (DSS) is a computer-based application for collecting, organizing, and analyzing business data to facilitate high-quality business decisions for management, operations, and planning. Well-designed DSS helps decision makers compile data from multiple sources, providing decision makers with the data, information, and background materials needed to make decisions, help identify decision objectives and identify problems, build or modify decision models, and provide Alternatives, evaluation and optimization of various programs, analysis, comparison and judgment through human-machine dialogue to provide useful help for correct decision-making. Unlike operational applications for collecting data, DSS is an application that generates comprehensive information. DSS is primarily used by middle and senior managers and is the key to understanding large amounts of data.

The dispatching decision support system is an application system platform that specifically implements the prediction and scheduling of cascade reservoirs and provides technical support for decision-making and management departments. The dispatch decision support system can automatically and accurately collect the water condition, rain situation, meteorology, hub operation and other information required for the cascade reservoir dispatching, according to the flood control dispatch of the received flood control command department, the power dispatching department of the power dispatching department, and the shipping department. The scheduling requirements and constraint information such as the navigation scheduling are calculated, analyzed and integrated.

3.4.1 Development process of decision support system

3.4.1.1 Research progress of watershed management decision support system in China

In the past, the decision support system was mainly based on the power grid departments, and the power plants and networks were not separated. Later, with the separation of power plants and networks, the cascade reservoirs of the same river may belong to different stakeholders. In order to pursue the greatest overall benefit of the cascade hub, the hydropower development companies of each river basin established cascade dispatching agencies successively. Under the premise that ensure the requirements of the power grid, power generation optimization control and regulation are made for the cascade group. Most of the established reservoir dispatching automation systems are C/S systems, or multi-layer C/S systems, and some reservoirs are even single-machine systems. Under the new situation, reservoir management and reservoir cluster dispatching advantages cannot meet the requirements. With the development of computing and technology, B/S reservoir dispatching system based on service-oriented (SOA) architecture emerges as the times require. At present, this kind of application is gradually applied in pilot projects.

The development process of reservoir operation decision support system is divided into four stages. As shown in Figure 3-6, the early 1980s and before, most of the reservoir operation methods in China are very primitive. The water regime information of the reservoir basin is transmitted by telephone and teletypewriter. The flood forecasting method basically adopts manual experience method, and all kinds of operation schemes are manually checked through charts. A few power stations use microcomputers, but due to the limitations of computer software and hardware, the work efficiency is very low. From the late 1980s to the 1990s, the development of automation technology provided necessary conditions for the construction of reservoir dispatching decision support system, provided hardware resources for hydrological forecast and reservoir water resources dispatching calculation, and enabled the task of large amount of calculation and table lookup to be completed quickly by computer program. At this point, the prototype of reservoir operation decision support system emerges. In the mid and late 1990s, the reservoir dispatching automation system with perfect function and reasonable structure was basically built, which can greatly improve work efficiency, save manpower, make reservoir dispatching safer and more economical, and make the technical management of reservoir dispatching more standardized and standardized. The main functions of the system include information monitoring, inquiry subsystem, flood forecasting subsystem, short-term meteorological quantitative precipitation forecasting subsystem, operation model subsystem, operation calculation and planning statistical report subsystem. Since the end of 1990s, the construction of reservoir dispatching decision support system in China has been the fastest developing decade. The structure of reservoir dispatching decision support system has changed from client/server structure to distributed browser/server structure. It is more convenient to use and deploy, and the maintenance cost has been greatly reduced. A large number of complex and time-consuming computations use this architecture for parallel transformation, greatly improving the overall performance of the system, laying the foundation for the next intelligent construction.

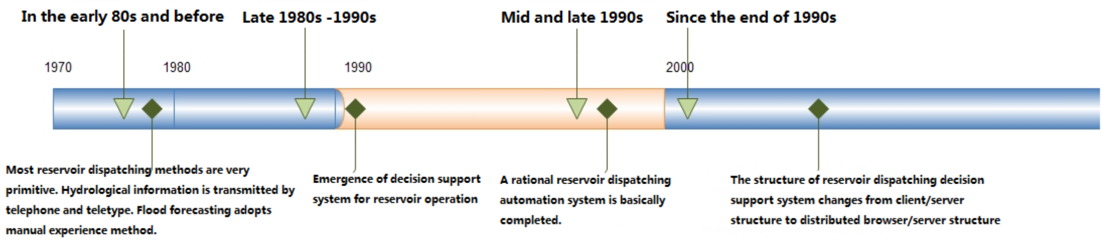

Figure 3-6 Development of decision support system for reservoir operation

3.4.1.2 Research progress of foreign watershed management decision support system

The research on watershed management decision support system in foreign countries started earlier. Some systems with certain functions have been designed and completed since the early 1990s, mainly focusing on water quality analysis, water allocation and planning, and water diversion of tank system. Especially after the promulgation of the European Water Framework Directive (WFD) in 2000, watershed management decision support system (DSS) has entered a period of vigorous development in Europe. At the same time, it has also actively promoted the research and development of other countries in the world, such as the United States, Mexico, India and so on. At present, most of the popular watershed management decision support systems adopt the conceptual model framework of driving force, pressure, status, influence and response (DPSIR), which evaluates the state of the watershed through index calculation or maximizes the comprehensive benefits of the watershed through policy scheme simulation.

As for the decision support system of water resources management, the United

States Army Corps of Engineers(USACE), the Electricite De France (EDF), the Canadian Quebec Hydropower Company (Hydro Quebec), the Danish Hydraulic Institute(DHI) and the Georgia Institute of Technology (GT) have successively developed different reservoir group joint operation models and engineering application systems. In recent years, with the rapid development of distributed architecture and cloud computing technology, the research of decision support system for water resources management has turned to more specialized, customized and efficient. The most representative research is model-driven decision support system based on Cloud Architecture platform.

3.4.2 System structure

The lower reaches of the Jinsha River-Three Gorges cascade reservoirs (Wudongde, Baihetan, Xiluodu, Xiangjiaba, Three Gorges, Gezhouba) are the largest cascade reservoirs in the Yangtze River Basin, which are responsible for flood control, power generation, shipping, water supply, ecological protection, etc. Comprehensive tasks, the large-scale reservoir group, complex connections between reservoirs, and diverse scheduling tasks, joint optimization scheduling operation is extremely difficult, there is no precedent at home and abroad, and there is no unified and effective management and coordination decision support system.

On the basis of investigating advanced model algorithms and decision-making systems for reservoir dispatching at home and abroad, the water resources management decision support system for the downstream of the Jinsha River-Three Gorges cascade hydropower station fully considers the comprehensive utilization needs of the downstream Jinsha River-the Three Gorges cascade reservoir group, as well as the operating conditions of other power plants upstream In line with the power market environment, we have developed a set of decision support systems for water resources management of the Three Gorges cascade power stations on the lower reaches of the Jinsha River with complete intellectual property rights. The system integrates the dispatching simulation of the upper reaches of the Yangtze River reservoir group, high-precision river evolution simulation, the long, medium and short-term cascade reservoir group and the integrated joint optimization dispatching of the plant nesting, the comprehensive evaluation of forecasting and dispatching benefits, and realizes the integration of all river basin information and cross-regional reservoirs. Group joint scheduling, multi-model and multi-scheme comparison decision-making, and the comprehensive application and visual display of multi-scheduling scenarios provide technical support and important guarantee for the scientific configuration and intelligent management of water resources.

The system uses the front-end and back-end separation method to build the overall system framework. The back-end framework is responsible for the calculation of model methods, database interaction and service interface provision, and the front-end framework is responsible for human-computer interaction, model result display and spatial data visualization. The corresponding database table structure is designed for the input parameters of each model, model results, and the data that the model needs to share. At the same time, in response to the needs of system distributed services, the model and database access interface are decoupled, and a unified database access service is written. . The back-end of the system integrates a microservice framework and builds a basic development environment for distributed model services. The front end integrates the current mainstream data-driven progressive framework VUE to build a model data interaction interface. In order to realize the visual display of spatial data, the system has carried out the development of spatial data visualization based on the standard 3D drawing protocol, using the web-side hardware 3D accelerated rendering capabilities provided by WebGL and the spatial map development framework Cesium to build a spatial interactive interface with good interactive performance , And integrated it into the front-end framework to complete the design and implementation of the system interface.

3.4.3 Key technologies of decision support system

With the development of hydropower in China, more and more cascade hydropower stations are being developed, and the amount of data needed to be processed is becoming more and more huge. It is necessary to integrate multi-regional business with distributed database technology and process these data reasonably on cloud computing platform. For example, make the whole life cycle management of data and the effective management of multi-source and multi-professional massive heterogeneous data, so as to achieve full source coverage, whole process traceability, full data cleaning, full information transparent smart perception system. On this basis, machine learning technology is used to make decision support system have the behavior of artificial intelligence, which can make full use of human knowledge to describe scheduling decision-making problems, acquire the process knowledge of decision-making process and reasoning knowledge of solving problems, and thus carry out creative thinking, logical reasoning and judgment.

The dispatch decision support system is horizontally divided into five decision process stages: data provision—data analysis—decision plan generation—decision plan selection—decision plan implementation. Verticality includes the level of decision support: a completely unsupported original system; auxiliary support at the information level (for example, by monitoring the acquisition of accumulated water data); system analysis (modeling implementation); system analysis and forming several alternatives Decision-making scheme; the system selects (better and optimal) decision-making scheme according to (optimized) model; automates the implementation of decision-making scheme.

The development of dispatching decision support system is essentially the process of GIS/database system and model system, gradually liberating dispatching decision-makers and finally realizing intelligent decision-making.

In the process of system development, there are a large number of internal/external network data communication and exchange functions, third-party interface and system secondary development functions. It is necessary to establish a unified data model and provide a standard data access interface.The application of Service Oriented Architecture (SOA) technology in system development can help to achieve unified and centralized data access control, shield the impact of database and data storage, structure, distribution and other underlying data source differences on the application, and improve the security, scalability and efficiency of system data access services.

In the aspect of visualization, on the one hand, it is necessary to realize multi-terminal indifference display, including supporting C/S indifference display, B/S display, mobile terminal, large screen and other terminal human-computer interaction, which can meet the needs of different terminal display interaction of cloud platform.

On the other hand, through rich charts and vivid visual, auditory, and tactile technologies, users will be able to provide a 360-degree full range of real-time and interactive experience, which can not only display the scene that is happening in the distance in real time, but also reproduce what has happened in the past and what may happen in the future, so that users can see, see clearly and understand. Then help users make the correct analysis and decision-making.

To sum up, the development of decision support system for reservoir group joint operation of cascade hydropower stations in river basin depends on the development of system platform technology and intelligent decision technology

3.4.3.1 System platform technology

1)Big data and cloud computing technology

The establishment of Joint Dispatching Decision Support System (JDSS) is a complex system engineering involving natural, economic, social, environmental and other factors. It is very complex and needs analysis and processing of massive data. At the same time, there are a lot of unstructured and structured problems in reservoir operation, which are difficult to be described by mathematical model. It must be analyzed by combining practical experience and expert knowledge. Traditional data processing methods show limitations.

Through the establishment of a unified large data center and cloud platform, the massive data in the joint dispatching decision support system are analyzed and processed, so as to obtain global information from a large number of data adequately and effectively, which can provide reliable data support for the operation of cascade hydropower stations joint dispatching business.

Cloud computing platform can provide a comprehensive business operation platform for users of hydrological information resources and backstage operation and maintenance managers, using three cloud computing models: SaaS, PaaS, IaaS, to achieve resource storage, processing, verification, analysis, deployment, monitoring and display functions.

2)Distributed database

Due to the geographical characteristics of river basins, dispatching decision support systems often need to integrate multiple services to achieve consistency of data, applications and functions. Compared with the traditional centralized database, the distributed database is more suitable for the application of river basin joint dispatching. It allows the regional power stations to store their commonly used data locally and store them locally, so as to improve the response speed and system recoverability, reduce communication costs, and achieve a high degree of unification of the platform.

Using distributed data processing, through redundant configuration and database mutual backup measures, virtualization of hardware resources, improve equipment utilization and save investment costs. The traditional database servers, application servers, communication servers, data processing servers and other special-purpose devices are virtualized, replaced by cloud computing servers, to reduce the number of devices and improve management efficiency. Ensure the integrity, uniqueness and high reliability of hydropower operation data.

3)Service Oriented Architecture (SOA) technology

Service-Oriented Architecture (SOA) is a component model that links different functional units of an application (called services) through well-defined interfaces and contracts between these services. Interfaces are defined in a neutral way and should be independent of the hardware platform, operating system, and programming language that implements the service. This allows services built in various such systems to interact in a unified and common manner.（Figure 3-8）

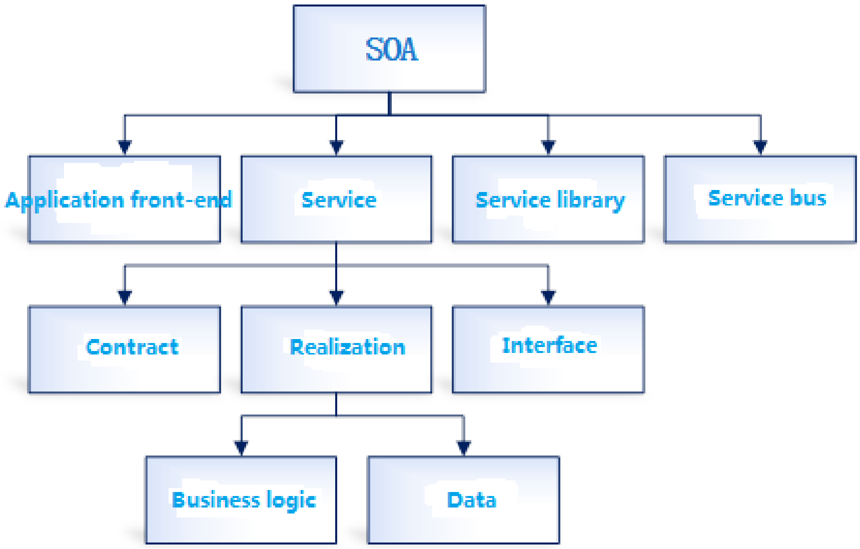

Figure 3-8 SOA Technical Chart

The goal of SOA is to make IT systems more resilient so that they can respond more flexibly and quickly to changing business needs of the enterprise, and solve the problem of "how to reuse software functions" that has existed in the software field for a long time. Using SOA to build information platform is undoubtedly the future direction of development.

3.4.3.2 Intelligent decision technology

1)Data lifecycle management

Data is the most important information asset of an enterprise, the quality of data in the system directly affects the rationality and scientificity of the dispatching decisions. Different data quality issues may be introduced at each stage of the life cycle of system data collection, transmission, processing, storage, maintenance, application, and extinction. The dispatching decision support system should provide a complete data quality management solution covering the entire life cycle of the data. Data monitoring functions such as data quality monitoring, analysis, evaluation, early warning, correction, auditing and auditing for data improvement and management. Help users to continuously improve data quality and continuously improve the value of data in the operation of cascade reservoirs to build efficient, high-quality data support.

The data life cycle phase is at least divided into: data generation, data transmission, integration processing, data auditing, and archiving. Data generation refers to the process of data being sensed from sensors, exchanged with other systems, manually entered, and logically calculated. Data generation refers to the process of data being sensed from sensors, exchanged with other systems, manually entered, and logically calculated. Data transmission refers to the transmission process of data from the source to the data processing center, usually transmitted by means of wireless or wired communication. Data reorganization processing refers to the process of processing in accordance with the set logic and rules in the data processing center, usually including statistical reorganization of data in different time periods, generation of data by different data according to logic synthesis, etc. Data auditing refers to the process of discriminating data quality according to data quality discriminating rules and correcting them. Archiving refers to the process of storing and backing up data that has been audited.

Data quality discrimination: the original data is automatically discriminated according to the data abnormality rule, and the data quality discriminate rule is reasonable data, and if it is not passed, it is regarded as suspicious data; The suspicious data is analyzed by manual data, and the data is reasonable data. If it is not determined to be abnormal data, the abnormal data is revised to reasonable data or eliminated. Finally, the reasonable data is again subjected to manual data analysis (rationality, consistency, reliability), and then confirmed and archived. The data quality management process is shown in Figure 3-9:

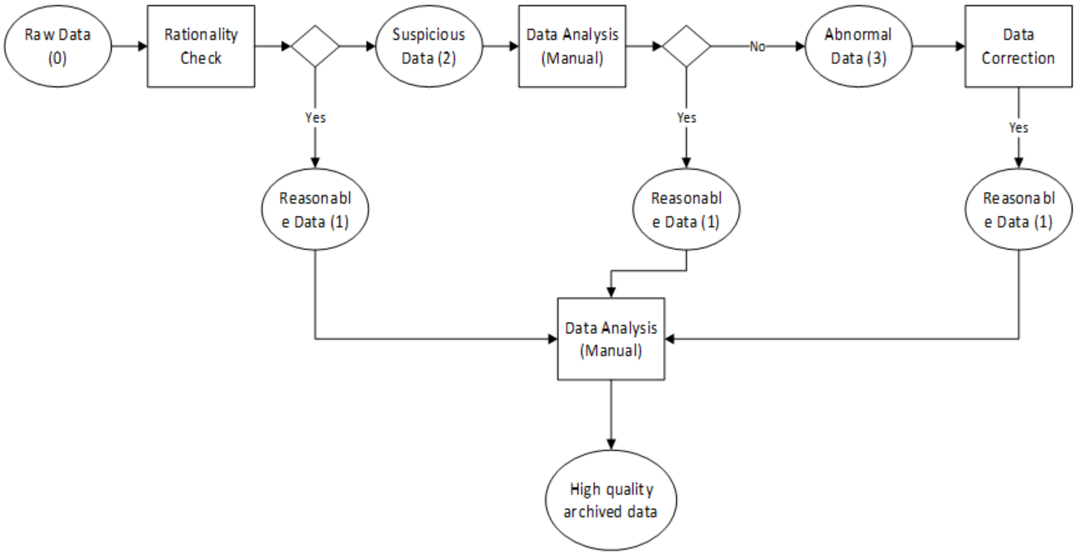

Figure 3-9 Data Quality Management Flowchart

Data quality inheritance: The data quality is inherited according to the worst principle, that is, after the original data is processed according to the set process, the numerical quality identifier is still the original data. In this way, numerical results of statistical data can be obtained, and quality reports of numerical results can also be obtained.

Data version setting: Each time the data is modified, the version number is incremented by a version number.

Data process traceability: Each time the data modification records the modification log, including the modification person, modification time, modification procedure, pre-modification value, and modified data. The data modification process can be traced through parsing and changing the log, and the data can be restored to any time

2)Multi-source and multi-professional massive heterogeneous data management

All kinds of information are important resources in the decision-making model, which mainly include three aspects: (1) Thematic data sources necessary for the daily work of key business information systems such as existing power grid, anti-total, hydrology, shipping, and various departments of the company. ; 2) Massive multi-source, multi-type, multi-element, multi-scale, multi-temporal spatial data; (3) Real-time monitoring of collected dynamic data through the Internet and monitoring equipment. (3) Real-time monitoring of collected dynamic data through the Internet and monitoring equipment. The intrinsic characteristics of large water resources

systems in complex river basins present new challenges in data integration, organization and sharing- How to achieve real-time collection, rapid processing, accurate analysis and effective sharing for massive and heterogeneous information based on dynamic configuration, multi-organizational Internet, and cross-industry, cross-department, and multi-level organization and form a key information processing theory and technical system for dealing with daily management of water resources in the basin and emergency response is the problems and difficulties that need to be addressed urgently.

(1) Firstly, it is necessary to identify many new features and new requirements in the multi-source, multi-professional and massive heterogeneous data integration of water resources in the basin, and adopt multi-source heterogeneous data integration technology route. Through the analysis and summarization of each data source, the configuration specification file for the data source is established, and the data extraction method of multi-source heterogeneous data in the pervasive computing environment is studied, and the semi-structured and unstructured data sources are integrated into a structured data set. On the basis of this, based on the credibility and similarity analysis method to solve the data discrepancies in multi-source heterogeneous data integration, a cross-domain automatic pattern matching method and data cleaning algorithm are proposed, which will come from multiple data sources. Data is merged into a unified data view and latest information technology is used to provide high-quality data support for subsequent decision-making;

(2) Combining the historical operation data of reservoir group and the results of optimal dispatching, break the traditional data analysis mode to restrict the application of multi-source spatio-temporal data of reservoir group, construct a deep learning model that can describe the characteristics of large data of reservoir group, and derive the evaluation function of reservoir big data mining. A linear regression enhancement learning method with local feature matching is proposed to establish an incremental intelligent dispatching knowledge base for large data mining of reservoirs; establishing meteorological, power supply, water and rain conditions, work conditions, production management, social economy, environment, and hydrology Forecasting and reservoir dispatching of the reservoir time-space data decision-making knowledge base,

providing inspirational information and related application services for sensitive factor early warning, flood identification, multi-temporal scale hydrological forecasting, and power generation, flood control, ecological and other reservoir dispatching decisions;

(3) Facing the multi-objective integrated dispatching needs of reservoirs, such as flood control, shipping, power generation, water supply, ecology, emergency, power market, etc., design a distributed storage organization and management model of massive spatial data, and abstract the optimal decision-making business model of the basin cascade joint dispatch into a standardized The database stores objects, builds a data layer based on object-relational mapping and object persistence, develops compatible system data and application interaction interfaces, develops leading water resources management data fusion, mining and sharing middleware with independent intellectual property rights, and builds The stable, reliable, fully functional, and easy-to-expandable PaaS (Platform-as-a-Service) platform for multi-source, multi-professional and massive heterogeneous data of reservoirs provides a unified development and application demonstration of the water resources management decision support system in the Yangtze River Basin Data support.

3)Visual interactive simulation environment platform

Research on massive data storage and integration processing technologies supporting digital watersheds, and carry out multi-source database construction in the basin. On the basis of the accumulation of previous work, the large-scale spatial database management system is improved to enable it to manage multiple types of data such as graphic data, image data, elevation data and attribute data, and to explore the coordination and management methods of database multi-source data logic consistency. Improve the system security management design, and maximize the interoperability between the spatial database system and the virtual reality system and computer aided design system.

(1) Based on three-dimensional geographic information, backbone water conservancy hubs along the river basin, dikes, flood control and drainage pumping stations, traffic gates and tunnels, etc., deep development and enhanced information query, terrain analysis, three-dimensional model Main functions such as drawing, 3D dynamic icon plotting, situational demonstration, networked plotting, mobilization

data, real-time video, real-time voice, flood prevention and evacuation dynamic demonstration, etc., for dispatching commanders to handle emergency emergencies, correctly analyze the situation, determine the situation Make up your mind and provide strong support.

(2) Support the direct import of models in 3ds format (common three-dimensional models of buildings, roads and bridges, and guide signs), and support the 3D model cross-sectional view of large-area buildings in cities. (After placing in 3D scenes, you can adjust the size of the model arbitrarily. , direction, angle and other related parameters);

(3) The system can draw vector label information on two-dimensional and three-dimensional image maps through multi-touch, and both the finger and the mouse can complete the plotting, and the mapped electronic map can output a large-screen high-precision satellite image mosaic image, and The icon can be superimposed to print the content; at the same time, all icons of the icon library can participate in dynamic icons and situational demonstrations by adding relevant multimedia information and real-time information (real-time audio and video, etc.) through the animation control of the timeline;

(4) Realize the monitoring connection of the network video in the area, and retrieve the real-time picture at any time.

4) Machine learning

With the advent of the era of big data, big data has gradually become a hot topic in academia and industry, and has been widely used in many technologies and industries. Because of the complex, high-dimensional, and variable nature of big data, how to extract the knowledge of human beings from real, messy, modeless and complex big data urgently requires more profound machine learning theory to guide.

Machine learning aggregates records into specific categories by searching for statistical patterns and relationships, producing rules and rule trees. The advantage of this approach is that it not only provides prediction and classification models, but also produces explicit rules from the data, such as the commonly used recursive classification algorithm, which separates the data into smaller subsets by gradually reducing the data's own entropy. This results in a decision tree that is used as reasoning for knowledge.

The problems of traditional machine learning mainly include the following four aspects: (1) understanding and simulating the learning process of human beings; (2) researching on natural language interfaces between computer systems and human users; (3) conducting incomplete information The ability to reason, that is, the automatic planning problem; (4) the process of constructing new things.

3.4.4 Decision Support System Features

The decision support system has an interactive interface that makes it easier to use and provides real-time response to user queries. Use various DSS tools to help each stage of the decision-making process, including viewing complex issues, designing models to analyze problems, developing alternatives to get solutions, and choosing solutions from available alternatives.

Decision support systems can analyze large amounts of data from different sources and store data collected from different sources in a data warehouse. A data warehouse is a database that stores current and past data extracted from various operating systems and provides some reporting and query tools.

Using decision support systems, managers can extract information from large amounts of data, which are usually in an unused or hidden state. The extracted information helps managers make better decisions.

4. Recommendations

4.1 Summary

Combining the development and management of cascade reservoirs in typical basins all over the world, the report introduces the characteristics of major river basins in the world, focusing on the management modes of cascade reservoirs, sustainable development, optimization and complementation of various energy resources. What's more, the four key technologies are analyzed and studied, including meteorology, hydrology, reservoirs dispatching and system development, to provide adequate technical support for cascade reservoir operation and management in the basin. The main results are as follows:

(1)With emphasis on the Nile, Amazon, Mississippi, Volga, Yangtze and Yellow River basins, the main rivers are introduced in the world. And the development and utilization of water resources are also introduced briefly, taking agricultural civilization, industrial civilization and modern civilization as the time node. The development of hydropower has been reviewed since 1882, at the time when Abel hydropower station was built, as the first hydropower station in the world. What's more, the different types of global energy development are compared, such as hydropower and thermal power, nuclear power, wind power and other power sources, through statistical comparison by the end of 2018, and it's shown that hydropower has better advantages and development potential. Considering the technique, hydropower plant operation, electric market, supervision and cooperation, the development directions of hydropower are put forward in future.

(2) The types of cascade reservoirs are briefly introduced, and their current management modes are also summarized. In terms of administrative management, water resources department, electric power department and inland navigation department respectively exercise the management right, for water conservancy, power generation and navigation of cascade reservoirs according to the division of responsibilities of departments.

In terms of operation management, the companies of hydropower developing and operation management are responsible for accepting and executing the operation instructions from administrative department. At the same time, they are participating in the coordination and formulation of professional operation plans for multi benefits, based on the working principles, including overall and public interest priority, maximum benefits, information sharing and risk sharing, and information sharing principles, including government leading, enterprise implementation, information disclosure, comprehensive sharing, platform co-construction and cost sharing.

In terms of benefit sharing, the cascade reservoirs are taken as examples in the middle reaches of Jinsha River, to show how to coordinate functional benefits. Future more, the benefit sharing methods are proposed exploringly for multi-issue benefit distribution, as well as thier measurement and distribution methods.

In order to clarify these issues, the models of comprehensive utilization management are introduced respectively in the Seine River basin, France and in the Yangtze River Basin, China. and the task and requirements of comprehensive utilization of cascade reservoir are also described, such as water quality, water quantity, dam safety and shipping accident. And in order to promote the sustainable development of cascade reservoirs, it is proposed that the comprehensive utilization of cascade reservoirs should give priorities to the emergency operation problems, such as ecological base flow, water eutrophication, protection of aquatic organisms and fish resources, and regulation of sediment. It's suggested that we should strengthen management and promote sustainable development through the establishment of watershed management institutions.

(3) According to the length of the forecasted period, the precipitation forecast can be divided into five categories: real-time precipitation forecast, short-term precipitation forecast, medium-term precipitation forecast, extended precipitation forecast and long-term precipitation trend forecast. And according to the technical methods, the precipitation forecast is divided into four development stages, by using statistical forecasting method, weather map forecasting method, numerical weather forecasting technology and grid forecasting technology respectively. In terms of the key techniques of rainfall forecast, the key techniques are used for short-time approach forecast, including radar observation data based on approach forecast method and fast assimilation mesoscale forecast system. Based on fusion forecast, Lattice point quantitative precipitation forecast is an important method to improve the accuracy of watershed precipitation forecast based on hydrological forecast. The extended period precipitation forecast usually adopts comprehensive technology, mainly including the integral length method of directly increasing meteorological forecast model, physical analysis and statistics method and big data prediction method. On this basis, the paper puts forward the development direction of rainfall forecast: integrating numerical forecast based on physical model and data-driven method. Finally, taking Norway, Iran, Brazil, China and other countries as examples, this paper introduces the application of rainfall forecast in reservoir operation, and expounds the important significance of rainfall forecast for reservoir operation.

The definition and development history of hydrological forecasting are introduced in detail, and hydrological forecasting methods are divided into parametric method and non-parametric method. Furthermore, the key techniques of hydrologic forecast are put forward from four directions: model parameter optimization, river system forecast, coupled forecast of precipitation and flood, and large-scale meteorological change. According to the analysis results, 3-5d hydrologic forecast can accurately predict, and 6-7d process can be estimated, and 8-10d process can be qualitatively analyzed. From the accuracy of different scales of forecast accuracy, medium- and short-term forecast can provide relatively reliable decision-making basis for optimal operation of reservoirs. The prediction of long-term runoff trend has a good grasp of runoff trend, which provides reference for long-term reservoir operation and generation plan making. However, the prediction accuracy of different forecast periods still needs to be further improved to fully meet the requirements of reservoir operation. Above all, it’s reported that the future focus of hydrological forecasting is to meet the challenges from the increasing requirements of forecasting, the change of forecasting results, the improvement of meteorological accuracy, and the impact of reservoir operation on runoff characteristics.

The report describes the significance of joint dispatching of cascade hydropower stations and reservoirs, as well as the development history of dispatching models, focusing on the big system, dynamic programming, step by step optimization method, discrete differential dynamic programming method, extension, linear quadratic gaussian method and the optimization of scheduling algorithm. What’s more, the report introduces the cascade reservoirs of economic operation inside the plant has a long and medium-term and different time scales, such as the united operation practice, in the basin from the lower reaches of Jinsha river to the upper reaches of Yangtze river.

The report also expounds the significance of DSS decision support system of cascade reservoirs dispatching, and introduces the development history of DSS in China, United States, France and Canada. Taking DSS of Jinsha River downstream and the Three Gorges cascade hydropower stations as an example, the system realized the full information integration, cross-regional reservoir basin group of joint scheduling, multiple model scheme contrast decision-making and comprehensive application and visualization display scheduling scene, for the scientific allocation of water resources and intelligent management provides the technical support and important guarantee.

It’s proposed that the key technologies of DSS, including big data and cloud computing technology, distributed database, service oriented Architecture (SOA) technology, and key functional decision-making technologies of DSS, such as data life cycle management, multi-source and multi-specialty heterogeneous data management, visual interactive simulation environment platform, and machine learning.

4.2 Prospect

With the construction of reservoirs and their putting into production in major basins around the world, the bases of cascade reservoirs already have been established in different countries. In future, we need to pay enough attention for how to efficiently manage and dispatch cascade reservoirs and how to get the comprehensive benefits of cascade reservoirs. There are five aspects in the following:

(1) Increase the information sharing. With the construction of reservoirs, the hydraulic connections of cascade reservoirs are increasingly close and the influence is increasing sharply. The degrees of sharing of operation information will directly affect the prediction accuracy and the accuracy of operation plan of cascade reservoirs, and become one of the main factors restricting the benefits of cascade reservoirs. At present, information sharing is not sufficient, and it's necessary to make greater efforts to change the current mode, sharing reservoir actual operation information in a small scope. Furthermore, we need to extend it to all-directional and cross-departmental information sharing among different units and departments, such as water and rain situation, operation plan, market information and transmission line.

(2) Improve the accuracy of forecast products. The accuracy of calculation of hydrometeorological forecast products is the core factor affecting the comprehensive benefits of cascade reservoirs. Although the currant accuracy of rainfall hydrological forecast is constantly developing and improving, with the continuous increase of comprehensive demand, the accuracy of operation plan is also increasingly required, which requires the forecast products with higher accuracy and longer forecast period.

(3) Strengthen the research on dispatching technology of cascade reservoirs. In recent years, the dispatching technology of cascade reservoirs has developed rapidly in many countries. However, with the increasing comprehensive demand of cascade reservoirs and the increasing number of joint operation reservoirs, it's difficult for the existing operation technology to meet the requirements in terms of efficiency and

precision at the same time. Therefore, it is necessary to study the operation technology with high efficiency and precision.

（4）Pay attention to the construction of dispatching system. the dispatch and operation of reservoirs becomes more and more complicated under the increase of reservoirs. And the traditional operation mode based on experience can't meet the requirements of complex operation of cascade reservoirs. Therefore, the construction of the dispatching system can release technicians from the complicated, repetitive and simple work and concentrate on the cascade reservoir dispatching work.

(5) Optimize the dispatch and management mode of cascade reservoirs. At present, the operation and management of cascade reservoirs involves multiple departments and development subjects, and there are many problems such as multi-head management, difficult coordination of interests, and complicated decision-making procedures. Therefore, it's necessary to optimize and adjust the existing operation and management mode, so as to meet the needs of various parties and give full play to the comprehensive benefits of cascade reservoirs.

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