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1 Introduction

Since the beginning of time, humans have endeavored to cope with various water-related issues, such as flooding and drought. The successful practices led to the establishment and subsequently the advancement of engineering hydrology and hydraulics, which are branches of science and technology concerned with design of water resources engineering infrastructure, such as channels, pipes, and reservoirs. This chapter presents an overview of the basic concepts and practices used to utilize and protect precious water resources. After highlighting some of the essential aspects of such practices, this chapter discusses the roles of hydrology and hydraulics in water resources engineering design.

1.1 Advances in Water Resources Engineering

Water is critical to human existence and is thus one of the most important resources. In ancient times, hunter-gatherers moved from one location to another in search of fresh water for themselves as well as for their animals. With the advent of agriculture, the first farmers planted crops close to rivers and streams. They passively relied on naturally available water. If the water at a settlement location became insufficient and/or difficult to access, the people moved to a new location where sufficient water could be easily utilized. In dry years, bloody conflicts could break out between tribes competing for limited water, whereas in wet years, flood waters could devastate communities, causing life and property losses. Throughout history people have had to contend with problems resulting from either too little (drought) or too much (flooding) water. Our ancestors' observations and persistent efforts led to some empirical knowledges of water phenomena and successful projects to mitigating drought and flooding. For instance, the Dujiangyan Irrigation System, located in Dujiangyan City, Sichuan Province, southwest China, was originally constructed around 256 BC by the State of Qin as an irrigation and flood control project (https://en.wikipedia.org/wiki/Dujiangyan). It is still in use today and irrigates more than

5300 km^2 of agricultural fields. Prior to construction of this system, the Minjiang River, which is the longest tributary of the Yangtze River, would rush down from the Min Mountains before slowing abruptly in the Chengdu Plain, filling the watercourse with silt and thus making the nearby areas extremely prone to flooding. The Dujiangyan Irrigation System was constructed to harness the river by channeling and dividing the watercourse rather than simply damming it. There are many other examples of ancient hydraulic engineering projects, such as irrigation canals in Egypt and Mesopotamia, diversion channels of the Euphrates River, and ceramic conduits for water supply in Pakistan.

In modern times, from the accumulated experiences gained from those ancient projects, new experimental results, and applications of basic sciences such as physics and calculus, two scientific disciplines, namely hydrology and hydraulics, emerged. These disciplines were established, advanced, and increasingly applied to the design of water resources engineering structures such as channels, culverts, and reservoirs. Hydrology studies the occurrence, storage, and movement of the Earth's water, whereas hydraulics deals with the conveyance of water through pipes and channels. In engineering, hydrologic principles are used to determine the design peak discharge and/or flow hydrograph, which in turn are used in the subsequent hydraulic analyses to determine the size of a structure of interest.

Averaged globally, the Earth receives 1028 mm precipitation annually, about 66% of which is lost to evapotranspiration and infiltration, generating 161 mm runoff as the surface water (Table 1.1). The gross amount of water resources, including groundwater and surface water, is about 10,633,450 km^3 (USGS, 2017), most of which is inaccessible to humans. However, both precipitation and runoff have large spatial variations. South America receives the most precipitation, about 43.8% of which is converted into runoff, whereas Antarctica receives the least precipitation, about 90.9% of which is converted into runoff. In comparison with Asia, Africa receives more precipitation but has a smaller runoff coefficient and thus is drier. North America and Europe receive almost the same amount of precipitation, but Europe has much less runoff because it has a lower runoff coefficient. In Australia and Oceania, only 9.1% of the precipitation (440 mm a^{-1}), which is relatively low, is converted into runoff, making this geographic region both climatically and hydrologically driest among the continents except for Antarctica. The oceans receive the second most precipitation, about 89.5% of which is evaporated back into the atmosphere.

Besides the spatial heterogeneity discussed above, for a given location, the precipitation can greatly vary from season to season in a year and from day to day in a season, resulting in too much water at one time but too little water at another. Such temporal variations have caused major floods and droughts all over the world. A major flood inundates extensive rural and/or urban areas, likely isolating properties and towns and closing major traffic routes. In contrast, a major drought is a prolonged period of abnormally dry weather that can be sufficiently long that the lack of water causes serious problems, including crop damage and/or water supply shortage (NWS, 2019). From 2000 to 2009, there were 175 major floods worldwide, about 70 of which occurred in Asia (Sohoulande-Djebou and Singh, 2016). Previous studies (e.g., Marengo and Espinoza, 2016) have shown that as a result of climate change, larger floods and severer droughts tend to occur more often in more geographic regions. It is interesting that Africa incurred 40 major floods even though its overall runoff was only 110 mm a^{-1}. Major floods also occurred on other continents 5 to 38

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Table 1.1 Runoff and number of major floods, droughts, and dams by continents.

Region	Area (km^2)[1]	Precipitation ($mm\ a^{-1}$)[2]	Runoff ($mm\ a^{-1}$)[2]	Runoff coefficient (%)[2]	Number of major floods in the 2000s[3]	Number c droughts 1900[4]
Africa	30,380,560	740	110	14.9	40	291
Antarctica	13,998,885	110	100	90.9	–	–
Asia	44,573,695	650	240	36.9	70	153
Australia and Oceania	7,692,265	440	40	9.1	5	22
Europe	10,181,245	820	230	28	22	42
North and Central America	24,708,485	800	330	41.3	38	134
South America	17,839,840	1600	700	43.8		
Oceans	361,044,345	1140	−120	−10.5	–	–
Global	510,419,320	1028	161	34.4	175	642

[1] *Source*: https://en.wikipedia.org/wiki/Continent, accessed on April 12, 2019.
[2] *Source*: www-das.uwyo.edu/∼geerts/cwx/notes/chap10/continents.html, accessed on April 12, 2019.
[3] *Source*: Sohoulande-Djebou and Singh (2016).
[4] *Source*: Masih *et al.* (2014).
[5] *Source*: https://akuinginhijau.files.wordpress.com/2008/11/number-of-dams-country.pdf, accessed on April 12, 2019.

times. In contrast, since 1900, a total of 642 major droughts have occurred worldwide, most of which occurred in Africa (Masih *et al.*, 2014). Countries in Asia and America have also incurred a number of major droughts, while European countries and Australia and Oceania have, so far, incurred relatively fewer major droughts.

To cope with floods and droughts, myriad dams have been constructed, forming reservoirs to regulate uneven runoff flows (Graf, 1999). A reservoir is usually operated to attenuate peak discharges as well as to store extra water during a wet season to be used during the following dry seasons. By doing this, the reservoir has proven to be a successful practice in mitigating flooding and drought issues. Globally, more than 57,000 major (56,700 large and 300 giant) dams have been constructed as of 2019. The height of a large dam is 15 m or more, whereas the height of a giant dam is at least 150 m; the latter forms a reservoir with a storage capacity of more than 3×10^6 m^3. Asia has the greatest number of major dams, followed by North and Central America. Europe has 517 more major dams than South America, while Africa has twice as many major dams than Australia and Oceania combined. In practice, a major dam is always designed to have multiple functions, such as flood control, navigation, power generation, recreation, and water supply. Herein, although the prioritization of these functions may be different from one dam to another, flood control is always the most important function for all dams.

In addition to one or more dams, an actual water engineering system may also include other hydraulic structures (Figure 1.1), such as channels, pipelines, pumps, turbines, bridges, culverts, spillways, and stilling basins, to name a few. At the road crossing, the bridge openings and/or culvert barrels must be large enough to convey the design peak discharge without overtopping the road deck. For the safety of the dam, during large floods, water is released through the spillway downstream into the stilling basin. After the extra energy is dissipated through hydraulic jumps in the basin, the flood water is discharged back into the river. Further, a pipeline conveys high-energy flows from the reservoir into the hydropower plant to drive turbines to generate electricity. After passing through the turbines, water from the plant is released back into the river through a channel. Moreover, a pumping station may be needed to supply water from the reservoir to locations at a higher altitude.

In the past decades, urbanization has rapidly increased throughout the world. This increase could significantly alter natural hydrologic processes by reducing infiltration and increasing runoff (Wang *et al.*, 2017). As illustrated in Figure 1.2, for a given location, as a result of urbanization, the runoff volume and peak discharge will increase, while the baseflow (i.e., groundwater recession flow) will decrease. Also, the peak discharge will appear at an earlier time. The possible consequences are more frequent floods with a larger magnitude and more contaminated stormwater. To minimize such adverse impacts of urbanization, various low-impact development (LID) (Figure 1.3) devices can be installed and/or retrofitted to recover the natural hydrology (Rossmiller, 2014). In an urban environment, the typical land uses include building roofs, driveways, sidewalks, parking lots, streets, and lawns and open spaces (e.g., public parks). The first five of these listed land uses usually have an impervious surface with near-zero infiltration capacity. The increased runoff from building roofs can be treated using two types of LIDs, namely green roof and rain garden, whereas the increased runoff from driveways, sidewalks, parking lots, and streets may be treated using another two types of LIDs, namely porous pavement and permeable

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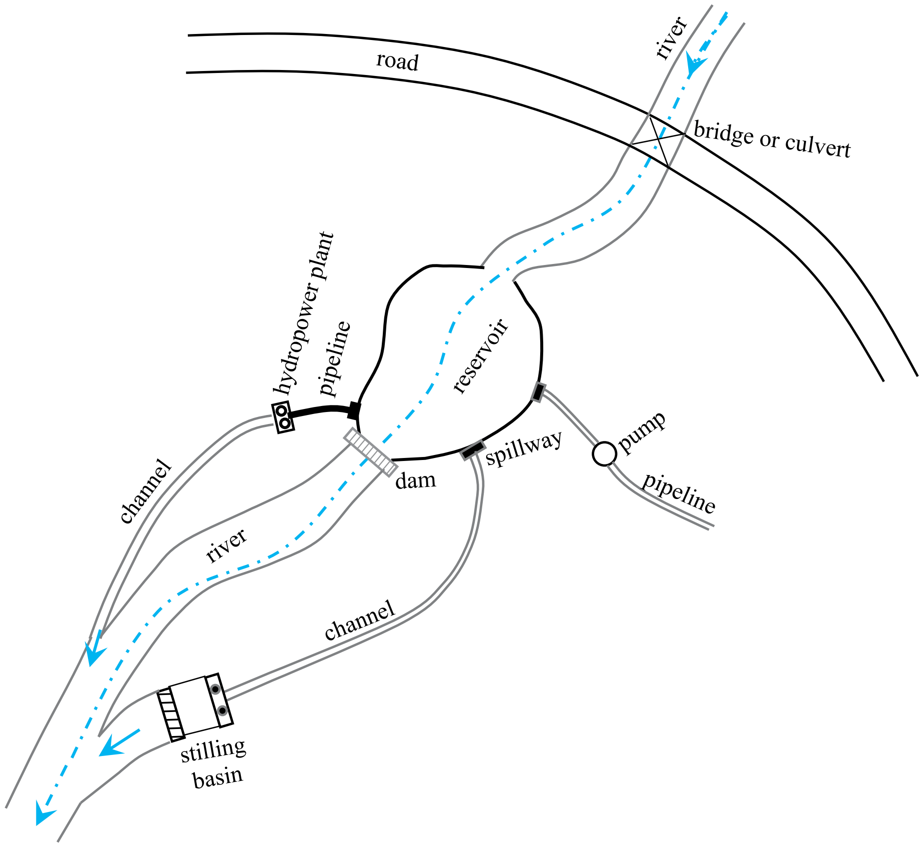

Figure 1.1 **A typical water engineering system showing the most common components.**

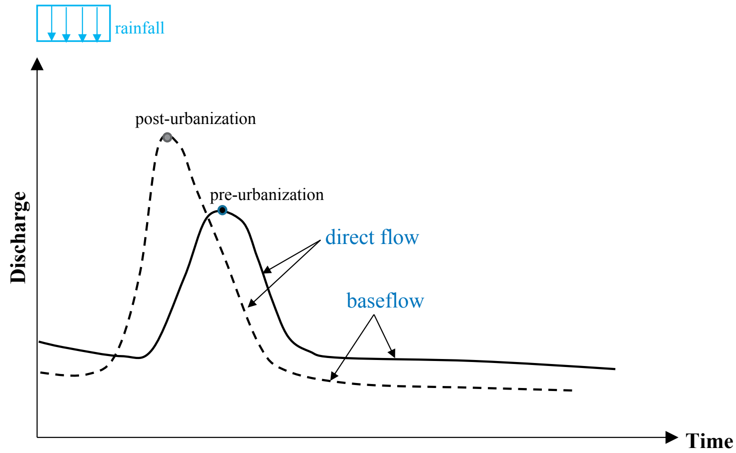

Figure 1.2 **Urbanization impacts on natural hydrology.** The flow hydrograph at a given location is affected by urbanization.

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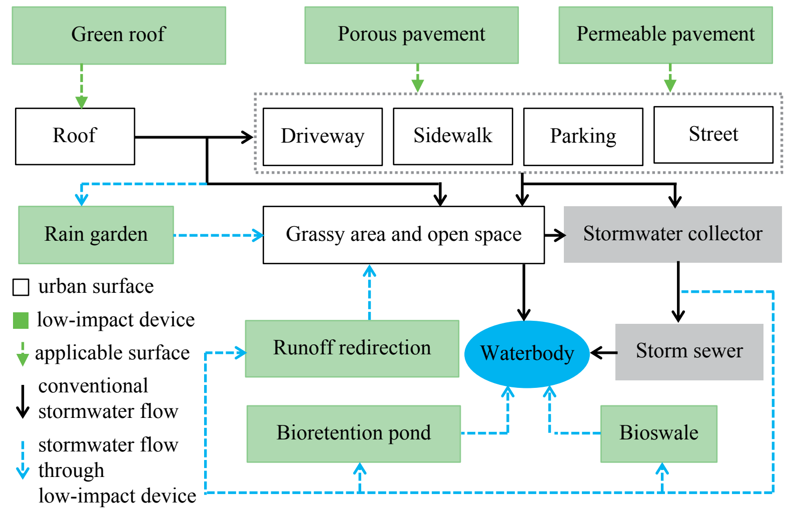

Figure 1.3 Various features in a typical urban environment. Land uses are indicated with hollow boxes and low-impact devices are shown with light green shading.

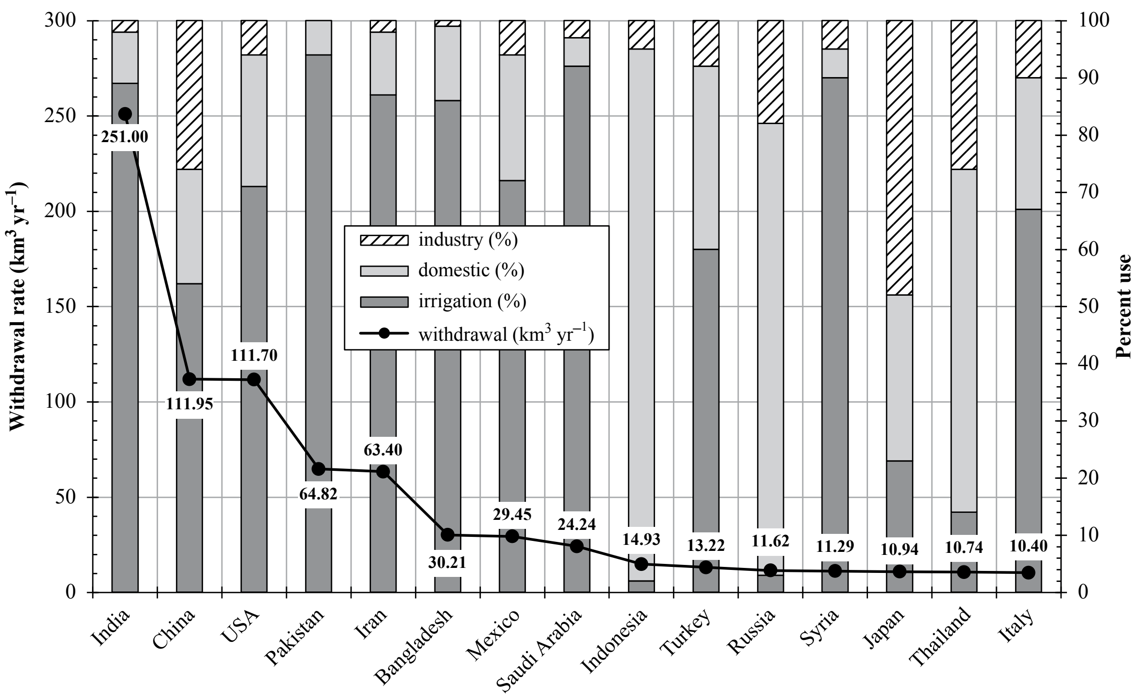

Figure 1.4 Groundwater exploitation. Withdrawal rate and uses in 15 countries, which represent nearly 80% of the groundwater withdrawal volume of the world.

pavement. The total runoff from a community of interest can be: (1) directed into three types of LIDs, namely bioswale, bioretention pond, and wet pond; (2) redirected to a pervious area for infiltration, evapotranspiration, and detention; and (3) discharged into a storm sewer system. The outflow from the LIDs may be partially redirected to a pervious area and/or directly released downstream into the storm sewer system and/or a receiving waterway. The runoff, which is redirected to the pervious area and has a reduced volume, will be discharged into the storm sewer, emptying into the receiving waterway. In practice, two or more LIDs, which may either belong to a same type or different types, can be installed in series to treat stormwater runoff to maximize the overall efficiency. In such a case, the outflow from one LID will be the inflow into another downward LID.

Currently, the world withdraws groundwater at an annual rate of 982 km^3 for irrigation, domestic use, and industry, with only 15 countries accounting for about 78.5% of that total, as shown in Figure 1.4 (Todd and Mays, 2005; Margat and van der Gun, 2013). In Indonesia, Thailand, and Russia, groundwater is primarily for domestic use, whereas in Japan, groundwater is mainly used for industry. In another 11 countries, groundwater is mostly used for irrigation. In addition, some countries (e.g., Bahrain and Mongolia) solely rely on groundwater for all water use sectors. Thus, groundwater hydraulics and extraction is an important component of water resources engineering.

1.2 Hydrology and Hydraulics in Water Resources Engineering

For an area of interest, quantifying the amount and spatiotemporal distribution of available water resources is always needed for its sustainable development. In practice, a variety of hydraulic structures, such as reservoirs, ponds, channels, and pipelines, usually need to be constructed to regulate runoff flows as mandated by flood control, drought resistance, and water supply. Also, road crossings, such as bridges and culverts, are imperative for transportation purposes. The design of those structures and crossings relies on the two related science disciplines introduced earlier in this chapter, namely hydrology and hydraulics.

Hydrology studies the occurrence, storage, and movement of the Earth's water. The occurrence concerns precipitation and its partitioning into infiltration, direct runoff, and evapotranspiration, whereas the storage concerns the percent of runoff and infiltrated water that will be detained and/or retained. The detained water will be held back for a limited time (e.g., from minutes to a year), after which it will be released from the holding space. In contrast, the retained water (e.g., film water adsorbed onto soil particles and groundwater in deep confined aquifers) may reside in a space permanently. Some of the detained and retained water can be evaporated back into atmosphere and/or infiltrated into deeper soils, starting a new cycle. The movement of water concerns the physical processes of runoff, infiltration, and evapotranspiration as well as their rates of occurrence. It usually involves quantifying runoff flow paths and velocities, infiltration rates, and evapotranspiration rates as functions of time.

Bras (1999) presented a brief history of hydrology. Precipitation as the original source of stream flow was hypothesized during the first century BC, but such a hypothesis was not supported by quantitative measurements until the seventeenth century. Since then, although the cause-and-effect relationship between precipitation and stream flow was mainly understood in a qualitative way, the understanding ultimately led to the establishment of the water balance concept. However, this fundamental concept did not become quantitative until the twentieth century, when Sherman (1932) enunciated the unit hydrograph method and Horton (1940) put forward the mathematical equations for estimating infiltration, soil moisture, and runoff. This greatly prompted and matured the applications of hydrology in water resources engineering and led to the creation of a new subject field called *engineering hydrology*, which was codified by the textbooks written by Linsley *et al.* (1958, 1982) and Chow (1964) and adopted by various universities to educate engineering hydrologists. In the 1970s, mathematical models were developed by integrating primary hydrologic processes such as infiltration, evapotranspiration, and runoff, making it feasible to predict responses of stream flow to precipitation as influenced by land uses and soil properties. The models had a lumped structure, using one set of parameters to represent a drainage area through its physiographic characteristics, which might have large spatial heterogeneities. Nevertheless, the development of the models was a revolution of the subject of hydrology and its engineering applications.

In the late 1980s and 1990s, recognizing the importance of spatial variability of rainfall, soil properties, land cover and land use, and topography on hydrology, researchers redeveloped the models to have a distributed structure. In this regard, the drainage area of interest is subdivided into a number of hydrologic response units (HRUs), each of which can be assumed to be spatially uniform and homogenous. Since the 2000s, extensive research efforts have been made to predict what the future climate would look like, leading to the development of various General Circulation Models (GCMs) and Regional Climate Models (RCMs) (Laprise, 2008). The GCMs were used to predict the future precipitations and temperatures at a coarse spatial resolution (e.g., 250 to 600 km) at the global scale, while the RCMs were paired with the GCMs to predict the future precipitations and temperatures at a fine spatial resolution (e.g., $\leq$ 50 km) at the regional scale. How to incorporate climate change and its uncertainties into hydrologic engineering design is becoming an important topic that is driven by the practical needs to sustain and improve the resilience of water infrastructure to worsening flooding and drought disasters. Moreover, as an important component of the water cycle, groundwater has been extensively studied since the 1970s. The results have been used widely in practice to direct exploration, utilization, and protection of groundwater resources. The existing models (e.g., MODFLOW) (Harbaugh, 2005) use various algorithms and parameters to represent influences of spatially variable medium properties on groundwater flow and transport.

Hydraulics deals with the conveyance of water through waterways such as pipes and channels. Its practices (e.g., the aforementioned Dujiangyan Irrigation System) began during prehistoric times, but the rationalization of hydraulics as a science was first attempted by Greeks (e.g., Archimedes) in 287 to 212 BC and continued slowly until the time of the Renaissance (i.e., from 1300 to 1600). During those three centuries, hydraulics was primarily acknowledged by observations and empiricisms with minimal uses of mathematics. However, in the seventeenth century, some researchers (e.g., Bernoulli) established the discipline of *hydrodynamics* by describing physical phenomena of flows using the modern mathematics, which produced an array of intimidating equations and methods. This classical hydrodynamics discipline was based on a pure mathematical approach and neglected observations and experimental works. On the other hand, other researchers (e.g., Chezy, Venturi, Darcy, Weisbach, Reynolds, and Froude) devised various apparatuses and experiments to measure flow velocities and resistances and established the discipline of *experimental hydraulics*. In the subsequent two centuries, these two disciplines were far apart and progressed essentially independently, though both aimed to quantitatively describe flow phenomena.

In the twentieth century, researchers (e.g., Prandtl) fused these two superficially interdependent disciplines into one unified science of fluid mechanics, which in turn was applied in almost every branch of engineering. Both the science and its engineering applications were tremendously advanced by the systematic laboratory works of Prandtl, von Kármán, Moody, Colebrook, and Saint-Venant, to name just a few. This textbook presents applications of fluid mechanics in water resources engineering. Since the 1940s, the advent of computers and sensors has led to the development and use of various software packages (e.g., HEC-RAS) to analyze sophisticated hydraulic systems with or without manmade structures. Given the increasing challenges of sustainable development, hydraulics will continue to progress and play an increasingly important role in water management. A detailed overview of the history of hydraulics can be found in Rouse (1983).

PROBLEMS

1.1 By conducting an internet search, identify three prehistoric water resources engineering projects and document their construction years, locations, and major purposes. Are they still being used today?

1.2 Based on an internet search, generate a bar chart showing the mean annual precipitation and evapotranspiration by each state of the USA.

1.3 Based on an internet search, document the mean annual water consumptions by categories (e.g., irrigation, domestic, and industrial) for a selected state in the United States.

1.4 Based on an internet search, document the construction years, locations, materials, heights, storage capacities, major purposes, and accessary structures of the dams for a selected state in the United States.

1.5 Select and sketch a water engineering system as shown in Figure 1.1.

1.6 Based on an internet search, document the impacts of urbanization on water resources for a selected city and the LIDs installed to mitigate the impacts.

1.7 Based on an internet search, document the available groundwater resources and its exploitations for a southwestern state in the United States.

1.8 Based on an internet search, document the impacts of climate change on water resources and possible adaptive measures.

1.9 Describe the roles of hydrology in water resources engineering.

1.10 Describe the roles of hydraulics in water resources engineering.