Chapter 1
Introduction

1.1 Hydraulic Projects and Hydraulic Structures

The major function of a hydraulic project (i.e., water project) is to alter the natural behavior of a water body (river, lake, sea, groundwater) by concentrating its flow fall. It is intended for purposeful use for the benefits of national economy and to protect the environment, including electric power generation, flood control, water supply, silt mitigation, navigation, irrigation and draining, fish handling and farming, ecologic protection, and recreation. It is common that a number of hydraulic structures (i.e., hydraulic works) of general or special purposes are constructed to form a single or integrated hydraulic project to comprehensively serve foregoing purposes. Such a project is known as the water resources project or hydropower project in China, and the latter is primarily for electric power generation in addition to other possible benefits. The general-purpose and special-purpose hydraulic structures which are parts of a hydraulic project can be further divided into main, auxiliary, and temporary structures.

1.1.1 Types of Hydraulic Structures

Hydraulic structures are submerged or partially submerged in water. They can be used to divert, disrupt, or completely stop the natural flow. Hydraulic structures designed for integrated river, lake, or seawater projects are referred to river, lake, and marine water works, respectively. By the features of their actions on the stream flow, main hydraulic structures are distinguished as water retaining structures, water conveying structures, and special-purpose structures.

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1. Water retaining structures

Dams (inclusive barrages) are typical water retaining structures that affect closure of the stream and create heading-up afflux. Made of various materials, dams fall into soil and/or rockfill embankment, concrete, reinforced concrete, masonry, and wooden. Of which, the first two are the most prevalent nowadays.

(a) Concrete dams

By the structural features, concrete dams are termed as gravity (massive), buttress, and arch.

A gravity dam is a concrete structure resisting the imposed actions by its weight and section without relying on arch. In its common usage, the term is restricted to solid masonry or concrete dam which is straight or slightly curved in plan. The downstream face of modern gravity dam is usually of uniform slope which if extended would intersect the upstream face at or near the maximum reservoir level. The upstream face is normally of steep uniform slope or vertical with a steep batter (flared) near the heel. The upper portion is thick enough to resist the impact of floating debris and to accommodate a roadway and/or a spillway. The thickness of section at any elevation is adequate to resist sliding and to ensure compressive stresses at the heel under different loading conditions.

A buttress dam depends principally upon the water weight in addition to the concrete weight for stability. It is composed of two major structural elements: a water-supporting deck of uniform slope and a series of buttresses supporting the deck. Buttress dams are customarily further classified according to the deck type: A flat slab dam is one whose deck comprises flat slabs supported on the buttresses; a multi-arch dam consists of a series of arch segments supported by buttresses; and a massive-head buttress dam is formed by flaring the upstream edges of the buttresses to span the spaces between the buttresses.

An arch dam is always curvilinear in plan with its convex side facing headwater. On its vertical cross section, the dam is a relatively thin cantilever slightly curved. An arch dam transmits a major part of the imposed actions to the canyon walls mainly in the form of horizontal thrusts from it abutments.

By the water flow features, concrete dams may be non-overflow and overflow, and the latter releases water through openings (outlets) that can be free overflow and/or submerged under the headwater level, i.e., orifices, deep openings, and bottom outlets.

(b) Embankment dams

Embankment dams are massive fills of natural ground materials composed of fragmented particles, graded and compacted, to resist seepage and sliding. The friction and interlocking of particles bind the material particles together into a stable mass rather than by the use of a cementitious substance (binder). All modern embankment dams have basically trapezoidal cross section with straight or broken contour of upstream and downstream slopes. The topmost edge of the slope is the crest, and the lowermost edge of the slope is the toe or heel. Horizontal portions on the dam slope surfaces are termed as “berms.”

The actions of the impounded reservoir create a downward thrust upon the mass of the embankment, greatly increasing the pressure of the dam on its foundation, which in turn adds force effectively to seal and make the underlying dam foundation waterproof, particularly at the interface between the dam and its streambed.

There are various types of embankment dams. On the basis of the natural ground materials used, earthfill dams are compacted by fine-grained soils accounted for over 50 % of the whole placed volume, whereas rockfill dams are compacted by coarse-grained materials accounted for over 50 % of the whole placed volume. On the basis of section zoning, homogenous and zoned embankment dams may be distinguished, and among the latter category, the term “decked rockfill dams” is used particularly for the rockfill dams employing thin upstream membrane of non-natural materials such as asphaltic concrete, reinforced concrete, and geomembrane.

Embankment dams are commonly constructed as non-overflow. However, small rockfill dams are occasionally allowed for being topped over the crest if the dam crest and downstream face are adequately reverted (Chanson 2009; Manso and Schleiss 2002).

2. Water conveying structures

Water conveying structures are artificial channels cut in the ground and made of either ground materials such as soil and rock (e.g., canals and tunnels) or artificial materials such as concrete and metal (e.g., aqueducts, flumes, siphons, pipelines).

3. Special-purpose hydraulic structures

Special-purpose hydraulic structures are accommodated in a hydraulic project to meet the requirements of:

- Hydroelectric power generation, inclusive power plants, forebays and head ponds, surge towers and shafts, etc.;
- Inland waterway transportation, inclusive navigation locks and lifts, berths, landings, ship repair and building facilities, timber handling structures and log passes, etc.;
- Land reclamation, inclusive sluices (head works), silt tanks, irrigation canals, land draining systems, etc.;
- Water supply and waste disposal (sewerage), inclusive water intakes, catchment works, pumping stations, cooling ponds, water after treatment plants, sewage headers, etc.
- Fish handling, inclusive fish ways, fish locks and lifts, fish nursery pools, etc.

1.1.2 Layout of Hydraulic Projects

A hydraulic project is usually huge and comprises several hydraulic structures erected over an extensive geographic area and is intended to serve large-scale social and economic program. The hydraulic project with retaining structures built on the

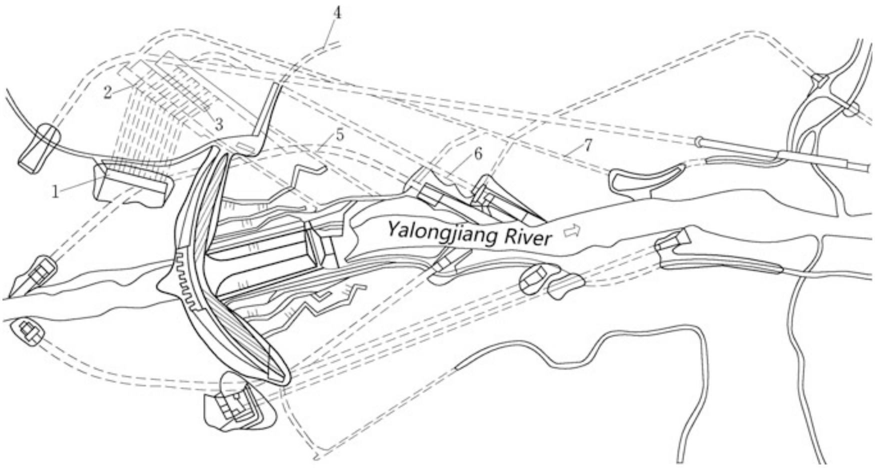

Fig. 1.1 Ertan Hydropower Project (arch dam)—China *1* Power intake, *2* Main machine house, *3* Main transformer chamber, *4* Left bank high way, *5* Number 2 tail race tunnel, *6* Number 1 tail race tunnel, *7* Access tunnel for power house

main stream of a river or canal, which creates afflux head of water, is known as operating under head; otherwise, it would be a headless (non-head) water project. Figures 1.1, 1.2, and 1.3 show three typical water resources and hydropower projects in China.

Fairly number of alternative layout schemes are compared with respect to technology and economy aspects before the final optimal layout scheme is decided, which should facilitate the construction and the management as well as reduce the investment, on the premise of ensuring project safety. The key issues facing the layout of a hydraulic project are as follows:

1. Flood release during service period and river diversion during construction period commonly dominate the project layout. The spillway should attain sufficient discharge capacity; meanwhile, its detrimental effects such as downstream scouring, silt depositing, and disturbance to power plant operation should be avoided or alleviated. The possibility of the reconstruction and reuse of temporary diversion structures as part of permanent flood or silt releasing structures is taken into account in the project layout, too.
2. Power plant should be located at places of easy to access and outgoing power lines. Concrete dam projects usually install power plant at dam toe. Bank power plant or underground power plant is also frequently employed under the situation of narrow river rapids or for the purposes to avoid construction interference and/or to collect more head.
3. Navigation structures (e.g., ship lock and lift) are located on the one or on the both riverbanks, where the flow conditions are advantageous for the upstream and downstream approach and berth of vessels. To avoid the interferences in the

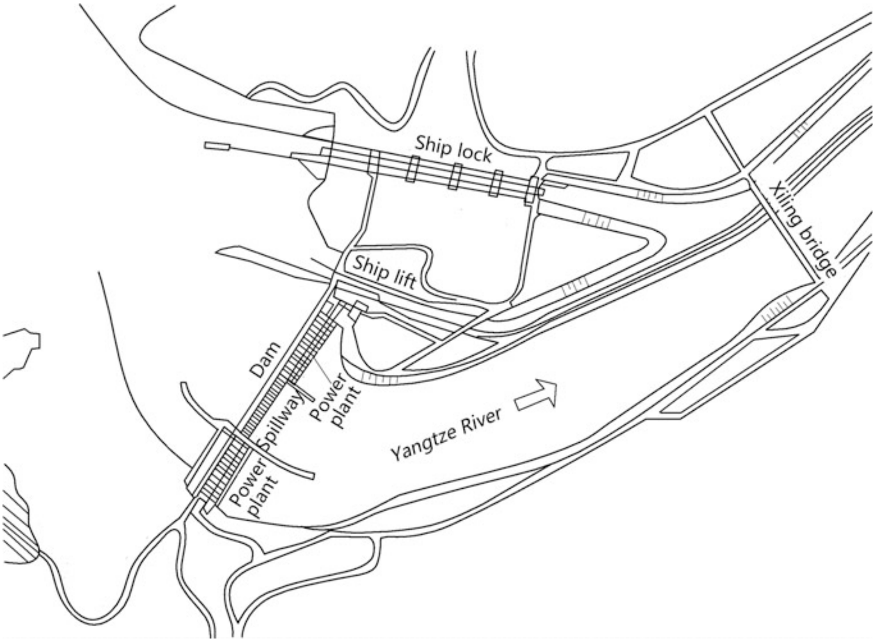

Fig. 1.2 Three Gorges Water Resources Project (gravity dam)—China

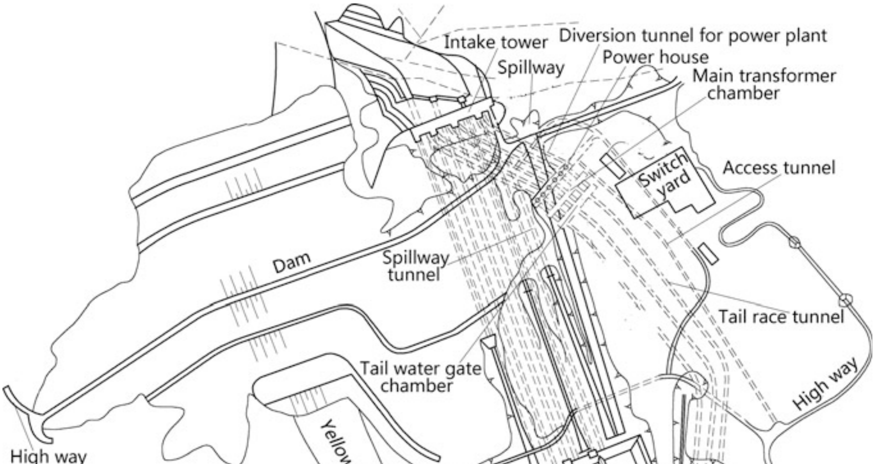

Fig. 1.3 Xiaolangdi Water Resources Project (embankment dam)—China

construction and operation, navigation structures are best to be separated with the intakes and the tailrace channel of the power plant.

4. Silt flushing structures should be layout carefully with respect to the reservoir/pool sedimentation process and the silt protection requirement of the project, of which the intakes of power plant and canal head works are particularly emphasized. It is customarily to provide certain sized bottom outlets as desilting sluices (excluders) for flushing silt, to keep effective reservoir storage capacity and free of silt in front of intakes. The solid gravity dams and arch dams may meet this requirement by providing bottom outlets with low intake elevation and large orifice size. On the contrary, tunnels for releasing flood inflow and flushing silt are demanded for the projects using embankment dams.
5. Dam safety is the most important. Particularly, the serious structural and equipment accidents as well as the civil air defense of dams and power plants should not be overlooked. The major countermeasure is drawing down or emptying reservoirs in time. To meet this requirement, in addition to crest spillway, intermediate and bottom outlets have to be provided to control the reservoir water level as flexibly as possible.

Viewing from the high dams and large power stations in operation or under construction in China, the project layout is often, although not always, focused on flood releasing and powerhouse locating, which may be grouped into several representatives with respect to major dam types, and will be presented in the subsequent corresponding chapters of this book.

1.1.3 Classification of Hydraulic Projects and Their Design Safety Standards

In the first step, water resources and hydropower projects are distinguished as 5 classes in China according to their scales, benefits, and importance in the society and national economy. Secondly, permanent hydraulic structures in the project are classified into 5 grades according to their importance in the project concerned. The higher the structure grade, the higher the design safety standard is stipulated, regarding:

- Flood-resisting ability, e.g., flood standard (recurrence interval), freeboard height, etc.;
- Earthquake-resisting ability, e.g., seismic design standard, earthquake countermeasures, etc.;
- Strength and stability, e.g., material strength, allowable safety factor against sliding, crack prevention requirements, etc.;
- Material type, quality, durability, etc.;
- Operation reliability, e.g., margin of structural size, monitoring instrumentation, etc.

There are two state standards in China for the classification of water resources and hydropower projects with corresponding design safety standards, due to the organization reshuffling history of the state central government: One is mainly adopted by the design institutes belong to the formal Ministry of Water Resources (with entry word of SL), and another one is mainly adopted by those belong to the formal Ministry of Electric Power (with entry word of DL).

1. Classification indices according to SL252-2000 2000 "Standard for classification and flood control of water resources and hydroelectric project" (Tables 1.1 and 1.2)
2. Classification indices according to DL 5180-2003 2003 "Standard for classification and design safety of hydroelectric project" (Table 1.3)
3. Grading of permanent hydraulic structures and flood standards

Permanent structures are classified into 5 grades according to their importance in the project accommodated, both in the design codes of SL252-2000 2000 and DL 5180-2003 2003 (Table 1.4).

The design reference period of permanent retaining structures with grade 1 is stipulated as 100 years, while that of the other permanent structures is 50 years. For particular large-scale projects, the design reference period of permanent retaining structures must be decided after special studies; the design reference period of temporary structures may be decided according to their anticipated service time plus possible construction delay.

The flood standard in terms of recurrence interval for permanent structures is listed in Tables 1.5, 1.6, and 1.7.

DL 5180-2003 also recommends the structural reliability theory for the design of hydraulic structures, and the target reliability index is stipulated to represent the design safety standard. However, where the structural reliability design is not available due to the delay in the design code updating for a certain structure, the determinant design method may have to be employed, and under such circumstances, the allowable safety factor is stipulated to represent the design safety standard. In the application of structural reliability theory, the structural grades 1–5 (Table 1.4) are corresponding to the structural safety grades I, II, and III, respectively.

The other design safety standards for specific structural problems, if any, will be discussed in the subsequent chapters of this book.

1.2 History of Hydraulic Engineering

The history of applying water to the farmland and residences may date back to the dawn of human civilization. The remote history of hydraulic structures concerning when and where irrigation systems and dams were first constructed is not very clear. However, study on ancient Egypt, Iraq (Babylonia), Iran (Persia), India, Sri Lanka (Ceylon), China, Greece, and Roman does confirm that such hydraulic works in these lands were begun thousands of years ago (Jansen 1980).

Table 1.1 Classification indices of water resources and hydropower projects (SL252-2000)

			Flood control		Water logging control	Irrigation	Water supply	Electric power generation
Class	Scale	Gross storage capacity of reservoir (10^8 m^3)	Importance of the cities and industry enterprises protected	Farmland protected (0.66667×10^3 ha)	Water logging control area (0.66667×10^3 ha)	Irrigation area (0.66667×10^3 ha)	Importance of water receiver	Installed capacity (MW)
I	Large (1)	≥10	Very important	≥500	≥200	≥150	Very important	≥1200
II	Large (2)	10–1.0	Important	500–100	200–60	150–50	Important	1200–300
III	Medium	1.0–0.10	Moderate	100–30	60–15	50–5	Moderate	300–50
IV	Small (1)	0.10–0.01	General	30–5	15–3	5–0.5	General	50–10
V	Small (2)	0.01–0.001	N/A	<5	<3	<0.5	N/A	<10

Table 1.2 Classification indices of barrage (sluice) projects (SL252-2000)

Class	I	II	III	IV	V
Scale	Large (1)	Large (2)	Medium	Small (1)	Small (2)
Flow discharge through barrage (m^3/s)	≥5000	5000–1000	1000–100	100–20	<20

Table 1.3 Classification indices of hydropower projects (DL 5180-2003)

Class	Scale	Gross storage capacity of reservoir (10^8 m^3)	Installed capacity (MW)
I	Large (1)	≥10	≥1200
II	Large (2)	<10 ≥ 1.0	<1200 ≥ 300
III	Medium	<1.0 ≥ 0.10	<300 ≥ 50
IV	Small (1)	<0.10 ≥ 0.01	<50 ≥ 10
V	Small (2)	<0.01	<10

Table 1.4 Grading of permanent hydraulic structures

Project class	Grade of permanent hydraulic structures	
	Main structures	Auxiliary structures
I	1	3
II	2	3
III	3	4
IV	4	5
V	5	5

Table 1.5 Flood standard for the permanent structures in mountainous and hilly areas

Item		Grade of hydraulic structures				
		1	2	3	4	5
Recurrence interval of design flood (year)		1000–500	500–100	100–50	50–30	30–20
Recurrence interval of check flood (year)	Embankment dams	MPF, or 10,000–5000	5000–2000	2000–1000	1000–300	300–200
	Concrete and masonry dams	5000–2000	2000–1000	1000–500	500–200	200–100

In the Black Desert of modern Jordan, there is a ruin of a dam built between 3000 BC and 4000 BC with some real skill. Egypt claims to have the world's oldest dam built about 5000 years ago to store water for drinking and irrigation, relating to the founding of Memphis city on the River Nile. The historian Herodotus attributed it to Menes, the first king of the initial Egyptian dynasty.

In Babylonia and Assyria, irrigation technique was extensively booming along the Tigris and Euphrates river valleys as early as 2100 BC and reached its peak later in Sassanian times.

Table 1.6 Flood standard for the permanent structures in plain areas

Item		Grade of hydraulic structures				
		1	2	3	4	5
Reservoir project	Recurrence interval of design flood (year)	300–100	100–50	50–20	20–10	10
	Recurrence interval of check flood (year)	2000–1000	1000–300	300–100	100–50	50–20
Barrage (sluice) project	Recurrence interval of design flood (year)	100–50	50–30	30–20	20–10	10
	Recurrence interval of check flood (year)	300–200	200–100	100–50	50–30	30–20

Table 1.7 Tide standard for the permanent structures in littoral areas

Grade of hydraulic structures	1	2	3	4, 5
Recurrence interval of design tidal level (year)	≥100	100–50	50–20	20–10

The Persians of ancient times recognized well the importance of irrigation to the civilization. By excavating underground water tunnel and gallery systems—Kanats (also called Karez in Baluchistan)—they led water flow down the system and then collected and carried it to the farmlands. Although the origin of Kanats has not been ascertained well, yet in the ruins at Sialak near Kashan, their traces considered to be as much as 6000 years old have been discovered.

Near Lakorian Pass and in the Mashkai Valley in the southern region of Baluchistan (Pakistan), ruins of pre-Aryan dams are found, which shows that there were ancient irrigation systems. In the centuries following the Aryan invasions in the middle of the second millennium BC, irrigation on this subcontinent was boosted. Archeological excavations at Harappa, Mohenjo Daro, and Kot Dijji all revealed the existence of advanced civilizations supported by irrigation systems.

Sri Lanka (Ceylon) also possesses ancient irrigation systems. After their immigration from south Asia subcontinent in the fifth century BC, the Sinhalese engineers established daring precedents in earthfill embankment construction and implemented irrigation systems, which supported a flourishing economy and society until the land was overcome by new invaders (Malayan) in about 1200 AD.

Water resources application in China onsets very early attributable to her brilliant and ancient civilization. Engineers constructed massive canals with levees and dams to channel the water flow for irrigation, as well as locks to allow ships to pass through. Originally, the Chinese solved the problem of ship transportation in the region of river rapids by building dikes with slopes on the banks of the canal. The boats were then manually hoisted up and down the slopes. Later, they discovered that by constructing two dams (as sidewalls) a certain distance apart, the boats could enter the pool created between them where the water level might be slowly raised or lowered down. Vertical grooves were cut into opposite sides of the sidewalls, and tree trunks were fitted horizontally into the grooves, which held the water at the highest level. This invention is now recognized worldwide as the ancestor of hydraulic gates. The Anfeng Tang (dyke) of 10 m high, the oldest operational embankment dam in China located in the Shouxian County, Anhui Province, was built in 598–591 BC, by Sun Shu'ao, the premier of the State Chu who is respected as the first hydraulic engineer in China. Another important hydraulic engineer in China, Ximen Bao, was credited of starting the practice of large-scale canal irrigation systems during the Warring States Period (481–221 BC). The famous Dujiangyan (weir or barrage), still a functioning hydraulic project today, was built by Li Bing and his son in the Qin dynasty (221–207 BC), which provided irrigation water for the vast rice fields in the prosperous Western Sichuan Plain.

Hydraulic engineering had been highly developed in Europe under the aegis of the Roman Empire where the people were especially creative in the construction and maintenance of aqueducts, for the purposes of supplying water to and removing sewage from their prospered cities. They also used hydraulic mining methods to prospect and extract alluvial gold deposits in a technique known as hushing.

Eupalinos, an ancient Greek engineer, built the tunnel of Eupalinos on Samos in the sixth century BC, which is an important contribution to both civil and hydraulic engineering. It was dug from both ends which required the workers to keep an accurate direction and elevation so that the two tunnel segments met and to maintain a sufficient slope to allow for the flowing of water.

The mechanical power of falling water is a traditional resource used for services and productive purposes in the whole civilization history. However, prior to the widespread availability of commercial electric power, hydropower in ancient period was merely used for irrigation and operation of simple hydraulic machines, such as water mills, textile machines, and sawmills. For example, it was used by the Greeks to turn water wheels for grinding wheat into flour more than 2000 years ago.

According to various well-known literatures (ICOLD 2013; Smith 1971; Jansen 1980; Schnitter 1994; Zhu 1995), the history of hydraulic engineering may be roughly divided into four major stages based on the technique features, which will be summarized in the following subsections.

1.2.1 3000 BC–300 AD

This is a dawn period of hydraulic engineering in the human history featured by embankment dams and their impounding reservoirs mostly for water irrigation, with or partially with (insufficient) spillways or intakes. Ancient Roman dams for drinking and SPA water supply were often combined with other hydraulic structures such as upstream masonry, downstream embankment fill, aqueduct, and canal.

Ruins in ancient India and Sri Lanka provide evidences of how reservoirs and embankment dams were built by early people: It involved the placement of earthfill across streams using materials transported in baskets or other containers. Turning to the most available materials, the ancient dam builders made use of soils and gravels freely. Compaction was accomplished incidentally by the trampling feet of the carriers. Due to the lack of or only have preliminary understanding of the material mechanics and hydraulics, these works often failed.

Table 1.8 lists several important historical hydraulic structures, particularly the dams, in this period which are recorded exactly by history documents or verified by ancient ruins.

1.2.2 300 AD–1800 AD

This is a period featured by the appearance of masonry and “concrete” dams (gravity, buttress, arch) and embankment dams with steep slopes.

This is also a historical period mostly overlapped by the Christian “Middle Ages” (from 476 AD to 1453 AD) (Hill 1996) and the “Islamic Golden Age” (from the eighth to sixteenth centuries) (Burke 2009). In 711 AD, Spain was conquered by the Muslims, and their rule continued until 1492. Age of autocracy overlapped the whole period in the most eastern dynasties, particularly in China.

Under the rule of a single Islamic Caliphate, different regional hydraulic technologies were assembled into a water management technological complex as “toolkit,” which has a global impact and whose various components developed in different parts of the Afro-Eurasian landmass. These include the canals and dams as well as the qanats from Persia, the water-lifting devices including the noria and the shaduf as well as the screw pump from Egypt, the windmill from Afghanistan, the saqiya with a flywheel effect from Islamic Spain, the reciprocating suction pump and crankshaft—connecting rod mechanism—from Iraq, and the geared and hydraulic driven water supply system from Syria.

Hulagu Khan led his Mongols into Baghdad in 1258 and into Damascus in the second year (1259). They crashed Arabic rule, and most of the ancient public works in that region were reduced to ruin. As a result, the rich farmlands bordering the upper Tigris reverted to desert.

The Renaissance started from the sixteenth century profoundly affected European intellectual life in the early modern period. It initiated in Italy and spread to the rest of Europe. Its influence is still strongly felt in literature, philosophy, art, music, politics, science, religion, and other aspects of intellectual inquiry inclusive hydraulic structures.

The design concepts of the early Spanish dam engineers were conveyed to the colonies in America continent since the sixteenth century. However, it is widely believed that hydraulic projects had been well developed before the conquest of the Spanish. For example, near the Teotihuacan, Mexico, and in the Nepena and Canete valleys in Peru, there are still signs of ancient dams.

Since the 1700s, mechanical hydropower was used extensively for milling and pumping. During the 1700 and 1800s, water turbine development continued.

As the accumulation of engineering expertise, an increasing number of the works built in this period had lasted a long time. Table 1.9 lists several important historical dams in this period.

Table 1.8 Historical hydraulic structures in the period of 3000 BC–300 AD

Year	Name and features	Location	Remark
3000 BC–4000 BC	Jawa Dam	The Black Desert, Jordan	With some real skill already
2950 BC–2750 BC	“Sadd el-Kafara,” a masonry gravity dam, 14 m high	Nile River, Egypt	Arabic name meaning “Dam of the Pagans,” with some engineering expertise already
Around 2100 BC	Nahrwan Canal and Dijail Canal	Diversion from the Tigris River, Babylonia and Assyria	The ruins found at the river near the ancient head works are of massive rubble masonry
1900 BC	Joseph’s Canal, by Prophet Joseph when he was the Grand Vizier to the Pharaoh	Medinet-el-Faiyum, Egypt	For the purpose of irrigating the green fruit gardens of that area by taking off the Nile River
1319 BC–1304 BC	Lake Homs Dam (Quatinah barrage), 7 m high and 20 m wide at base	Syria (during the reign of the Egyptian Pharaoh Sethi)	The oldest operational dam in the world
Around 800 BC	Marib Dam, 3.2 km long, 37 m high, and 152 m wide at base	Wadi Sadd (Saba River), North Yemen (since 1990, a part of the Republic of Yemen)	At a site 5 km upstream of this ancient dam, a new Marib dam was commissioned in 1986
705 BC–681 BC	Ajilah Dam, about 240 m long and at least 3 m high	Khosr River, Mesopotamia (Iraq)	Attributed to the Assyrian King, Sennacherib, to serve his capital city of Nineveh
600 BC	Tunnel of Eupalinos on Samos, dug from both ends	Greece	First known hydraulic tunnel
598 BC–591 BC	Anfeng Tang (dyke or dam), 10 m high	Shouxian County, Anhui Province, China	Embankment. Still in functioning today
539 BC	Diyala dam	A tributary of the Tigris, Persia	Embankment to create diversion works for an extensive water distribution network composed of reportedly 30 canals
505 BC–100 BC	Dams of Kalabalala, 24 m high and about 6 km long	Ceylon	Embankment type
322 BC–298 BC	Sudarsana Dam	India, during the reign of Chandragupta	Embankment. Survived until at least 457 AD

(continued)

Table 1.8 (continued)

Year	Name and features	Location	Remark
240 BC	Gukow Dam, 30 m high and almost 300 m long	Jingshui River, Shansi Province, China	Stone-crib embankment. For the water diversion into the Zhengguoqu Canal
214 BC	Lingqu Canal, part of a historical inland waterway between the Yangtze River Delta and the Pearl River Delta	Xing'an County, Guangxu Province, China	The first canal with ship locks in the world for the purpose of inland waterway transportation
193 BC	Alcantarilla Dam, 20 m high and at least 550 m long	Spain (after the Romans gained control of Toledo)	The oldest dam in Spain and is possibly the earliest Roman dam. Spillways were accommodated
100 BC	Dam of Glanum, approximately 6 m high and 9 m long at crest. It is also known as the "Vallon de Baume Dam"	Southern France, Roman Empire	The oldest masonry arch dam. In 1891 AD, a new arch dam was constructed on the ruins, concealing evidence of this ancient work

Table 1.9 Historical hydraulic structures in the period of 300 AD–1800 AD

Year	Name and features	Location	Remark
Second century	Proserpina Dam, 19 m high and 427 m long. A concrete core sandwiched between two masonry walls	About 6 km north of Merida, Spain	It possesses large capacity spillways. The upstream face is battered steeply, while the downstream masonry face is vertical on which the masonry buttresses were erected to provide resistance against overturning
Second century	Cornalbo Dam, 24 m high and 200 m long. Its cross section is trapezoidal with masonry revetment	Near Merida, Spain	One of the oldest embankments is still operational. The core of the dam was made up of masonry walls forming interconnected boxes filled with stones or clay
Second century	Kasserine dam, 10 m high, about 150 m long at crest. It is remarkable that the dam was curved	217 km southwest of Tunis	A masonry-faced structure with a core composed of earth and rubble. Cut stone blocks with mortared joints were used in the vertical upstream facing, while the downstream side was stepped down from the crest
162	Kaerumataike Dam, 17 m high and 260 m long	On the Yodo River near the Nara, Japan	Earth embankment
270	Shushtar Dam-Bridge, approximately 550 m long	On the Karun River in Khuzestan, Persia (by the King Shapur I)	For the purpose to improve the irrigation projects
Third century	Dam of Horns, 6.1 m high. The thickness varies from 7 m at the top to approximately 20 m at the base	On the River Orontes, Syria (Roman period)	It survived and provided service for seventeenth centuries; until in 1934, a new and larger dam was superimposed on the ancient one. The core of the dam was of basaltic rubble masonry, cemented with mortar. Cut basalt stones were placed on both faces of the dam, and the joints were mortar sealed
459	Kalaweva Dam, about 19 km long	Ceylon	Earthfill embankment to create irrigation reservoir (tank)

(continued)

Table 1.9 (continued)

Year	Name and features	Location	Remark
833	Tashan Yan (barrage), 27 m high	On the Zhangxi creek, Zhejiang Province, China	Masonry gravity type, serving for irrigation
Around 960	Dam on the Rio Guadal quiver, zigzag alignment of about 427 m in total length	Cordova, Spain	The oldest remaining Muslim dam in Spain. In addition to its original functions of water supply and mill operation, the pool created by this rubble masonry dam protected the bridge piers of the Puente Romano (Roman Bridge) from erosion
Around 960	Band-i-Amir Dam, 9 m high and 76 m long, has a downstream slope about 1–1	On the River Kur, Persia	Built entirely of cut stones with mortared joints reinforced by iron bars anchored in lead. It still stands although its function has been impaired by siltation
Around 960	Moti-Talab Dam, 24 m high and 157 m long, has a cross section with a broad crest of 27 m wide	Near Mandya (Mysore), India	Earthfill embankment with steep slopes (2:3 upstream and 1:1 downstream) protected by cut stone facing
Eleventh century	Bhopal reservoir with an area of 650 km^2 impounded by two earthfill dams covered on both slopes with immense blocks of cut stone	Bhopal (Madhya Pradesh), India	Evidence of this great pool still remains, and a spillway was excavated in the rock of a hill saddle
Thirteenth century	Almonacid de la Cuba Dam, 29 m high and 85 m long, with a downstream face composed of large stone blocks placed in tiers and set in mortar	On the Rio Aguavivas, about 40 km south of Zaragoza, Spain	The oldest surviving Christian dam in Spain with original spillway at the left abutment. As part of the enlargement, the spillway crest was elevated by a curved weir
1300	Kebar Dam. The constant intrados radius is 38 m, the height is about 26 m, the chord length is 55 m, and the crest thickness is 5 m	On the Kebar River, about 170 km southwest of Tehran, Persia	The oldest known surviving arch dam. Materials used in the construction were cemented rubble masonry with mortared stone block facing

(continued)

Table 1.9 (continued)

Year	Name and features	Location	Remark
1350	Kurit Dam, 60 m high. Later, 4 m was added to the dam height in 1850	Persia	Masonry arch. Even though part of its lower downstream face fell off, it remained the highest dam in the world until the early twentieth century
1384	Almansa Dam, about 14.6 m high and curved to a intrados radius of about 26 m, whose thickness is approximately 10 m at the base and 4 m at the crest	Near the town of Almansa, Spain	Arched gravity dam composed of rubble masonry and regarded as the first known arched dam in Spain. It was enlarged in 1586 and again in the years 1736 and 1921 and is still in sound condition
Fifteenth century	Daimonike Dam, 32 m high	Near Nara, Japan	Earthfill embankment
	Padawiya Dam, 18 km long and approximately 21 m high	60 km northeast of Anuradhapura, Ceylon	Earthfill embankment with slope facing consisted of cut stone
1500	Mudduk Masur Dam, 33 m high	Madras Province, southern India	Embankment whose height was unsurpassed for about 300 years
1594	Alicante Dam, 41 m high. The plan is curvilinear with a crest length of about 80 m and a thickness varies from approximately 20.5 m at the top to 33.7 m at the base	Tibi, Spain	Rubble masonry arch dam, also known by the name of the nearby Tibi village. It was installed with silt excluding system and vertical shaft outlet. Originally, there was no separate spillway. The dam was rehabilitated in 1738, and a side-channel spillway was constructed later. The dam was enlarged in 1943; therefore, its present height is 46 m
Mid-seventeenth century	Elche Dam. The mean radius is 62.6 m and the crest length is about 70 m. The dam height is 24 m and the arch thickness varies from about 9 m at the top to 12 m at the base	Rio Vinalop, Spain	It is the first true arch dam in Spain, using traditional rubble masonry with cut stone facing

(continued)

Table 1.9 (continued)

Year	Name and features	Location	Remark
Seventeenth century	Ponte Alto Dam, about 5 m high and 2 m thick, with a radius of approximately 14 m	On the River Fersina just east of Trento, Italy	Masonry blocks with unmortared joints. The first masonry arch dam in Italy. In 1752, the addition of a second stage increased the height to 17 m. Subsequent enlargements in 1825, 1847, 1850 and 1887 created a dam of present height of 38 m
1642–1667	Pul-i-Khadju Bridge-Dam, whose slotted weir is about 6 m high, 30 m thick, and 141 m long	Persia	Cut stone blocks masonry built during the reign of Shah Abbas II
1667–1675	St. Ferreol Dam, 36 m high and 780 m long	On the River Laudot, about 50 km southeast of Toulouse, France	It is an earthfill embankment having three parallel masonry walls extending the full length of the dam, one at each face and one in the center. The fill between the walls is composed of stones and earth
1714–1721	Oberharz Dam, 22 m high and about 151 m long. It has a width varying from about 16 m at the crest to 44 m at the base	Germany	The first large dam in Germany composed of two stone block face walls confining a central zone of sand
1747	Almendralejo Dam, 170 m long, approximately 20 m high, with a thickness varying from 10 m at the crest to 12 m on the base	About 51 km south of Badajoz, Spain	Rubble masonry buttress dam, also known as the dam of Albuera de Feria. It has survived without any significant deterioration. Successive enlargements increased the height to 23.5 m

1.2.3 1800 AD–1940 AD

This is a period featured by the fast development in techniques for concrete dams, along with the sophisticated application of sciences (e.g., mathematics and material mechanics). Climbing formwork, Portland cement, modern concrete, and multipurpose reservoirs started to prevail.

Before the mid-nineteenth century, rational theories and criteria for dam design had few acceptance, and problems encountered in construction were ordinarily tackled by trial and error. Take the Puentes Dam on the Rio Guadalentin (Spain) as an example: It is a 50-m-high rubble masonry gravity dam intended to be built on rock foundation. However, after the foundation clearance, a deep crevice was found, and the countermeasure decision was to pile in the alluvial fill under the central portion of the dam. As a result, after 11 years of service, the dam failed in 1802 due to the foundation blew out under reservoir pressure.

After the mid-nineteenth century, the masonry gravity dam design and construction had made important breakthrough. In 1853, Sazilly, a French engineer, advocated that pressures within a gravity dam should be held to specific limits and that the structure should be dimensioned to preclude sliding. The concept of keeping the resultant of forces within the middle third of each horizontal plane was emphasized later by Rankine (1881) of England. The ideas of Sazilly and Rankine showed the way toward rational analysis of gravity dams. The first project accomplished according to the principles proposed by Sazilly was the Furens Dam (France, $H = 50$ m). In 1858, two French engineers, Graeff and Delocre, initiated the process of the selection and subsequently the design of the Furens Dam that would be, for about 10 years, the largest in the world. Located in the vicinity of Rochetaillée, close to Saint Etienne, the construction of the Furens Dam began in 1860 and the first filling took place in 1866. In the stage of design, Delocre initially used the “practical section” proposed by Sazilly, changing the sectional configuration to a polygonal profile.

Mining also gave impetus to the dam construction. Discovery of gold in California (USA) in 1848 led to extensive placer workings which necessitated the use of dams and conduits as a result of the need to impound water for mining operations. Drill and blast mining techniques by miners provided an abundant supply of rock materials for the use in dam construction. The miners used the rock quarry materials to construct water storage dams in remote areas with available mine haul and dump equipment, or even by hand solely. At the beginning, these dams were built with stone-filled log cribs. A later development was the dumped rockfill confined by dry rock walls at the faces and lined with two or more layers of wood planking. One of the highest dumped rockfill dams constructed in the California Sierras (USA) during this earlier period was the Meadow Lake dam of 23 m high.

While these relatively rough works were being practiced by the western USA pioneers, European engineers were engaged in more sophisticated projects in contrast to their crude predecessors. In France, the Zola Dam regarded as the first "rational arch dam" was completed in 1854. With an unprecedented arch height of 42 m, its stress analysis was firstly carried out by the cylinder method, which looks at an arch dam as a part of vertical cylinder in the water. This rubble masonry structure with cut stone faces is still intact.

Darcy's Law concerning the rate of seeping water flow through a soil (permeability) was promulgated in 1856 and is still very relevant today. It dictates how and where different types of earth materials (clay, silt, sand, gravel, cobbles, and rockfill) can be used in an embankment dam.

In 1875, the first stage of the Lower San Leandro (Chabot) Dam was completed to serve the communities on the east shore of San Francisco Bay in California (USA). It was built by Anthony Chabot in charge of San Francisco's first public water supply. A special feature of this earthfill embankment ($H = 35$ m) is a central foundation trench excavated 9 m below the streambed. In the bottom of the trench, three parallel concrete cutoff walls were built, each at 0.9 m thick and 1.5 m high, with about half of this height anchored in the foundation and rest half protruding. The fill contains a core zone which is about 27 m wide at its bottom of the foundation trench. The dam was enlarged in the 1890s, its new height above foundation is 47 m, and its length is 137 m.

Design concept and theory for gravity dams continued to advance. The middle third criterion was being questioned, which had been generally accepted as sufficient guarantee against the overturning of dams. However, several failures (e.g., the Bouzey Dam of France at height of 22 m failed in 1895) demonstrated that uplift and sliding could be of greater concern. Designers began to consider these factors in new projects. As early as 1882, a draining network to reduce uplift had been incorporated into the body of the Vyrnwy Dam in Liverpool (UK). Engineers in the USA firstly took into account of the uplift in the design for the Wachusetts Dam in Massachusetts (1900–1906), which gave rise to a fat section of flat slope. The Olive Bridge Dam in New York State (1908–1914), USA, was constructed with drains in the dam body but with none in the foundation. Among the first dams with both dam and foundation drainage were the Medina in Texas (1911–1912), the Arrowrock in Idaho (1914–1915), and the Elephant Butte in New Mexico (1914–1915). Since then, drilling of drainage holes has been commonly exercised for large gravity dams.

The New Croton Dam (also known as Cornell Dam, USA, $H = 91$ m), a gravity dam completed in 1905, was one of the first applications of American Portland cement. In later projects, Portland cement found increasing acceptance.

Series accidents waked up engineers concerning the importance of foundation treatment for gravity dams. The Austin Dam in the Freeman Run Valley, Pennsylvania (USA), failed partially due to the foundation problem on September 30, 1911, destroyed much of the town of Austin, and resulted in the deaths of 78 people (Greene and Christ 1998). A little more recently, in 1928, the failure of the St. Francis dam near Los Angeles, California (USA), also due to the foundation problem, killed hundreds of people (Outland 1963). Since then, foundation stability analysis has become an indispensable task in the safety calibration of gravity dams, considering the possibility of various sliding mechanisms and seepage effects, which may either take place along the foundation surface and/or involve deep-seated rock fractures.

The design of high arch dams requires more advanced methods for stress analysis. New methods for the analysis of arch dams emerged around the first decade of the twentieth century. In 1889, Vischer and Wagoner described several horizontal arches and only one crown cantilever in the stress check of the Bear Valley Dam (USA, $H = 19.5$ m) and the Sweetwater Dam (USA, $H = 33$ m). But it was unknown to engineers in the other countries until several years later. In 1904, Woodard applied this method second time to the Cheesman Dam (USA, $H = 64$ m); thereafter, the method started to attract the wider interest of dam engineers. In 1905, two US engineers—Wisner and Wheeler—under the request of the Reclamation Service, initiated studies to better understand the load distribution on arch dams. Using an iterative process with respect to the force sharing and the compatibility of displacements among several arch rings and a central cantilever, they obtained the load distribution across the various sections, which led to the conclusion that at higher elevations, the behavior of the arch was decisive, whereas close to the bottom, the cantilever effect prevailed. Noetzli (1921,1922) summarized the situation in a landmark paper by giving relatively simple formulas for calculating the cantilever and the arch actions and then applied his formulations to the design of the Pathfinder Dam ($H = 65$ m, USA), which was completed in 1909, and the Buffalo Bill Dam ($H = 99$ m, USA).

Started from around mid-1920s, the arch dam design and construction had achieved amazing progress attributable to the advancement in material sciences, construction techniques, and well-formulated analysis methods.

The Swiss engineer, Gryuner, tried the American experience in the Montsalvens Arch Dam erected in 1920. His two assistances, Stucky and Gicot, analyzed side cantilevers, apart from the crown one, which enabled to improve the profile of the arch dam in the vertical direction. By 1925, Vogt had shown that the displacement of foundation rock could be estimated approximately using three formulae derived from the Boussinesq's theory of the elastic semi-space. In 1929, Howell and Jaquith, both from the Bureau of Reclamation, formalized comprehensively the calculation method using various arches and cantilevers developed through scattered contributions, as the "trial load method."

In the 1920s studies using physical models were exercised to analyze arch dams, and experimental centers were established in Portugal (Civil Engineering Laboratory in Lisbon), Italy (ISMES in Bergamo), England (Imperial College), and Spain (Central Laboratory in Madrid). The trial load method underwent its first application which was checked with a model test (scale 1:240) at the University of Colorado at Boulder (USA). The trial load method had been rigorously checked in 1926 with the help of the Stevenson Creek Dam -an 18 m high experimental arch dam near Fresno in California.

Techniques for mixing and placing concrete were undergoing significant changes, too. The Diablo Dam, for example, used a dry mix placed by a belt conveyor suspended from a derrick, with a short tube known as an "elephant trunk" at the discharge end. In the construction of the Calderwood Dam (Tennessee, USA) and

Chute a Caron Dam (Quebec, Canada), use was made of bottom-dump buckets that enabled placing relatively dry concrete in the forms without segregation.

The Danish immigrant engineer Jorgensen (1915) published a paper on the constant angle arch dam in which he showed how to configure an arch dam with a minimum volume at each level by using the cylinder formula and by reducing the radius of curvature in the lower regions where the water pressure is higher. He indicated that the volume of material needed would be a minimum if the central angle remained the same at a value of about 133.6 (°)—hence, his dam designs are called "constant angle dams." In 1914, in the design of the 52-m-high Salmon Creek Dam in Alaska (USA), Jorgensen abandoned the prevalent constant radius type of arch dam and realized the first constant angle dam, followed by the 84-m-high Lake Spaulding Dam in California in 1919. By 1931, he would state that over 40 constant angle arch dams had been completed. Since then, constant angle dams have been the dominant arch dam type in not too wide valley.

The birth of double-curvature arch dams is mainly attributable to the two arch dams. The Marèges Dam (France, $H = 90$ m) designed by André Coyne was constructed between 1932 and 1935. Coyne cut a 7 m wide portion at dam heel of tensile cracking area, instead of conventional US way to thicken the cantilever base to resist the tensile stress. His genius gave rise to a first step toward double-arch dams. The Osiglietta Dam (Italy, $H = 76$ m) completed in 1939 designed by Nicolai, who bended the upper portion of the dam in the direction of downstream. This creation was enlightened by the laboratory experimental findings during 1935–1939 in the ISMES that such bending might strengthen the upper portion of arch rings. The Osiglietta dam is also the first arch dam in the world having peripheral joint.

Embankment dams started to evolve from the relatively simple homogeneous or two-zoned earthfill into the extremely complex, highly analyzed, well-instrumented, and multi-zoned earthfill and rockfill structures. Rockfill technology was given new impetus in USA. From the 1910s to the 1940s, rockfill dump dams began to exceed 30 m in height. The "dry rock dump" technique in rockfill dam construction developed into the placement of thick single or multiple rockfill lifts in combination with upstream facing of relatively impervious materials (timber, steel, concrete, or asphaltic concrete). In 1924, the Dix River Dam for the water supply of Danville, Kentucky (USA), set a height record of 84 m for rockfill dams. In 1931, the Salt Springs Dam in California (USA) raised the record further up to 100 m.

Earlier of this period, settlement/consolidation behavior of granular materials was not tested, although settlement benchmarks were first installed along the edges of the embankment crest at the Belle Fourche Dam (also known as Orman Dam, USA, $H = 37.4$ m) in 1911. Field and laboratory testing of soil and rock materials began to emerge during the 1920s and early 1930s. In addition to the pioneering works on the topics such as soil permeability by Karl von Terzaghi who is generally considered the father of soil mechanics, others contributed greatly to the evolution of soil and rock testing, too, in the attempt to characterize these materials.

The grading from finer grained materials at the core to coarser grained materials toward the outer slopes was started to be employed in embankment dams, which demanded the understanding of the filtering actions for preventing soils from "internal erosion" (piping). The research works by Bertram with the assistance of Terzaghi and Casagrande resulted in a paper that is generally given the credit as the first document on filter criteria, in the early 1940s.

Anecdotal evidence from the soil slope failures in the early 1900s suggested that the failure surface is often cylindrical like curvilinear, especially in a homogeneous, isotropic, and cohesive soil mass. In 1916, Pettersson and Hultin proposed a slope stability analysis method of arc to analyze the failure of a quay wall in Goteborg, Sweden. But it did not appear to be introduced to the engineers in the other countries. The method of slices was formally introduced by Fellenius where he divided the sliding soil mass contained within the arc into slices and analyzed their equilibrium by equating the forces and moments to zero.

The world's first hydroelectric power plant was installed in Cragside, Rothbury (England), in 1870. Industrial use of hydropower started in 1880 in Grand Rapids, Michigan (USA), when a dynamo driven by a water turbine was used to provide theatre and storefront lighting. In 1881, a brush dynamo connected to a turbine in a flour mill provided streetlighting at Niagara Falls, New York (USA). The key breakthrough came when the electric generator was coupled to the turbine, and thus, the world's first hydroelectric station (of 12.5 kW in capacity) was commissioned on September 30, 1882, on the Fox River at the Vulcan Street Plant, Appleton, Wisconsin (USA), lighting two paper mills and a residence (Edenhofer et al. 2011).

China's first hydropower station is the Shilongba on the Tanglangchuan River in the city of Kunming, Yunnan Province. The station was put into operation in 1912 and has since provided power to the Kunming city through a 32-km-long power line. Outfitted with two sets of generators manufactured by Germany and Austria, respectively, the power station had an installed capacity of 480 kW when it was completed. One of the generators is still in use, and the station added two 3000 kW generators in the 1950s. The station has supplied more than 1 billion kWh of electricity since putting into operation and is still supplying voltage to nearby residences. Although the Shilongba Hydropower Station has generated less electricity in recent years due to decreased water flow in the river, the station has assumed a relatively new role as tourist attraction. In 2006, this power station was listed as one of the China's key cultural relics Table 1.10 lists several historical hydraulic structures in the period of 1800AD-1940AD.

1.2.4 1940–End of Twentieth Century

It is an exciting era featured by high concrete and embankment dams as well as giant hydropower plants. Drinking water supply for quickly growing cities required large reservoirs. After the invention of electricity transmission with alternating current, high dams were necessitated for increasing demand of clean and convenient hydropower. Since the 1950s, the increase in the number and height of dams was accelerated around the whole globe, and dams of several types (gravity, arch,

Table 1.10 Historical hydraulic structures in the period of 1800 AD–1940 AD

Year	Name and features	Location	Remark
Around 1800	Meer Allum Dam. The arch thickness is 2.6 m. Each buttress is 7.3 m thick and 12.8 m long	Hyderabad, India	The first true multiple-arch buttress dam of mortared masonry. The spans of the 21 vertical arches vary up to a maximum of 45 m
1839	Yeni Dam, 16 m high and 93 m long. Its crest thickness is 7 m, and base thickness is 9.5 m	Istanbul, Turkey. By the decree of Sultan Mahmut II	A curved masonry gravity structure also known as the Sultan Mahmut Dam
1854	Zola Dam, 42 m high	Aix-en-Provence, France	Rubble masonry. The first arch dam whose stress analysis was rationally carried out by the cylinder method
1882	Vyrnwy Dam	Liverpool, UK	Masonry gravity. A draining network to reduce uplift had been firstly incorporated into the dam body
1892	Tansa Dam, 2.8 km long and 41 m high	Bombay, India	Embankment
1887–1897	Mullaperiyar Dam, 53.66 m high	Kerala, India	Masonry gravity
1902	Aswan Dam, 20 m high and 1951 m long. Enlargement of this gravity dam to a height of 27 m was completed in 1912, followed by a further raise in 1933 to 53 m high	River Nile, Egypt	It was built with quarried granite. Successful operation of the dam was attributable in part to provision of sluiceways in the structure which allowed silt to flow through to the irrigated lands of the lower Nile
1904	Cheesman Dam, at height of 72 m and curved in plan on a radius of 122 m	Colorado, USA	Arched gravity to which, in 1904, Woodard applied crown cantilever method (initiated by Vischer and Wagoner)
1900–1906	Wachusetts Dam	Massachusetts, USA	Masonry gravity. Gave firstly the consideration to the uplift in the design, which resulted in fat section
1905	New Croton Dam, 90.5 m high. The last major American cut stone masonry dam	New York, USA	Masonry gravity. While natural cement was used on this project, it was also one of the first applications of American Portland cement
1909	Pathfinder Dam, 65 m high	Wyoming, USA	Masonry arch dam

(continued)

Table 1.10 (continued)

Year	Name and features	Location	Remark
1915	Kensico Dam, 94 m high	New York, USA	Introduced a new era in dam construction by the invention of “cyclopean concrete”
1924	Dix River Dam, 84 m high	Kentucky, USA	Set a height record of rockfill dam
1931	Salt Springs Dam, 100 m high	California, USA	Set a height record of rockfill dam
1931–1936	Hoover (Boulder) Dam, 221 m high and 379 m long on crest. Thickness varying from 13.7 m at the top to 201 m at the base	Colorado River, USA	It is an concrete arched gravity structure set a height record in the world
1935	Marèges Dam, 90 m high	Dordogne River, France	Designed by André Coyne. It initiated the practice of double-arch dams. It also incorporated several innovative features such as the ski-jump spillway
1939	Osiglietta dam, 76 m high	Italy	Designed by Nicolai. It initiated the practice of double-arch dams by bending the upper portion of the dam in the direction of downstream

multiple arch, zoned earthfill or rockfill) continued to mount toward new height until exceeding 250 m. Up to 1939, there were only 11 completed dams higher than 100 m, of which 5 were in Western Europe and 6 were in USA; by 1960, there were already 88 dams higher than 100 m in service throughout the world. New dam height and volume records were set and broken in quick succession.

New dam type, material, construction method, etc., had been developed fast. Some of them had limited influences, and the others, particularly on the aspects of material and construction, have profound influences until today.

Three events are the most worthwhile to be noted for this significant historical period, namely the invention of RCC dams, fast development of rockfill dams, and comprehensive design theory of super-arch dams. These three dam types are prevalent in the construction of modern high dams, particularly on the west southern areas in China.

1. RCC dams

Featured by the dry lean concrete of lower cementitious material and roller compaction construction method, the roller compacted concrete (RCC) dam is one of the most competent type in the design of modern high dam project. Research works on RCC dams started from 1960. The first experiment of RCC was carried out for the cofferdam of the Shimen embankment dam in Taiwan, China ($H = 133$ m). A high gravity dam—the Alpe Gera ($H = 172$ m) in Italy—tried to use the construction technology of embankments to construct the concrete dam in 1963. Later on, this method was quickly developed for dams, cofferdams, and dam rehabilitations in Canada, USA, UK, Pakistan, Japan, and Brazil. By these practices, engineering experience and expertise were accumulated step by step. The Shimajigawa Dam in Japan ($H = 89$ m) and the Willow Creek Dam in USA ($H = 52$ m) belong to the initial batch of RCC dams in the world. The world's highest RCC gravity dam—Longtan ($H = 216.5$ m)—is now erected in China. Since the 1990s, the RCC started to be exercised in the construction of arch dams. Just a bit of later after the construction of the first two RCC arch dams in South Africa (Wolwedans at height of 70 m in 1990, and Knellpoort at height of 50 m in 1989), the first two Chinese RCC arch dams were completed in 1993—the Puding RCC Arch Dam (Guizhou Province, China, $H = 75$ m) and the Wenquanbao RCC Arch Dam (Hebei Province, China, $H = 48$ m)—which became the landmarks of the RCC arch dams in the southern and northern China. They were followed by a series of high RCC arch dams such as the Shapai (Sichuan Province, China, $H = 132$ m) and the Dahuashui (Guizhou Province, China, $H = 134.5$ m).

2. Rockfill dams

The 1940s also initiated the first use of earthfill core and filter materials in the interior section of the rockfill dams, this evolution gave the impetus to the growth of several related disciplines, including soil mechanics, engineering geology, seismology, hydraulics, and instrumentation. Another consequence of this evolution is the invention of larger, faster, more powerful, and more efficient earthwork construction equipments.

High-pressure jet wetting or irrigation flooding techniques were applied to the dry rock dump surfaces—"wet dump" to consolidate and to reduce large post-construction settlements down to acceptable levels. From the 1960s to the present day, rockfill construction shifted from wet rock dump placement in thick loose lifts to compacted rockfill placement in thin controlled lifts using heavy roller compaction. In 1958, the Quoich Dam (UK, H = 38 m) became the first rockfill dam using thin controlled lifts by heavy vibration roller compactor. The wet rock dump technique was essentially terminated by around 1965 on large rockfill dams in the world. The New Exchequer Dam (USA, H = 150 m) completed in 1966 became the last rockfill dam by the mixed methods of "dry rock dump" technique of thick rockfill lifts and "wet" roller compacted of thin rockfill lifts. From the Foz do Areia Dam (Brazil, H = 160 m) completed in 1980, to the Salvajina Dam (Colombia, H = 148 m) completed in 1985, until the Aguamilpa Dam (Mexico, H = 187 m) completed in 1993, the design and construction techniques of compacted rockfill dams achieved amazing progress. In 1989, the Alberto Lleras Dam, also known as the Guavio Dam erected in Columbia, mounted a record height at 243 m. The highest compacted rockfill dam with central core in China is the Nuozhadu Dam in the Yunnan Province at a height of 261.5 m, completed in 2012. Until now, the highest record of the central core rockfill dam is kept by the Nurek Dam (Tajikistan, H = 300 m) completed in 1980. However, the Rogun (Raguni) Dam with a designed height of 330 m in Tadzhikistan is sometimes rated as the highest in the world although it has not been completed so far. The Tarbela Dam on the Indus River, Pakistan, with 142 Million m^3 of earth and rock is keeping the world record of the embankment volume so far.

A remarkable event in the modern rockfill dam construction is the boost of concrete-faced rockfill dams (CFRD). The Cethana Dam (Australia, H = 110 m) completed in 1971 established technique landmarks for the modern CFRD. Nowadays, in parallel to concrete arch dam and RCC dam, CFRD is very competent in the selection of dam type in China. The world's highest CFRD (Shuibuya, H = 233 m) is erected in China.

In 1970, the hardfill dam—a kind of symmetrical trapezoidal shaped embankment using low-cost cemented sand and gravel materials and having a concrete impervious face on its upstream face, was proposed by Raphael (1971), as "the optimistic gravity dam." And later, Londe and Lino (1992) named it as "Faced Symmetrical Hardfill Dam (FSHD)." Nowadays, the European countries commonly name it as hardfill dam, and Japan calls it cemented sand and gravel dam (CSG dam) (Toshio et al. 2003). Actually, it may be looked at as an "intermediate dam" between the concrete gravity type and rockfill type. Since the beginning of the 1990s, with the first application to the cofferdam (H = 15 m) in the construction of the Nagashima Dam (Japan), the employment of this dam type has been accelerated. The Cindere Dam (Turkey, H = 107 m) completed in 2005 is the tallest hardfill dam in the world at present.

3. Arch dams

The trial load method had revealed that along an arch ring, the arch load is maximum at the crown and minimum at the abutments. Therefore, the curvature should be largest at the crown and minimum at the abutments, to obtain both good stress conditions for the dam body and good stability conditions for the abutments. Gicot is the first who suggested parabola arch ring, and the idea was first realized in the Vieux Emosson Arch Dam (Switzerland, $H = 45$ m) completed in 1955. Famous Chinese parabola arch dams are Ertan ($H = 240$ m), Xiluodu ($H = 278$ m), Xiaowan ($H = 294.5$ m), and Jinping 1 ($H = 305$). Gicot also suggested ellipse arch ring, implemented it in the Les Toules arch dam (Switzerland, $H = 86$ m), and completed in 1963. Representative Chinese ellipse arch dams are the Gaixiaba ($H = 141$ m) and the Jiangkou ($H = 140$ m). Leroy, from Coyne and Bellier, France, suggested logarithmic spiral arch ring and designed the Vouglans Dam (France, $H = 130$ m) that was completed in 1962. The highest Chinese logarithmic spiral arch dam is the Laxiwa ($H = 250$ m).

Due to the relatively conservative conclusions by the Stevenson Creek Test Dam (Engineering Foundation (US) 1927), the enthusiasm in the arch dam construction was cooled down in USA. Since the 1950s, the center of arch dam construction was moved to Europe. The Marèges dam at a height of 90 m on the Dordogne River (France) was constructed between 1932 and 1935. The dam, designed by André Coyne, incorporated several innovative features by the first application of the double curvature and the ski-jump spillway. The Kariba Dam (Zambia and Zimbabwe, $H = 128$ m), 6 orifices of 9.1 m × 9.46 m in size were installed with the total discharge of 9500 m^3/s and the unit flow rate of 176 m^2/s. The Kariba Dam was also designed by André Coyne in 1955 and completed in 1959. Along with the mounting in the height, the arch dam also had tendency of becoming thinner and thinner. The Tola dam of 90 m high designed by André Coyne was only 2.43 m thick at the base.

However, a somewhat Pollyanna atmosphere in the construction of high arch dams was waked up by a timely warning lesson—the failure of the Malpasset Dam in 1959 (Londe 1987), which brought a lawsuit against more than ten engineers. Arch dam construction suffered a serious setback in the world (Ru and Jiang 1995). For example, the arch dams under construction such as the Contra (Switzerland, $H = 220$ m) and the Kurobe 2 (Japan, $H = 186$ m) were suspended for the reinforcement of abutment rock; the Shimen Arch Dam (Taiwan, $H = 141$ m)was replaced by embankment type. After a series of systematic investigations, it became fully recognized that abutment stratum conditions were critical to the stability of high arch dams. Step by step, the confidence and construction of high arch dam had been recovered. Precedent setting for arch dams since the mid-twentieth century in the world is the Mauvoisin Arch Dam (Switzerland, $H = 237$ m) completed in 1957, the Vajont Arch Dam (Italy, $H = 265$ m) completed in 1960, and the Contra Arch

Dam (Switzerland, $H = 220$ m) completed in 1965. In Soviet Union, the double-curvature concrete arch dam of the Inguri ($H = 271.5$ m) was completed in 1987, which is located 7 km from the Dzhvari Village in a narrow gorge of the Inguri River, Georgia (since 1991, it is an independent country officially named as the Republic of Georgia). In 2012, the Xiaowan Arch Dam (China, $H = 294.5$ m) set a new height record.

Apart from the other areas in civil engineering (e.g., highways, railways, mines), the requirement on the dam foundation and abutments gave strong impetus to the fast progress in the rock mechanics led by Leopold Müller et al., nearly 20 year later than the soil mechanics (Müller et al. 1964). The evolution of soil mechanics and rock mechanics gave rise to the birth and maturation of geotechnical engineering, as an important civil engineering specialty. The use of computers and computer programs for the analysis and design became a routine practice within a fairly short time after they were developed by geotechnical engineers.

According to the statistics by ICOLD, there were only 15 dams higher than 30 m in China up to 1950. Among them, 8 were earthfill or rockfill dams and 7 were gravity dams. Alternatives for dam-type selection at that time were quite limited. After 1950, especially after the economy reform and opening to the outside world initiated around 1980, dam constructions and techniques have achieved great progresses in the country (Jia 2013). Also according to the statistics by ICOLD, averagely 335 dams were completed per year in the world except China from 1951 to 1977, but only altogether 420 dams were built in China during this period. In contrast, according to the incomplete statistics at the end of 2004, there were about 47,500 large dams in the world, of which 26,278 were erected in China that accounted for approximately 55 %. By the end of 2005, there were 130 large dams higher than 100 m in China, of which 9 are higher than 200 m.

Early hydropower plants (HPP) were proliferated of small to medium sized and distributed wherever there was an adequate supply of flowing water and a need for electricity. As the electricity demand grows, the number and size of hydropower plants were increasing. Hydropower plants today span a vast range of scales, from a few watts to tens of GW. The largest projects, the Itaipu in Brazil and Paraguay with 14,000 MW installed generator and the Three Gorges in China with 22,400 MW installed generator, both produce between 80 and 100 TWh/year. The great variety in the size of hydropower plants gives the technology able to meet both large centralized urban energy demands and decentralized rural needs.

Conventionally, hydropower is used to meet mechanical energy needs as well as to provide space lighting and heating and cooling. More recently, hydropower has also been investigated for the use in the electrolysis process of hydrogen fuel production, provided there is abundance of hydropower in a region and a local goal to use hydrogen as fuel for transportation (Yumurtacia and Bilgen 2004). Table 1.11 lists several historical hydraulic structures in the period from 1940 to around the end of the twentieth century.

Table 1.11 Historical hydraulic structures in the period from 1940 to around the end of the twentieth century

Year	Name and features	Location	Remark
1948	Escaba Dam, 83 m high	Tucumán, Argentina	The highest flat slab buttress dam in the world
1954	Malpasset Dam, 66 m high	Reyran River, France	Arch dam. Failure in 1959 waked up dam engineers the importance of the dam abutment stability
1955	Vieux Emosson Dam, 45 m high	Valais, Switzerland	The first parabola arch dam, designed by Gicot
1957	Mauvoisin Dam, 237 m high	Valais, Switzerland	Double curvature
1957	Zeuzier Dam, 156 m high	Valais, Switzerland	Arch dam. Sustained damage from deformation occurred in 1979, due to a change in groundwater arising from the driving of a tunnel nearby. After 4 years of repair, it has been back in operation
1959	Kariba Dam, 128 m high, 24 m thick at base. Six orifices of 9.1 m × 9.46 m are installed	Zambia and Zimbabwe	Arch dam designed by André Coyne whose total discharge is 9500 m^3/s and unit flow rate is 176 m^2/s
1960	Vajont Dam, 265 m high	Monte Toc, Italy	A landslide in 1963 generated an immense surge wave overtopping the world's highest concrete arch dam at that time
1962	Grande Dixence Dam, 285 m high	Valais, Switzerland	Highest concrete gravity dam in the world
1962	Vouglans Dam, 130 m high	Franche-Comté, France	The first logarithmic spiral arch dam designed by Leroy
1963	Alpe Gera Dam, 172 m high	Lombardy, Italy	It tried to use the construction technology of embankments to place concrete dam, which initiated the practice in RCC dams
1963	Les Toules Dam, 86 m high	Bourg-St-Pierre, Switzerland	The first ellipse arch dam designed by Gicot
1964	Glen Canyon dam, 216 m high and 475 m long. Arch thickness varies from 7.6 m at the crest to 91.5 m at the base	Colorado River in Arizona, USA	The highest arch dam in USA
1965	Contra Dam, 220 m high	Ticino, Switzerland	Double-curvature arch dam

(continued)

Table 1.11 (continued)

Year	Name and features	Location	Remark
1967	Oroville dam, 235 m high with a volume of 61,000,000 m^3	Feather River, USA	Zoned earthfill dam made use of the abundant supply of ideal pervious materials that had been produced by dredgers mining for gold in the flood plain
1968	Daniel Johnson (Manicouagan No. 5) Dam, 214 m high	Quebec, Canada	The highest multi-arch buttress dam in the world. It consists of 13 arches supported by 12 buttresses, with the central arch spanning 161.5 m
1972	Dworshak Dam, 219 m high and 1002 m long	North Fork of the Clearwater River, Idaho, USA	A straight concrete gravity dam with a concrete volume of 4,970,000 m^3
1973	Mica Dam, 242 m high and 792 m long	British Columbia, Canada	An earthfill dam which has a nearly vertical core of glacial till and outer zones of compacted sand and gravel
1976	Tarbela Dam, 143.26 m high	Indus River, Pakistan	The world record for the volume of dam with 142,000,000 m^3 of earth and rock
1979	Kolnbrein Dam, 200 m high	Malta River, Carinthia, Austria	While the reservoir was filling, several cracks appeared in the arch dam and it took more than a decade of repairs before the reservoir could operate at maximum level
1980	Foz do Areia Dam, 160 m high	Paraná, Brazil	Record setting of the CFRD at that time
1980	Shimajigawa Dam, 89 m high	Yamaguchi, Japan	Gravity type belongs to the initial batch of the Japanese RCD—RCC wrapped with thick and high-quality CVC
1980	Nurek Dam, 300 m high	Vaksh River, Tadzhikistan	World's highest rockfill embankment dam
1983	Willow Creek Dam, 52 m high	Oregon, USA	Gravity type belongs to the initial batch of RCC dams with dry lean concrete of low cementitious material (66 kg/m^3)
1984	Itaipu Dam, 196 m high and 7919 m long	Brazil and Paraguay	Combination of gravity, buttress, and embankment sections. It is the highest massive-head buttress dam. It also has the largest annual energy generation in the world (98.2 TWh in 2012)
1986	Kengkou Dam, 56.8 m high and 122.5 m long	Fujian Province, China	The first RCC gravity dam in China. Concrete amount 60, 600 m^3, of which 42, 000 m^3 is RCC

(continued)

Table 1.11 (continued)

Year	Name and features	Location	Remark
1987	Inguri Dam, 271.5 m high, 10 m thick at the crest and 52 m thick at the altitude 50 m above its base	Inguri River, Georgia	Double-curvature dam had been keeping the world's record of arch dam height until the completion of the Xiaowan Dam (China)
1987	Upper Stillwater Dam, 87 m high	Utah, USA	Gravity type belongs to the initial batch of RCC dams, with dry lean concrete of high cementitious material (240–250 kg/m^3)
1989	Alberto Lleras Dam, 243 m high	Guavio, Columbia	Also known as the Guavio Dam
1989	Knellpoort Dam, 50 m high	Free state, South Africa	One of the first batch of RCC arch gravity dams
1990	Wolwedans Dam, 70 m high	Western Cape, South Africa	One of the first batch of RCC arch gravity dams
1993	Aguamilpa Dam, 187 m high	Tepic, Mexico	Record setting of the CFRD at that time
1993	Wenquanbao Dam, 48 m high	Hebei Province, China	The first RCC arch dam in the Northern China
1993	Puding Dam, 75 m high	Guizhou Province, China	The first RCC arch dam in the southern China
1999	Ertan Dam, 240 m high	Yalongjiang River, China	The first Chinese particular high double-curvature arch dam
2001	Shapai Dam, 132 m high	Sichuan Province, China	The second highest RCC arch dam in the world
2005	Cindere Dam, 107 m high	Turkey	The highest hardfill dam in the world
2007	Dahuashui Dam, 134.5 m high	Guizhou Province, China	The highest RCC arch dam in the world
2008	Shuibuya Dam, 233 m high	Hubei Province, China	The world's highest CFRD
2008	Three Gorges Dam, 181 m high	Yangtze River, Hubei Province, China	Gravity dam, with generator installation of 22,400 MW, it is the world's largest hydropower station
2009	Longtan Dam, 216.5 m high	Guangxi Province, China	The world's highest RCC gravity dam
2009	Guangzhao Dam, 200.5 m	Guizhou Province, China	The world's second highest RCC gravity dam
2009	Laxiwa Dam, 250 m high	Qinghai Province, China	The Chinese highest logarithmic spiral arch dam
2010	Xiaowan Dam, 294.5 m high	Yunnan Province, China	The highest double-curvature arch dam in the world
2010	Pubugou Dam, 186 m high	Sichuan Province, China	Central cored rockfill dam, on an riverbed with alluvial deposit of 77.9 m deep,the concrete cutoff wall in the foundation is 82.9 m deep

(continued)

Table 1.11 (continued)

Year	Name and features	Location	Remark
2012	Nuozhadu Dam, 261.5 m high	Yunnan Province, China	The Chinese highest central core rockfill dam
Under construction	Xiangjiaba Dam, 165 m high	Sichuan/Yunnan Province, China	Concrete gravity. With generator installation of 7750 MW, it is the fifth largest hydropower station in the world
Under construction	Xiluodu Dam, 285.5 m high	Sichuan/Yunnan Province, China	Double-curvature concrete arch dam. With generator installation of 13,860 MW, it is the third largest hydropower station in the world
Under construction	Jinping 1 Dam, 305 m high	Sichuan Province, China	Will create the new height record of double-curvature arch dam when it will be completed soon
Under construction	Bakhtiari Dam, 325 m high	Lorestan Province, Iran	Double-curvature concrete arch dam

1.3 Water Resources and Hydropower Resources in China

Be situated in the southeast part of the Eurasian continent on the west coast of the Pacific Ocean, adjacent to the Himalayas Mountain known as the “Roof of the World” in the southwest and to the Siberia and the Mongolian Plateau in the north, China has a complex and diversified landscape varying greatly in altitude. The Qinghai–Tibet Plateau in the west of the country is a vast area with the highest altitude in the world. In the north of the Qinghai–Tibet Plateau, there are mountain systems of Altai, Qilian, Daxing’an, etc., and in its south, there are mountain ranges of Himalayas, Hengduan, Wuyi, etc. A great number of rivers originate on these plateaus and mountain systems and flow across the country. These mountains and rivers determine the basic features of the state landscape and create superior natural conditions for the two major elements of hydropower resources: runoff and fall. The theoretical and technically exploitable as well as the economically exploitable hydropower resources in China are all ranked at the first place in the world (Pan and He 2000; Jia 2013).

There are seven main river systems in China, namely the Yangtze, the Yellow, the Pearl, the Huaihe, the Haihe, the Liaohe, and the Songhuajiang, which are shown in Fig. 1.4 (Ministry of Water Resources of the People’s Republic of China

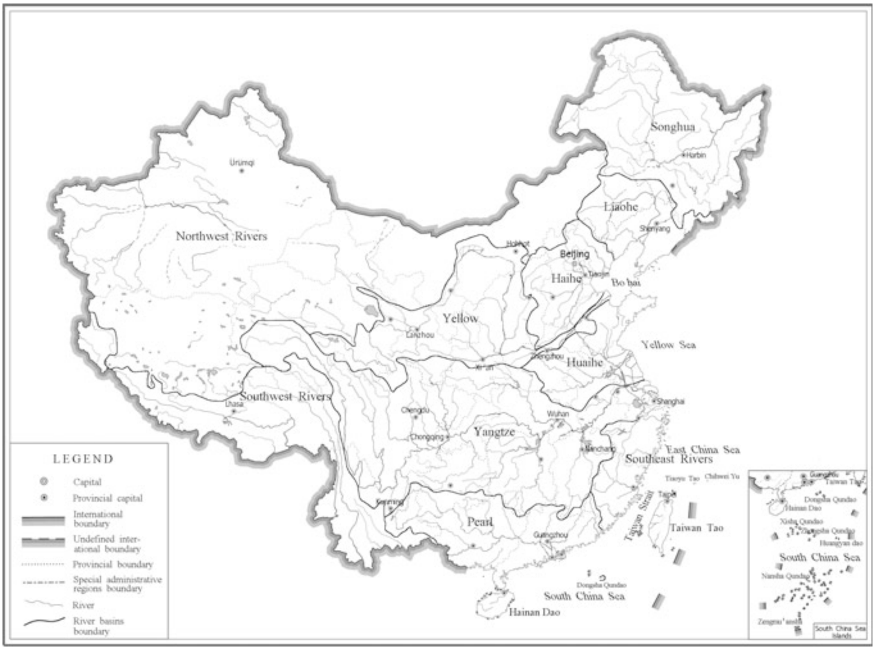

Fig. 1.4 River systems in China

2012). In addition, there are also the southeast coastal river systems including the Qiantangjiang and the Mingjiang, the northeast international river systems including the Heilongjiang and the Yalujiang, and the southwest international river systems including the Lancangjiang and the Nujiang and the Yaluzangbujiang (Brahmaputra), the northwest international rivers of the Ertix and the lli. There are also several interior river systems of Tarim and others in the provinces or autonomous regions of Xinjiang, Gansu, Inner Mongolia, and Qinghai.

According to the statistics data, there are more than 50,000 rivers in China with a drainage area of over 100 km^2. Among them, there are more than 1600 rivers with a drainage area of over 1000 km^2, 20 rivers with a length of over 1000 km, and 3019 rivers with theoretical hydropower resources of over 10 MW.

The average annual precipitation in China is 648 mm, i.e., about 6190 billion m^3 in total. Accordingly, the total amount of annual river runoff in China is about 2711 billion m^3. There are 17 rivers having an annual runoff over 50 billion m^3, which is ranked at the fifth place in the world after Brazil, Russia, Canada, and USA.

According to the data provided by the State Development and Reform Commission in 2004 (National Leading Group for the Re-check of the National Hydropower Resources Survey 2004), the theoretical hydropower resources in the Chinese mainland are 695 GW, corresponding to an annual energy output of 6083 TWh; the technically exploitable hydropower resources are 542 GW, which are at the first place in the world. Accordingly, China has planned 270 hydropower power stations with installed generator capacity over 300 MW, of which 100 are over 3000 MW and 800 are between 50 and 300 MW. The hydropower resources of the major river basins in China are listed in Table 1.12.

Due to the geographic features of the country, scarce cultivable land and huge population are highly concentrated in the eastern China, while 82.9 % of water and hydropower resources are distributed in the vast western part of the country. The society development, particularly in the middle and lower river reaches with huge population, is often encountered with difficulties to satisfy multiple purposes such as flood control, agriculture irrigation, navigation, water supply, aquaculture, recreation, and ecology and is liable to conflicts among those purposes to some extent in terms of quantity and quality of water consumption, as well as spatial-time allocation. Therefore, China is actually a country in short of water resources: The average water resources per capita is about 2100 m^3 and per hectare is about 22,500 m^3, which is only 30 and 50 % of the world's level, respectively. In order to give priority to the full use of clean and renewable hydropower resources and meet the electric power demands, the high-quality management, rational exploitation, careful protection, and sustainable utilization of water resources are and will continue to be a strategically paramount issue in the economical and social development of the country.

Table 1.12 Hydropower resources of the major river basins in China

River basin	Theoretical hydropower resources		Technically exploitable hydropower resources		
	Annual energy output	Average capacity	Annual energy output	Average capacity	Number of power stations
	TWh	MW	TWh	MW	Planned
Yangtze	2433.598	277,808.0	1187.899	256,272.9	5748
Yellow	379.413	43,312.1	136.096	37,342.5	535
Pearl	282.394	32,236.7	135.375	31,288.0	1757
Haihe	24.794	2830.3	4.763	2029.5	295
Huaihe	9.800	1118.5	1.864	656.0	185
Northeast river system (Songhuajiang, Heilongjiang, Liaohe, etc.)	145.480	16,820.8	46.523	16,607.4	644 + 26/2
Southeast river system (Qiantangjiang, Minjiang, etc.)	177.611	20,275.3	59.339	19,074.9	2558 + 1/2
Southwest river system (Lancangjiang, Nujiang, etc.)	863.007	98,516.8	373.182	75,014.8	609 + 1/2
River system in Tibet (Yaluzangbujiang)	1403.482	160,214.8	448.311	84,663.6	243
Northwest river system (Ertix, lli, Tarim, etc.)	363.357	41,479.1	80.586	18,471.6	712
Total	6082.9	694,400	2473.9	541,640	13,286 + 28/2

N.B.: According to the data of the general surveys in 2005

1.4 Hydraulic Engineering in China

Hydraulic engineering in China has gained rapid progress since the 1950s until the end of the 2000s, as has been interspersed foregoing. In the twenty-first century, the hydropower exploitation in China will attain a greater breakthrough by two steps (Peng 2006; Zhu 2009).

The first step was from 2001 to 2010. By the end of 2010, the national hydropower capacity reached 210,000 MW, and the corresponding annual energy output was 650 TWh. The hydropower accounted for about 30 % in the national electric power supply. The 5200 dams higher than 30 m were completed or under construction, of which 145 exceeded 100 m. Among the 450 completed hydroelectric stations larger than 50 MW in generator installation capacity (including 21 pumping storage stations), 100 exceeded 300 MW (including 15 pumping storage stations) and 40 were of especially large scale whose installation capacity exceeded 1000 MW(including 7 pumping storage stations). By the year of 2010, the total reservoir storage capacity reached 1/6 of the river annual runoff of the whole country, which played important role in the flood protection, irrigation, and water supply by covering 0.35 Billion population and 0.033 Billion ha farmland as well as hundreds of large to medium cities including Beijing, Tianjing, Guangzhou, Shanghai, and Wuhan. To meet the development requirements of metropolis cities, a large number of long distance water diversion projects were constructed, and more than 100 large to medium cities relied mainly on the reservoir supply for domestic living and industry, such as the Miyun reservoir for Beijing, the Panjiakou reservoir for Tianjing, and the Shenzhen reservoir for Shengzhen and Hongkong.

The second step is from 2011 to 2050. During this period, under the state policy guidance of exploiting her vast western area, China will nearly complete the exploitation of her hydroenergy potential, and there will be tens of super-large-scale hydropower plants built in the western China. Specially, the Motuo hydropower project, with design installed generator capacity larger than 40,000 MW, will be put into operation. It will become the greatest base of the hydropower in the world. The capacity of electricity transferred from the West to the East will exceed 150,000 MW.

Following the progress in the construction of large-scale water resources and hydropower projects, China has reached international level concerning the research, design, and construction technologies. The largest hydraulic project completed in the world—the Three Gorges project—provides electric capacity of 22,400 MW; the world's highest arch dam (Xiaowan, H = 294.5 m), the world's highest concrete-faced rockfill dam (Shuibuya, H = 233 m), and the world's highest RCC gravity dam (Longtan, H = 216.5 m) are all erected in China. The various giant projects under construction or nearly to be completed such as the Xiluodu, Xiangjiaba, Jingping 1, and Jingping 2 will further give an impetus to push the technologies of water resources and hydropower engineering in China up to a greater height (Table 1.13).

Table 1.13 Large-scale hydropower projects to be constructed during the "twelfth five-year plan" (2012–2017)

River basin	Projects
Jinshajiang	Baihetan, Wudongde, Longpan, Liyuan, Ahai, Longkaikou, Ludila, Guanyingyan, Suwalong, Yebatan, Lawa
Lancangjiang	Cege, Kagong, Rumei, Guxue, Gushui, Wulonglong, Lidi, Tuoba, Huangdeng, Dahuaqiao, Miaowei, Ganlanba
Daduhe	Shuangjiangkou, Jinchuan, Anning, Badi, Danba, Houziyan, Huangjinping, Yingliangbao, Laoyingyan, Zhentouba, Shaping
Upreach of the Yellow river	Ningmute, Maerdang, Chiha, Banduo, Yangqu, Heishanxia
Yalongjiang	Lianghekou, Yangen 1, Yangen 2, Mengdigou, Yangfanggou, Kala
Nujiang	Songta, Maji, Yabiluo, Liuku, Saige

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