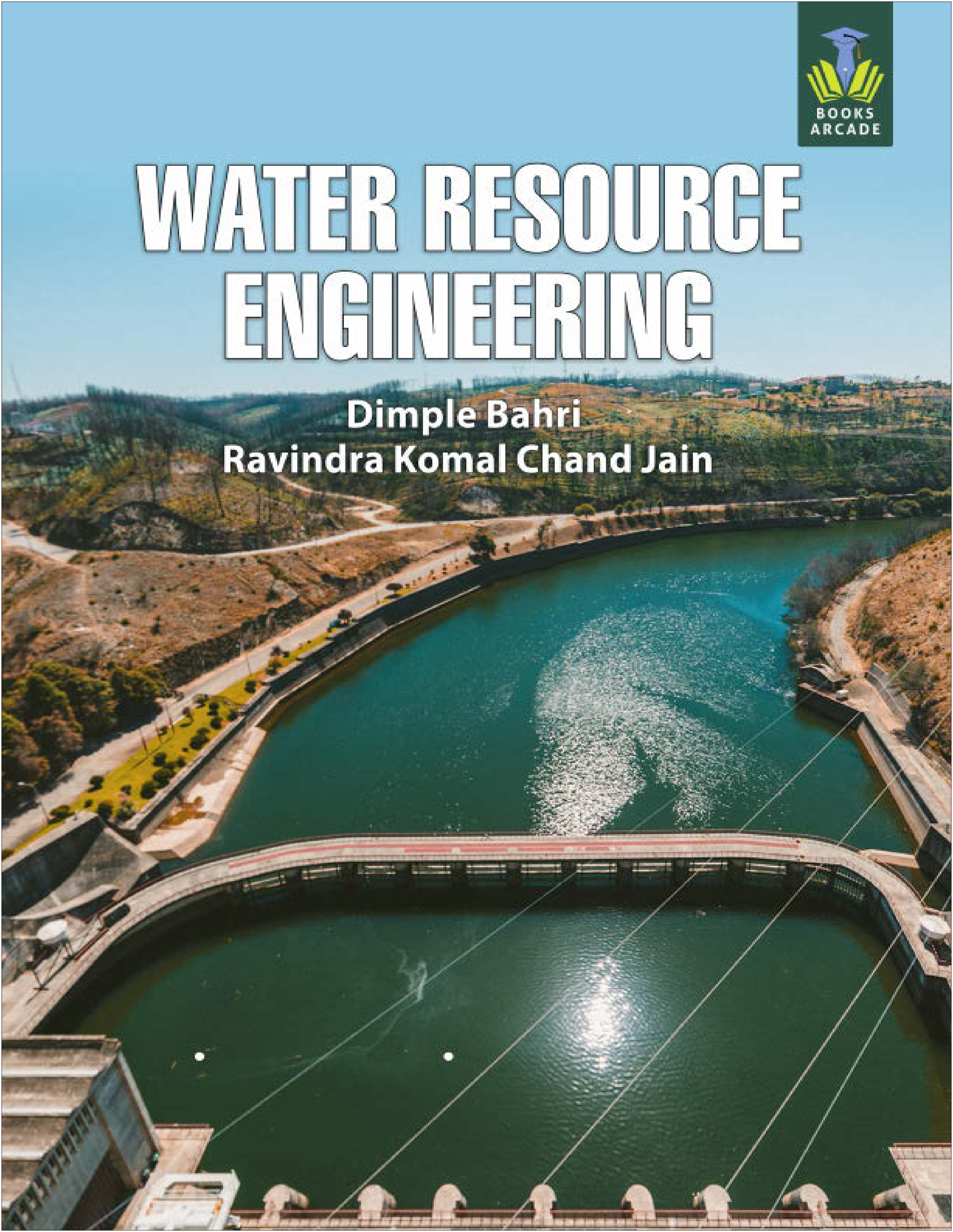

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WATER RESOURCE ENGINEERING

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Water Resource Engineering

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CONTENTS

CHAPTER 1

AN INTRODUCTION TO WATER RESOURCE

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Water resources engineering and management as defined for the purposes of this book includes engineering for both water supply management and water excess management. This book does not cover the water quality management or environmental restoration aspect of water resources engineering. The two major processes that are engineered are the hydrologic processes and the hydraulic processes. The common threads that relate to the explanation of the hydrologic and hydraulic processes are the fundamentals of fluid mechanics. The hydraulic processes include three types of flow: pipe (pressurized) flow, open-channel flow, and groundwater flow. The broad topic of water resources includes areas of study in the biological sciences, engineering, physical sciences, and social sciences, as illustrated in Figure 1. Areas in the biological sciences range from ecology to zoology, those in the physical sciences range from chemistry to meteorology to physics, and those in the social sciences range from economics to sociology. Water resources engineering as used in this book focuses on the engineering aspects of hydrology and hydraulics for water supply management and water excess management[1], [2].

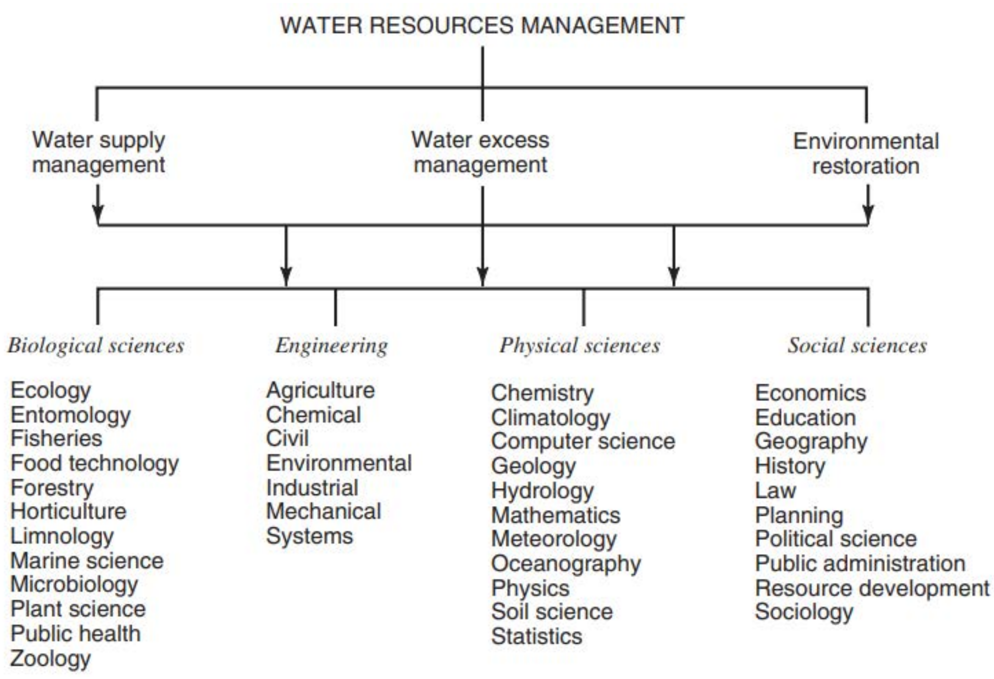

Figure 1: Represented the Ingredients of Water Resources Management

Water resources engineering not only includes the analysis and synthesis of various water problems through the use of the many analytical tools in hydrologic engineering and hydraulic engineering but also extends to the design aspects. Water resources engineering has evolved over the past 9000 to 10,000 years as humans have developed the knowledge and techniques for building hydraulic structures to convey and store water. Early examples include irrigation networks built by the Egyptians and Mesopotamians and by the Hobokam in North America. The world's oldest large dam was the Sadd-el-kafara dam built in Egypt between 2950 and 2690 B.C. The oldest known pressurized water distribution (approximately 2000 B.C.) was in the ancient city of Knossos on Crete. There are many examples of ancient water systems throughout the world[3].

The World's Freshwater Resources

Among today's most acute and complex problems are water problems related to the rational use and protection of water resources. Associated with water problems is the need to supply humankind with adequate, clean freshwater. These obviously are only approximations and should not be considered as accurate. The dynamics of actual water availability in different regions of the world.

Water Use in the United States

Dziegielewski et al. define water use from a hydrologic perspective as all water flows that are a result of human intervention in the hydrologic cycle. The National Water Use Information Program (NWUI Program), conducted by the United States Geological Survey (USGS), used this perspective on water use in establishing a national system of water-use accounting. This accounting system distinguishes the following water-use flows[4], [5]:

i. Water withdrawals for off-stream purposes,
ii. Water deliveries at point of use or quantities released after use
iii. Consumptives use,
iv. Conveyance loss,
v. Reclaimed wastewater,
vi. Return flow,
vii. In-stream flow

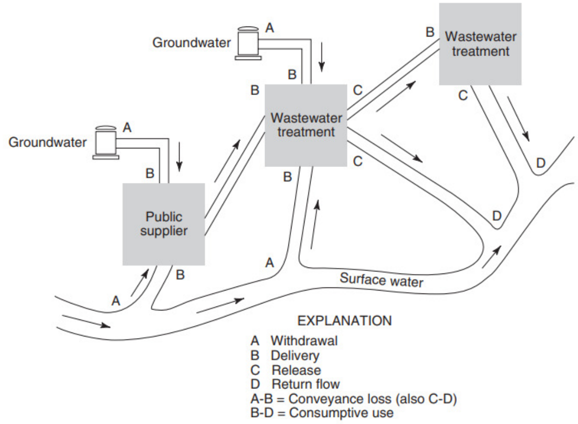

Figure 2: Represented the Definition of Water use Flows and Losses

The relationships among these human-made flows at various points of measurement are illustrated in Figure 2. The estimated water use by tracking the sources, uses, and disposition of freshwater using the hydrologic accounting system given in Figure 2[6], [7].

The Future of Water Resources

The management of water resources can be subdivided into three broad categories:

- **i.** Water-supply management,
- **ii.** Water-excess management,
- **iii.** Environmental restoration

All modern multipurpose water resources projects are designed and built for water-supply management and/ or water-excess management. In fact, throughout human history all water resources projects have been designed and built for one or both of these categories. A water resources system is a system for redistribution, in space and time, of the water available to a region to meet societal needs.

Water can be utilized from surface water systems, from groundwater systems, or from conjunctive/ground surface water systems[8], [9].When discussing water resources, we must consider both the quantity and the quality aspects. The hydrologic cycle must be defined in terms of both water quantity and water quality. Because of the very complex water issues and problems that we face today, many fields of study are involved in their solution. These include the biological sciences, engineering, physical sciences, and social sciences, illustrating the wide diversity of disciplines involved in water resources.

In the twenty-first century we are questioning the viability of our patterns of development, industrialization, and resources usage. We are now beginning to discuss the goals of attaining an equitable and sustainable society in the international community. Looking into the future, a new set of problems face us, including the rapidly growing population in developing countries; uncertain impacts of global climate change; possible conflicts over shared freshwater resources; thinning of the ozone layer; destruction of rain forests; threats to wetland, farmland, and other renewable resources; and many others. These problems are very different from those that humans have faced before[10]–[12].

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CHAPTER 2

WATER RESOURCES SUSTAINABILITY

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Traditionally, sustainability explores the relationships among economics, the environment, and social equity, using the three-legged stool analogy that includes not only the technical, but also the economic and social issues. The term “sustainable development” was defined in 1987 by the World Commission on Environment and Development as “development that can meet the needs of the present generation without compromising the ability of future generations to meet their own needs. Some of the questions related to sustainable systems and sustainable design are[1]:

- **i.** What are the characteristics of sustainable systems?
- **ii.** How does the design process encourage sustainability?
- **iii.** What is sustainable water resources development?
- **iv.** What are the components of sustainable development?

Definition of Water Resources Sustainability

We live in a world where approximately 1.1 billion people lack safe drinking water, approximately 2.6 billion people lack adequate sanitation, and between 2 and 5 million people die annually from water-related diseases. The United Nations Children’s Fund’s (UNICEF) report, “The State of the World’s Children 2005: Childhood under Threat,” concluded that more than half the children in the developing world are severely deprived of various necessities essential to childhood. For example, 500 million children have no access to sanitation and 400 million children have no access to safe water. One might ask how sustainable is this? The key to sustainability is the attention to the survival of future generations. Also important is the global context within which we must think and solve problems. The future of water resources thinking must be within the context of water resources sustainability.

The overall goal of water resources management for the future must be water resources sustainability. Water resources sustainability as follows: “Water resources sustainability is the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life, and to protect humans from the damages brought about by natural and human-caused disasters that affect sustaining life”[2].

The Brundtland Commissions’ report, “Our Common Future” (World Commission on Environment and Development, WCED), defined sustainability as focusing on the needs of both current and future generations. A development is sustainable if “it meets the needs of the present without compromising the ability of future generations to meet their own needs.” Because water impacts so many aspects of our existence, there are many facets that must be considered in water resources sustainability including:

- **i.** Water resources sustainability includes the availability of freshwater supplies throughout periods of climatic change, extended droughts, population growth, and to leave the needed supplies for the future generations.
- **ii.** Water resources sustainability includes having the infrastructure, to provide water supply for human consumption and food security, and to provide protection from water excess such as floods and other natural disasters.
- **iii.** Water resources sustainability includes having the infrastructure for clean water and for treating water after it has been used by humans before being returned to water bodies.
- **iv.** Water sustainability must have adequate institutions to provide the management for both the water supply management and water excess management.
- **v.** Water sustainability must be considered on a local, regional, national, and international basis.
- **vi.** To achieve water resources sustainability, the principles of integrated water resources management (IWRM) must be implemented.

The Dublin Principles

The following four simple, but yet powerful messages, were provided in 1992 in Dublin and were the basis for the Rio Agenda 21 and for the millennium Vision-to-Action:

- **i.** Freshwater is a finite and vulnerable resource, essential to sustain life, development and the environment, i.e. one resource, to be holistically managed.
- **ii.** Water development and management should be based on a participatory approach, involving users, planners, and policy-makers at all levels, i.e. manage water with people and close to people.
- **iii.** Women play a central role in the provision, management and safeguarding of water, i.e. involve women all the way.
- **iv.** Water has an economic value in all its competing uses and should be recognized as an economic good, i.e. having ensured basic human needs, allocate water to its highest value, and move towards full cost pricing, rational use, and recover costs.

Poor water management hurts the poor most! The Dublin principles aim at wise management with focus on poverty[3].

Urbanization: A Reality of Our Changing World

Urban populations demand high quantities of energy and raw material, water supply, removal of wastes, transportation, etc. Urbanization creates many challenges for the development and management of water supply systems and the management of water excess from storms and floodwaters. Many urban areas of the world have been experiencing water shortages, which are expected to explode this century unless serious measures are taken to reduce the scale of this problem. Most developing countries have not acknowledged the extent of their water problems, as evidenced by the absence of any long-term strategies for water management.

Changes Caused by Urbanization

Urbanization is a reality of our changing world. From a water resources perspective, urbanization causes many changes to the hydrological cycle including radiation flux, amount of precipitation, amount of evaporation, amount of infiltration, increased runoff, etc. Changes brought about by urbanization can be summarized briefly as follows:

- **i.** Transformation of undeveloped land into urban land (including transportation corridors);
- **ii.** Increased energy release (i.e., greenhouse gases, waste heat, heated surface runoff);
- **iii.** Increased demand on water supply (municipal and industrial).

Challenges to Water Resources Sustainability

Urban populations are growing rapidly around the world with the addition of many mega-cities populations of 10 million or more inhabitants. In 1975 there were only four mega-cities in the world and by 2015 there may be over 22 mega-cities in the world. Other cities that will not become mega-cities are also growing very rapidly around the world. By 2010, more than 50% of the world's population is expected to live in urban areas (World Water Assessment Program, 2006).

Mega-cities mean mega problems of which urban water supply management and water excess management are among the largest. Mega-cities and other large cities will be a drain on the Earth's dwindling resources, while at the same time significantly contributing to the environmental degradation. Many of the large cities around the world are prone to water supply shortages, others are prone to flooding, and many are prone to both. A large number of the cities of the world do not have adequate wastewater facilites and most of the waste is improperly disposed or used as irrigation of agricultural lands. As the Earth's population continues to grow, so will the growth of cities continue across the globe, stretching resources and the ability to cope with disasters such as floods and droughts. These factors, coupled with the consequences of global warming, create many challenges for future generations[4]. There are many factors that affect water resources sustainability including: urbanization, droughts, climate change, flooding, and human-induced factors. Developed areas of the world such as the United States are not exempt from the need for water resources sustainability.

Urbanization

The Urban Water Cycle

The overall urban water cycle is illustrated in Figure 1 showing the main components and pathways. How does the urbanization process change the water budget from predevelopment to developed conditions of the urban water cycle in arid and semi-arid regions? This change is a very complex process and very difficult to explain[5].

Urban Water Systems

Urban water system implies that there is a single urban water system and the reality of this is that it is an integrated whole. The concept of a single "urban water system" is not fully accepted because of the lack of integration of the various components that make up the total urban water system. For example, in municipalities it is common to plan, manage, and operate urban water into separate entities such as by service, i.e. water supply, wastewater, flood control, and storm water. Typically there are separate water organizations and management practices within a municipality, or local or regional government because that is the way they have been historically. That integration could be achieved by functional integration and area-wide integration. There are many linkages of the various components of the urban water system with the hydrologic cycle being what connects the urban water system together. There are many reasons for considering the urban water system in an integrated manner. Two of the principal reasons are:

a. The natural connectivity of the system through the hydrologic cycle,

b. The real benefits that are realized through integrated management rather than by independent action.

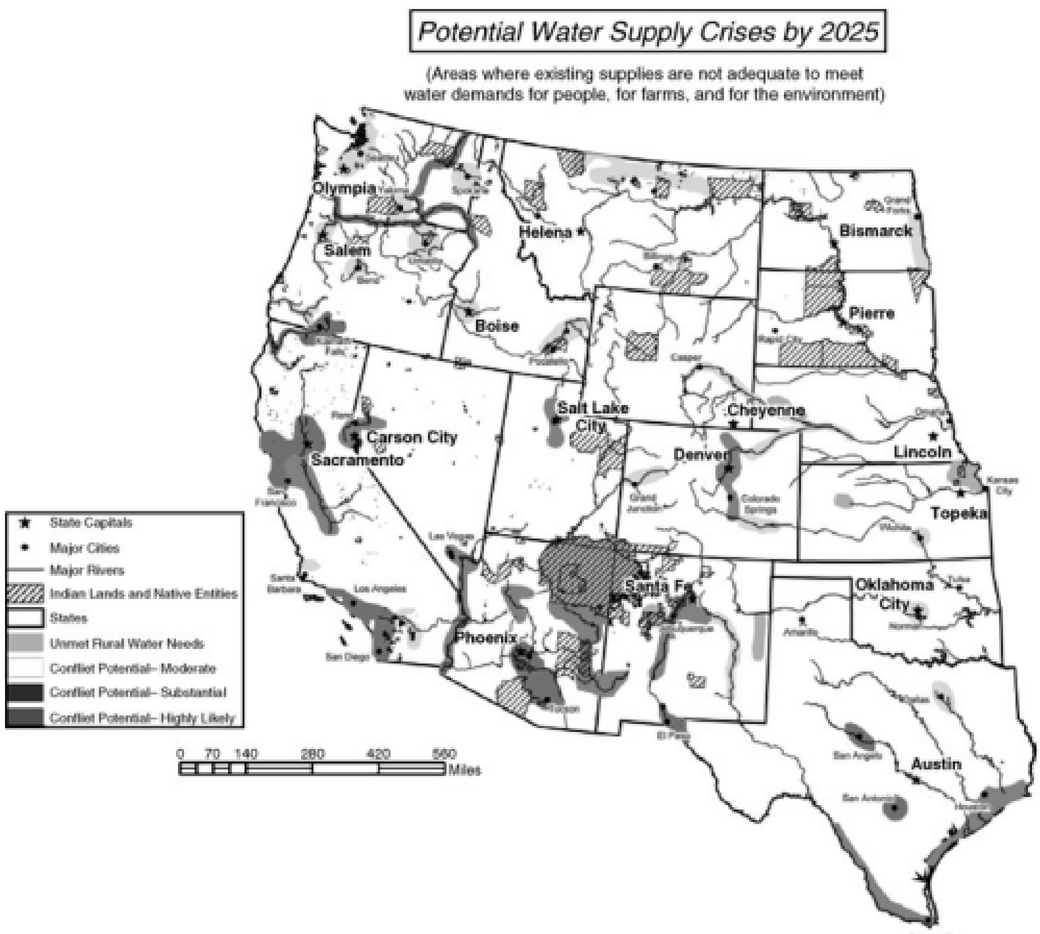

Figure 1: Illustrated That the Areas in the Western United States with Potential Water Supply Crisis By2025.

The urban water management system is considered herein as two integrated major entities, water supply management and water excess management. The various interacting components of water excess and water supply management in conventional urban water infrastructure are shown in Figure 2 [6].

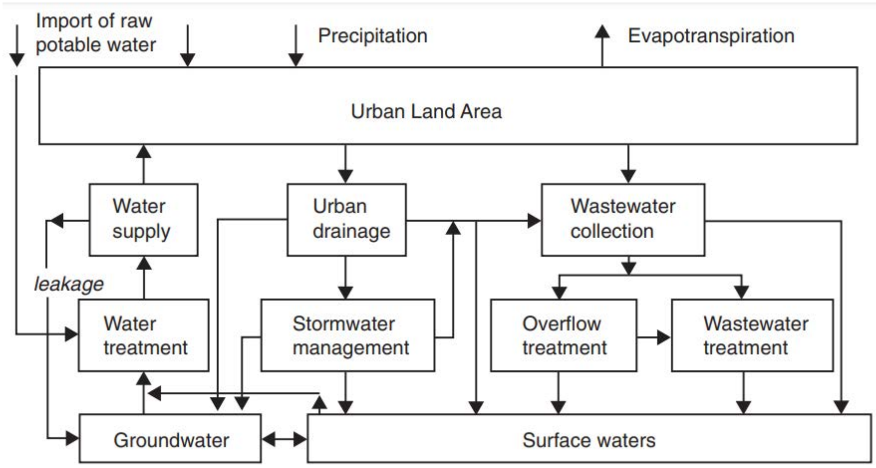

Figure 2: Illustrated the Urban Water Cycle: Main Components and Pathways.

Water Supply Management

a. Sources (groundwater, surface water, reuse)
b. Transmission
c. Water treatment (WT)
d. Distribution system
e. Wastewater collection
f. Wastewater treatment (WWT)
g. Reuse

Water Excess Management

a. Collection/drainage systems
b. Storage/treatment
c. Flood control components (levees, dams, diversions, channels)

Sustainable Urban Water Systems

Sustainable urban water systems are being advocated because of the depletion and degradation of urban water resources coupled with the rapid increases in urban populations around the world. The following basic goals for sustainable urban water systems:

a. Supply of safe and good-tasting drinking water to the inhabitants at all times.

b. Collection and treatment of wastewater in order to protect the inhabitants from diseases and the environment from harmful impacts.

c. Control, collection, transport, and quality enhancement of storm water in order to protect the environment and urban areas from flooding and pollution.

d. Reclamation, reuse, and recycling of water and nutrients for use in agriculture or households in case of water scarcity.

In North America and Europe many of the above goals have been achieved or are within reach. In many developing parts of the world these goals are far from being achieved. Climate change will be a major factor in both the developed and undeveloped parts of the world that has not been addressed for the future of water resources sustainability. The Millennium Development Goals put a strong emphasis on poverty reduction and reduced child mortality[7].

Urban Storm water Runoff

Urban Storm water Runoff includes all flows discharged from urban land uses into storm water conveyance systems and receiving waters. Urban runoff includes both dry-weather, non-storm water sources such that runoff from landscape irrigation, dewatering, and water line and hydrant flushing) and wet-weather storm water runoff. Water quality of urban storm water runoff can be affected by the transport of sediment and other pollutants into streams, wetlands, lakes, estuarine and marine waters, or groundwater. The costs and impacts of water pollution from urban runoff are significant and can include fish kills, health concerns of human and/or terrestrial animals, degraded drinking water, diminished water-based recreation and tourism opportunities, economic losses to commercial fishing and aquaculture industries, lowered real estate values, damage to habitat of fish and other aquatic organisms, inevitable costs of clean-up and pollution reduction, reduced aesthetic values of lakes, streams, and coastal areas, and other impacts.

Increased storm water flows from urbanization have the following major impacts:

i. acceleration of stream velocities and degradation of stream channels,

ii. declining water quality due to washing away of accumulated pollutants from impervious surfaces to local waterways, and an increase in siltation and erosion of soils from pervious areas subject to increased runoff,

iii. increase in volume of runoff with higher pollutant concentrations that reduces receiving water dilution effects,

iv. diminished groundwater recharge, resulting in decreased dry-weather flows; poorer water quality of streams during low flows; increased stream temperatures; and greater annual pollutant load delivery,

v. increased flooding,

vi. combined and sanitary sewer overflows due to storm water infiltration and inflow,

vii. damage to stream and aquatic life resulting from suspended solids accumulation, and increased health risks to humans from trash and debris which can also endanger,

viii. destroying food sources or habitats of aquatic life

Groundwater Changes

Urbanization often causes changes in groundwater levels as a result of decreased recharge and increased withdrawal. In rural areas, water supplies are usually obtained from shallow wells, while most of the domestic wastewater is returned to the ground through cesspools or septic tanks. Thus the quantitative balance in the hydrologic system remains. As urbanization occurs many individual wells are abandoned for deeper public wells. With the introduction of sewer systems, storm water, and (treated or untreated) wastewater are discharged to nearby surface water bodies. Three conditions disrupt the subsurface hydrologic balance and produce declines in groundwater levels[8].

- **i.** Reduced groundwater recharge due to paved surface areas and storm sewers
- **ii.** Increased groundwater discharge by pumping wells
- **iii.** Decreased groundwater recharge due to export of wastewater collected by sanitary sewers

Groundwater quality is certainly another challenge to water resources sustainability resulting in many cases from urbanization. Groundwater quality can be affected by residential and commercial development as illustrated in Figure 3. The U.S. Geological Survey's National Water Quality Assessment (NAWQA) program seeks to determine how shallow groundwater quality is affected by development.

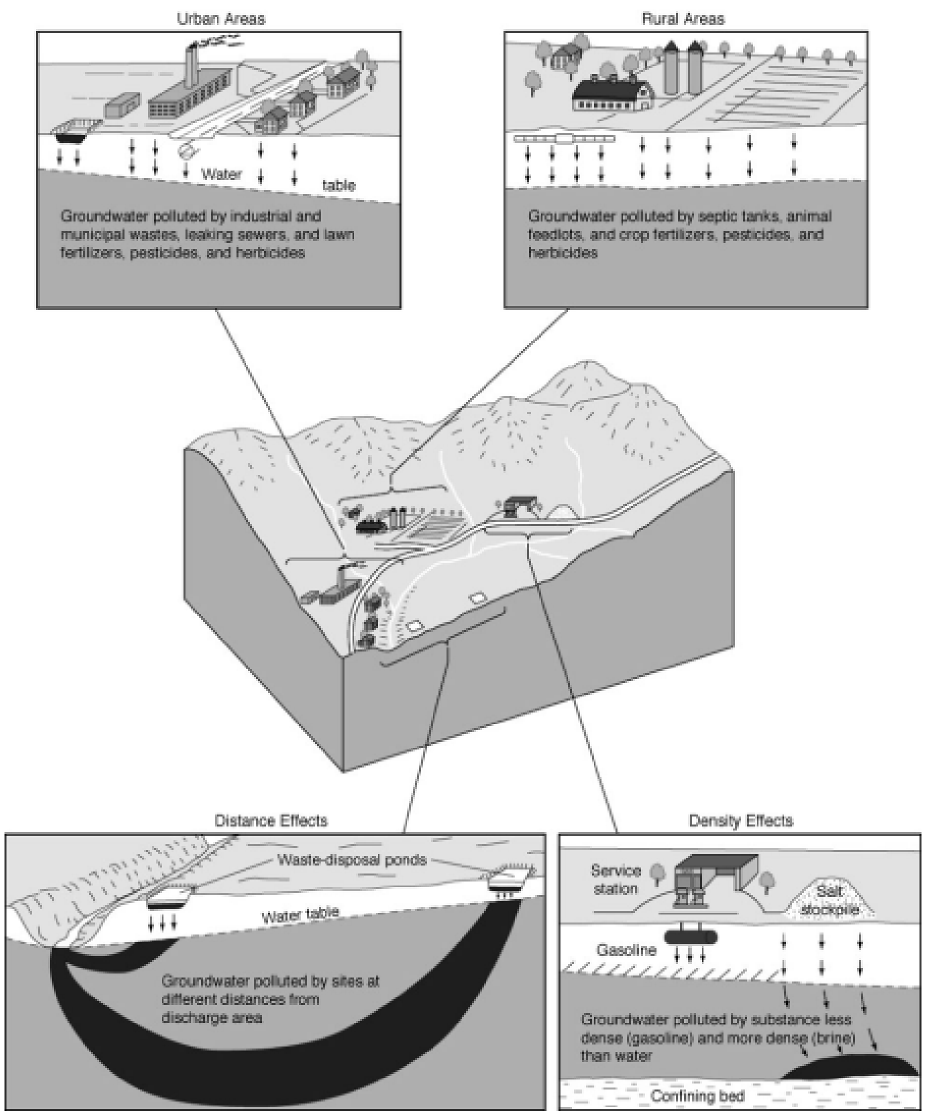

Figure 3: Illustrated that the Groundwater Pollution Affected by differences in Chemical Composition, Biological, and Chemical Reactions, and Distance from Discharge areas.

Residential developments have taken up very large tracts of land, and as a consequence, have widespread influence on the quality of water that recharges aquifers, streams, lakes, and wetlands. Liquids discharged onto the ground surface in an uncontrolled manner can migrate downward to degrade groundwater. Septic tanks and cesspools are another source of groundwater pollution. Polluted surface water bodies that contribute to groundwater recharge are sources of groundwater pollution.There are many examples of urbanization effects around the world. One example is on Long Island, New York, where there was not only a decline in water tables but also groundwater pollution, seawater intrusion, and reduced streamflow.

Droughts and Floods

Droughts

Droughts continue to be one of the most severe weather-induced problems around the world. Droughts can be classified into different types: meteorological droughts refer to the lack of precipitation; agricultural droughts refer to the lack of soil moisture; and hydrological droughts refer to the reduced streamflow and groundwater levels. Figure 4 presents the progression of droughts and their impacts. Drought management including management options, drought severity indices, and economic effects of water shortage. The following is a definition of drought from the "Colorado River Basin Management: Evaluating and Adjusting to Hydroclimatic Variability":

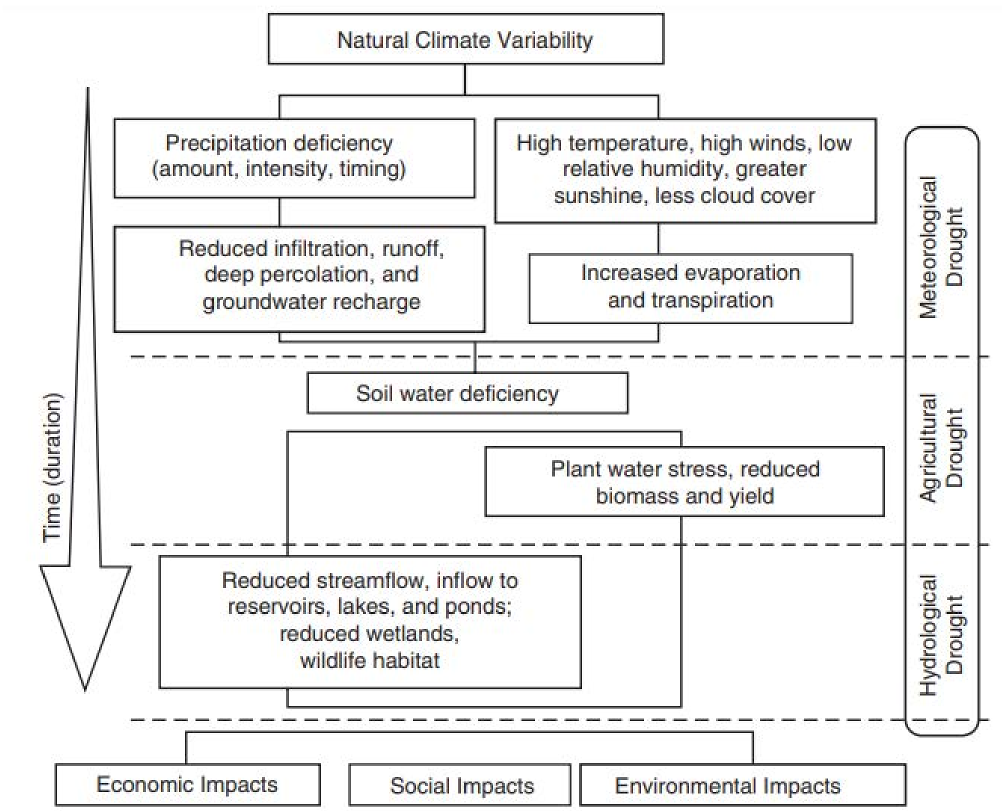

Figure 4: Represented the Progression of Droughts and their Impacts.

A basic concept invoked in understanding drought is that of a water budget. Water is held in storage buffers such as soil root zones, aquifers, lakes, reservoirs, and surface stream flows. These buffers act as water supplies, are subject to demands, and are replenished and lose water at varying rates. When losses exceed replenishment, impacts are experienced and, at lower storage levels, become increasingly severe. In essence, drought is defined by its impacts on both natural and manmade environments because without impacts there is no drought, no matter how dry it might be. Drought infers a relationship between supply rates and demand rates; drought is not simply a supply-side phenomenon, but also depends on water demands. Without demands, there is no drought, whether a given supply of water is big, small, or even zero.

Floods

Urban flood management also referred to as water excess management herein will be effected by the rapid urbanization and climate change among other factors and must be considered within the framework of water resources sustainability, which will require the principles of integrated urban water management. The impact of floods to cities can devastate national economies and industrial markets, even at the international level. Urban flood management must capture the following concepts that[9]:

- **a.** Floods are part of the natural resources that should be considered within the scope of integrated urban water resources management;
- **b.** Water resources sustainability captures integrated urban water resources management;
- **c.** The realization that floods never can be fully controlled.

Urban flood management in developing countries is affected by development with little or no planning; high population concentration in small areas; lack of storm water and sewage facilities; polluted air and water; difficulty of maintaining water supply with growing population; and poor public transportation among other things.

The urban poor are often forced to settle in flood prone areas and they lack the adaptive capacity to cope with flood events. The unplanned urbanization and poverty are dramatically increasing the vulnerability to floods. Increase in vulnerability of cities to flood disasters arises predominantly from the systematic degradation of natural ecosystems, increased urban migration, and unplanned occupation, and unsustainable planning and building.

Urban flood disasters are not only prevalent in developing countries but have also impacted urban areas significantly in developing countries. In Europe, during the 10-year time period of 1973–1982, there were 31 flood disasters, and during the ten-year time period of 1993 to 2002, there were 179 flood disasters.

The Mississippi River flooding and particularly the St. Louis area as display in Figure 5 are used as examples of flooding problems. The Mississippi River flood of 1993 caused major flood damage in nine Midwestern states in which 75 towns and millions of acres of farmlands disappeared under the floodwaters. Approximately 50 people died, and tens of thousands of people were temporarily or permanently evacuated. Thousands of homes were completely destroyed and hundreds of flood levees failed. Flood damage estimates ranged from $10 to $20 billion[10].

Houston, Texas, is an example of poor urban flood management in a large city in a developed country. A combination of poor urban planning, poor floodplain management, poor storm water management, and lack of integrated floodplain and storm water management has caused billions of dollars of flood damage over the last couple of decades. Subsidence has been a factor, but minimal compared to the effects of poor floodplain and poor storm water management in

Houston. Tropical Storm Allison is one of the several examples with damage estimates of up to \$5 billion. Hurricane Katrina in the Gulf of Mexico coastal region of the U.S. brought unprecedented death and destruction over a 90,000 m^2. Not only were the costs estimates vary between \$100 and \$200 billion and deaths over 1200 lives unprecedented, but a very large number of the residents who evacuated before the storm have not yet returned. Even to this date many of the essential city services have not yet been restored to pre-Katrina levels. Many lessons were learned.

- **i.** Government officials need to consider policies and plans that are more robust against a wider range of disaster scenarios such that on the Gulf of Mexico coast, storm surges had been anticipated, but not at the level of Katrina even though they had anticipated catastrophic flooding and levee failures.
- **ii.** Failure to anticipate the widespread regional breakdown in infrastructure and services and the disabling of first-response and public safety programs was the biggest blind spot throughout the region (e.g. the planning for regional infrastructure and services must cover total catastrophic breakdown and must include secondary, contingency responses that can be invoked when primary responses are overwhelmed).
- **iii.** Detection of the storm was adequate, but the detection of structural weakness, soil anomalies, and impending failure was not, as no monitoring was in place which was remedied through extensive deployment of sensors on all structural features of the flood protection system[11], [12].
- **iv.** Reconstruction efforts are strongly influenced by the answer to the question, what will the level of protection be in the future? Complicating this is the fact that many flood victims have chosen not to return and economic recovery remains uncertain.
- **v.** Integrated urban water management from the perspective of flood control includes conceding land to the water from time to time somewhat psychologically and politically difficult.

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CHAPTER 3

RESPONSIBILITY OF CLIMATE CHANGE IN WATER RESOURCE

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The United Nations Intergovernmental Panel on Climate Change (IPCC) defines climate change as “a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to natural variability or as a result of human activity.” The United Nations Framework Convention on Climate Change (UNFCC) defines climate change as “a change in climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparative time periods.” A schematic framework representing anthropogenic drivers, impacts of and responses to climate change, and their linkages, is shown in Figure 1[1].

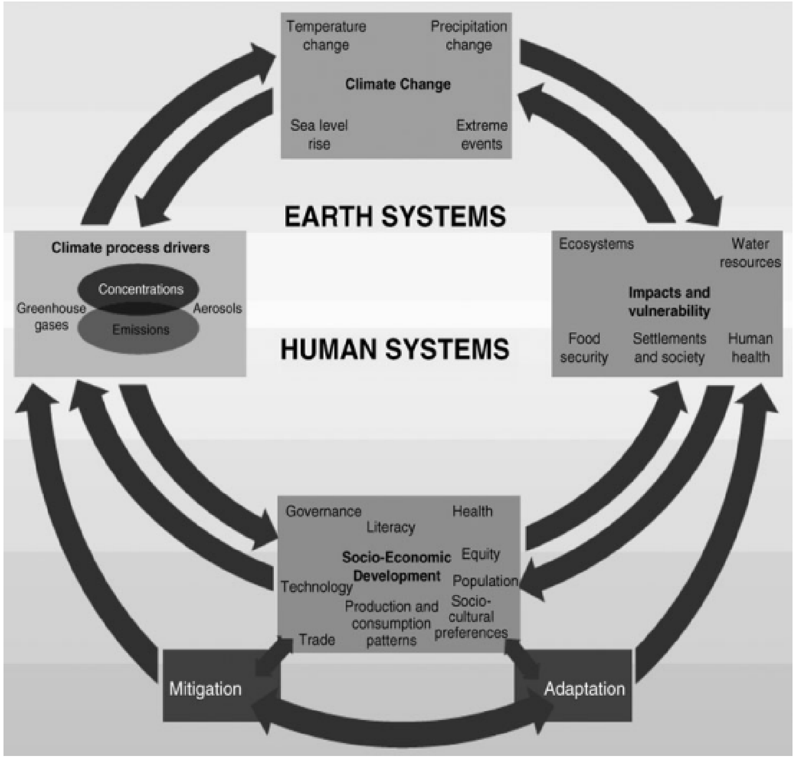

Figure 1: Represented that theSchematic Framework Representing Anthropogenic Drivers, Impacts of and Responses to Climate Change, and their Linkages.

In the last assessment report of the United Nations Intergovernmental Panel on Climate Change, the Working Group I states that “warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level.” The IPCC report also stated it is “very likely” that human activities are responsible for most of the warming of recent decades.

The IPCC shared the 2007 Nobel Peace Prize with Al Gore. The climate system is an interactive system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface, and the biosphere, forced or influenced by various external forcing mechanisms, the most important of which is the sun. The effect of human activities on the climate system is considered as external forcing. Climate change predictions are based on computer simulations using general circulation models (GCMs) of the atmosphere. The limitations of state-of-the-art climate models are the primary sources of uncertainty in the experiments that study the hydrologic and water resources impact of climate change. Future improvement to the climate models, hopefully resulting in more accurate regional predictions, should greatly improve the types of experiments to more accurately define the hydrologic and hydraulic impacts of climate change.

The impacts associated with global average temperature change will vary by the rate of temperature change, the extent of adaptation of humans, and the social-economic pathway. Water will be affected in general as follows[2]:

- **i.** Increased water availability in moist tropics and high latitudes.
- **ii.** Decreasing water availability and increasing droughts in mid-latitudes and semi-arid low latitudes.
- **iii.** Hundreds of millions of people exposed to increased water stress.

Hydrologic Response

Future precipitation and temperature are the primary drivers for determining future hydrologic response. Because of the uncertainties of the predictions of the future precipitation and temperatures, the hydrologic responses of various river basins are uncertain, resulting in uncertainties of our future urban water resources, particularly in arid and semi-arid regions.

In general, the hydrologic effects are likely to influence water storage patterns throughout the hydrologic cycle and impact the exchange among aquifers, streams, rivers, and lakes. In arid and semi-arid regions, relatively modest changes in precipitation can have proportionately larger impacts on runoff, and higher temperatures result in higher evaporation rates, reduced streamflow's, and increased frequency of droughts. The effects of climate change on groundwater sustainability include:

- **i.** Changes in groundwater recharge resulting from changes in average precipitation and temperature or in seasonal distribution of precipitation;
- **ii.** More severe and longer droughts
- **iii.** Changes in evapotranspiration resulting from changes in vegetation;
- **iv.** Possible increased demands of groundwater as a backup source of water supply.

As an example, we can consider in general the hydrologic effects of climate change on the Pacific Northwest United States such that the Columbia River as summarized in Figure 2. Starting in the winter, changes in temperature and precipitation during the winter affects the snowpack during the winter. The winter snowpack in turn affects the stream flow during the spring and summer. The streamflow affects the quantity, quality, and timing of the water supply, which in turn affects hydropower production, aquatic ecosystems, agriculture, and forests, municipal and industrial water supply. Both the winter snowpack and the spring/summer streamflow affect the groundwater recharge, the soil moisture, and the evapotranspiration which have terrestrial effects on the forests, agriculture, etc.

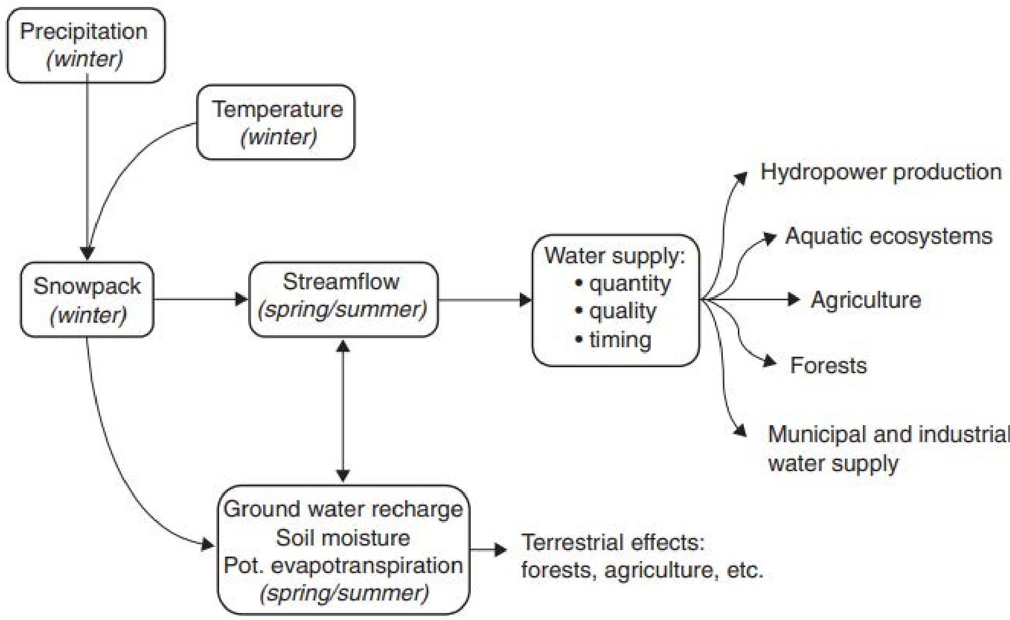

Figure 2: Represented the Dominant Impact through which Changes in Regional Climate are manifested in the Pacific Northwest

Some Realities of Climate Change

In the Fourth World Water Forum in March 2006, the Co-operative Program on Water and Climate (CPWC) pointed to "the alarming gap between international recognition of the risks posed by climate change and the general failure to incorporate measures to combat those risks into national and international planning strategies. The CPWC findings and recommendations to cope with climate extremes were encompassed within the following five key messages[3]:

i. Strategies for achieving the 2015 Millennium Development Goals (MDG) do not account for the climate variability and change.

ii. Climate-related risks are not sufficiently considered in water sector development and management plans. . Investment in climate disaster risk reduction is essential.

iii. The trend of increasing costs has to be reversed through the safety chain concept prevention, preparation, intervention, risk spreading, recondition, reconstitution.

iv. Coping measures need to combine a suite of technical/structural and nonstructural measures.

The first message addresses the fact that climate impacts on hydrological systems and on livelihoods threaten to undo decades of development efforts. The second message relates to the fact that to meet MDG targets, there will need to be substantial long-term investments in structural and nonstructural approaches to water management. Structural measures include storage, control, and conveyance; and nonstructural measures include demand-side management, floodplain management, service delivery, etc. The third message relates to the fact that the costs of disasters, especially those related to water, are increasing and substantial efforts are needed in mainstream climate reduction. The fifth message advocates a combination of both structural and nonstructural measures. Structural measures include dams, dikes, and reservoirs; and nonstructural measures include early flood warning systems, spatial planning, "living with water" insurance, etc[4]. The reality is that climate change impacts are already with us and manifesting in increasing occurrences of and intensity of climate extremes such as droughts and floods, and climate variability. From the water supply perspective, there are both supply-side and demand-side options that could be considered for urban water supply.

Surface Water System-The Colorado River Basin

The Basin

Of the many river basins in the southwest, the Colorado River Basin has been the center of many controversies. The Colorado River Basin is divided into the upper and lower basins as shown in Figure 3. The upper Colorado River Basin includes areas of the states of Arizona, Colorado, New Mexico, Utah, and Wyoming; the lower Colorado River Basin includes areas of Arizona, California, New Mexico, and Utah. The drainage basin area is over 240,000 mi^2. The Colorado River and its main tributary streams originate high within the mountains of western Wyoming, central Colorado, and northeastern Utah. The Colorado River receives large amounts of snowmelt from several major tributaries with snowpack accumulating as high as 14,000 ft above sea level[5].

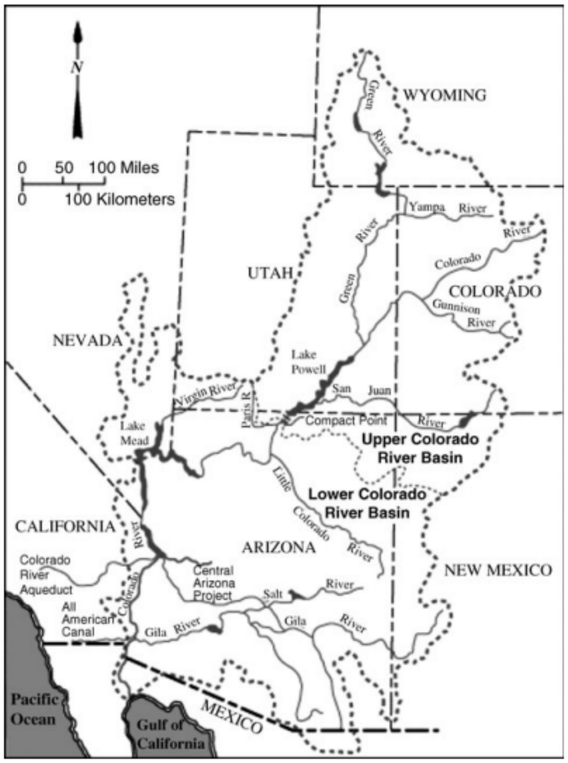

Figure 3: Represented the Colorado River Basin showing the upper and lower Colorado River Basins.

Annual average flow rate of the Colorado River is roughly 15 million ac-ft. The Colorado River is the most important source of water in the semi-arid and arid southwestern United States. It provides water for tens of millions of people from San Diego to Denver and a multitude of communities in between. Reservoirs of the Colorado River system have roughly 60 million ac-ft of storage capacity, approximately four times the Colorado's average annual flow. The two largest and most significant reservoirs are Lake Mead and Lake Powell, which are impounded respectively by Hoover Dam, located near Las Vegas, Nevada, and Glen Canyon Dam, located 15 mi south of the Arizona–Utah border. With storage capacities of roughly 28 and 27 million ac-ft, including dead storage, each reservoir can store roughly 2 years of annual mean flow of the Colorado River. Lake Mead and Lake Powell are major sources for water in southern California and Arizona. The storage in Lake Powell through December 1, 2006. Most of the precipitation in the Colorado River Basin falls as winter snowfall in higher elevations of Colorado, Utah, and Wyoming. Approximately 20% of the basin's precipitation falls in the highest 10 percent of the basin, and roughly 40% of the basin's precipitation falls in the highest 20% of the basin[6].

Climate

Precipitation on the Colorado River Basin exhibits high year-to-year variability, as illustrated for the upper part of the basin. This figure is for spatially averaged precipitation over the basin upstream of Lees Ferry and aggregated to annual resolution. It is evident that since the late 1970s there has been a steady upward trend in surface temperatures in the Colorado River Basin. The most recent 11-year average exceeds any previous values in the over 100 years of instrumental records. Notice how much warmer the basin has been in the drought of the early 2000s as compared to previous droughts. Temperatures across the basin today are at least 1.5F warmer than during the 1950s drought. Increasing temperatures have many hydrologic implications related to evaporation, infiltration, snow melt, surface water runoff, aquifer recharge, and streamflow's. One important result of these impacts is drought. The drought of the early 2000s has taken place in warmer conditions, comparing the temperature departures for the 6-year period as compared to the 1895–2000 averages. Both in terms of absolute degrees and in terms of annual standard deviation, the Colorado River basin has warmed more than any region of the United States.

Climate Change Affects the Basin

Climate change models have been used to project future precipitation and temperature changes for the Colorado River Basin. Long-term projections of precipitation are a greater modeling challenge than temperature projections. Precipitation projections for the Colorado River Basin using climate models suggest a wide range of potential changes in annual precipitation. Models have forecasted a slight decrease less than 10 percent below current values in annual precipitation in southwestern United States, with relatively little change in annual precipitation amounts forecast for headwaters regions of the Colorado River. The changes in seasonality of precipitation or changes in the type of precipitation rain or snow can be just as important as changes in annual amounts of precipitation. Future projections and past trends indicate a strong likelihood of a warmer future climate across the Colorado River Basin. Projected temperature increases across the Colorado River Basin have important direct and indirect implications for hydrology and streamflow, irrespective of the amount of the precipitation increases or decreases. The effects of warmer temperatures across the Colorado River Basin for hydrology include the following[7]:

i. Freezing levels at higher elevations, which means more winter precipitation will fall as rain rather than snow.

ii. Shorter seasons of snow accumulation at a given elevation;

iii. Less snowpack accumulation as compared to the present;

iv. Earlier melting of snowpack;

v. Decreased base flows from groundwater during late summer, and lowered water availability during the important late-summer growing season;

vi. More runoff and flood peaks during the winter months;

vii. Longer growing seasons;

viii. Reductions in soil moisture availability in the summer and increases in the spring and winter;

ix. Increased water demand by plants;

x. Greater losses of water to evapotranspiration.

A Short History of Water Development of the Basin

Due to the doctrine of prior appropriation, the states in the upper Colorado River Basin became worried that the rapidly developing California would obtain a large portion of the appropriated water, leaving them with a shortage in the future. As an attempt to settle the issues, the upper basin states agreed to support California on the Hoover Darn proposal that it needed to obtain Colorado River water for its growing development. In return, the states requested a guaranteed amount of water from the river for their own future development. This agreement between the states resulted in the Colorado River Compact in 1922, which Arizona did not ratify until 1944.

Under the Colorado River Compact, it was agreed that the upper and lower Colorado River Basin would each receive 7.5 maf. It was also agreed that the lower basin would have the right to increase its beneficial consumptive use by 1 maf annually.

All of the states supported the compact except Arizona, which opposed the Compact and refused to sign it. The dispute over the water continued as the Boulder Canyon Project Act was passed on December 21, 1928 by Congress, which authorized the construction of the Boulder Dam. However, the one stipulation was that California must agree to limit its use of Colorado River water to an amount of 4.4 maf. Arizona and California fought over both the Colorado River Compact and the Boulder Canyon Act. Arizona was against the Act and did not want California to have any of their water[8]

In order to help in settling the dispute, the U.S. Congress made it clear to Arizona that, until they could settle the dispute of water allocation in the lower Colorado River Basin, the state would not receive any support for their water canal system, the Central Arizona Project (CAP), which would later become a controversy in itself. Arizona finally agreed to share its water with California in order to receive funding for the CAP. As a result of the case Arizona v. California, which took place in 1964, the Supreme Court decreed that California would receive 4.4 maf of Colorado River water, Arizona would receive 2.8 maf, and Nevada 0.3 maf.

The CAP is a 336-mi-long system of aqueducts, tunnels, pumping plants, and pipelines that carries water from the Colorado River at Lake Havasu, through Phoenix, to the San Xavier Indian reservation southwest of Tucson. The main purpose of the CAP was to help Arizona conserve its groundwater supplies by importing surface water from the Colorado River. Figure 4 shows the layout and major features of the Central Arizona Project (CAP) system.

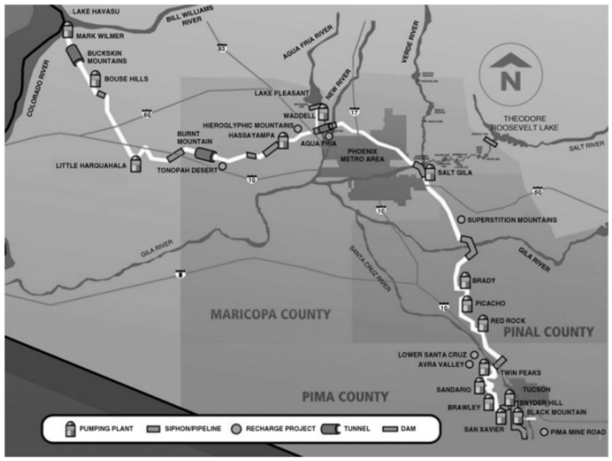

Figure 4: Represented the Layout and Major Features of the Central Arizona Project (CAP) System.

Examples of Water Resources Unsustainability

Aral Sea

The Aral Sea is located in Central Asia between Uzbekistan and Kazakstan both countries were part of the former Soviet Union as shown in Figure 5. The Amu-Darya and the Syr-Darya flow into the Aral Sea with no outlet from the sea. Over a 30-year-plus time period, water has been diverted from the Amu-Darya and the Syr-Darya to irrigate millions of acres of land for cotton and rice production, which has resulted in a loss of more than 60 percent of the sea's water. The sea has shrunk from over 65,000 km2 to less than half that size, exposing large areas of the lake bed. From 1973 to 1987, the Aral Sea dropped from fourth to sixth among the world's largest inland seas[9], [10].

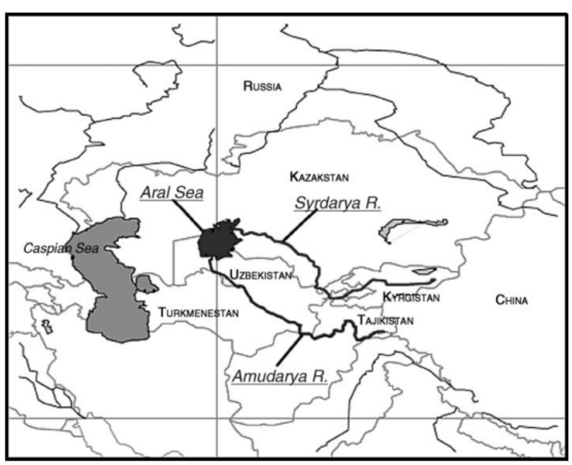

Figure 5: Represented the Aral Sea Basin.

The lake's salt concentration increased from 10% to more than 23%, contributing to the devastation of a once-thriving fishing industry. The local climate reportedly has shifted, with hotter, drier summers and colder, longer winters. With the decline in sea level, salty soil has remained on the exposed lake bed. Dust storms have blown up to 75,000 tons of this exposed soil has annually, dispersing its salt particles and pesticide residues.

This air pollution has caused widespread nutritional and respiratory ailments, and crop yields have been diminished by the added salinity, even in some of the same fields irrigated with the diverted water.

Additional literature on this subject includes. The major consequences of the continuous desiccation of the Aral Sea since 1960 are summarized as follows:

- **i.** Climatic consequences such as microclimatic changes, increase of salt and dust storms, shortening of vegetation period;
- **ii.** Ecological/economic consequences including degeneration of the delta ecosystems, total collapse of the fishing industry, and decrease of productivity of agricultural fields;
- **iii.** Health consequences such as increase in serious diseases, birth defects, and high infant mortality.

People of the region did not make the decision to use the rivers of the Aral Sea basin, but they have certainly suffered the consequences. As stated at the Conference of the Central Asian region ministers, States of Central Asia: Environment Assessment, Aarhus, Denmark, 1998 "The Aral crisis is the brightest example of the ecological problem with serious social and economic consequences, directly or indirectly connected with all the states of Central Asia. Critical situation caused by the Aral Sea drying off was the result of agrarian economy tendency on the basis of irrigated agriculture development and volume growth of irrevocable water consumption for irrigation"[11].

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CHAPTER 4

AN OVERVIEW OF THE WATER DISTRIBUTION

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Description, Purpose, and Components of Water Distribution Systems

The purpose of a water distribution network is to supply the system's users with the amount of water demanded and to supply this water with adequate pressure under various loading conditions. A loading condition is defined as a time pattern of demands. A municipal water supply system may be subject to a number of different loading conditions: fire demands at different nodes; peak daily demands; a series of patterns varying throughout a day; or a critical load when one or more pipes are broken. In order to insure that a design is adequate, a number of loading conditions, including critical conditions, must be considered. The ability to operate under a variety of load patterns is required of a reliable network.

Water distribution systems have three major components: pumping stations, distribution storage, and distribution piping. These components may be farther divided into subcomponents, which in turn can be divided into sub-subcomponents. For example, the pumping station component consists of structural, electrical, piping, and pumping unit subcomponents. The pumping unit can be divided farther into sub-subcomponents: pump, driver, controls, and power transmission. The exact definition of components, subcomponents, and sub-subcomponents depends on the level of detail of the required analysis and to a somewhat greater extent on the level of detail of available data. In fact, the concept of component–subcomponent–sub-subcomponent merely defines a hierarchy of building blocks used to construct the water distribution system. Figure 1 shows the hierarchical relationship of system, components, subcomponents, and sub-subcomponents for a water distribution system[1].

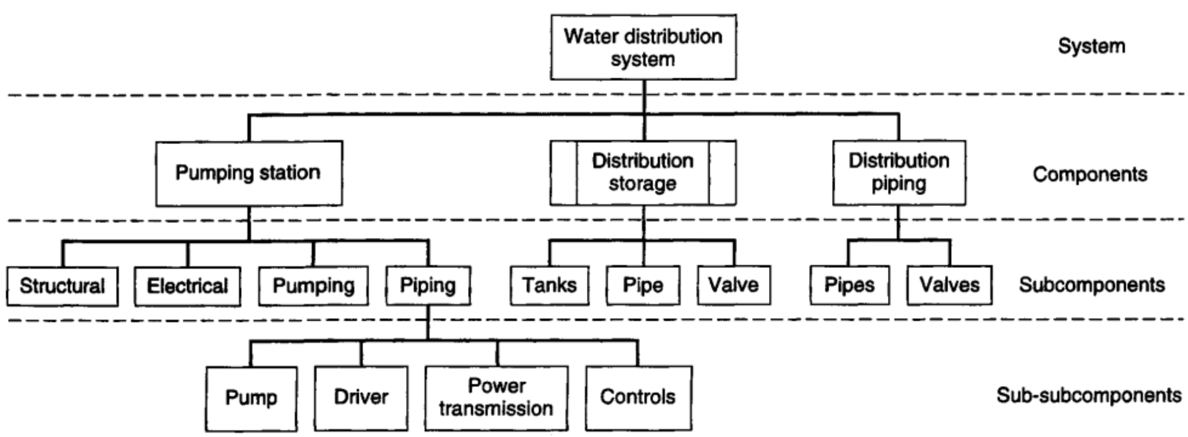


Figure 1: Represented the Hierarchical Relationship of System, Components, Subcomponents, and Sub-subcomponents for a Water Distribution System

A water distribution system operates as a system of independent components. The hydraulics of each component is relatively straightforward; however, these components depend directly upon each other and as a result affect one another's performance. The purpose of design and analysis is to determine how the systems perform hydraulically under various demands and operation conditions. Such analyses are used for the following situations:

- **i.** Design of a new distribution system.
- **ii.** Modification and expansion of an existing system.
- **iii.** Analysis of system malfunction such as pipe breaks, leakage, valve failure, pump failure.
- **iv.** Evaluation of system reliability
- **v.** Preparation for maintenance
- **vi.** System performance and operation optimization

Figure 2 illustrates a typical municipal water utility showing the water distribution system as a part of this overall water utility. In some locations where excellent quality groundwater is available, water treatment may involve only chlorination. Pipe sections or links are the most abundant elements in the network. These sections are constant in diameter and may contain fittings and other appurtenances, such as valves, storage facilities, and pumps. Pipes are manufactured in different sizes and are composed of different materials, such as steel, cast or ductile iron, reinforced or restressed concrete, asbestos cement, polyvinyl chloride, polyethylene, and fiberglass. The American Water Works Association publishes standards for pipe construction, installation, and performance in the C-series standards[2].

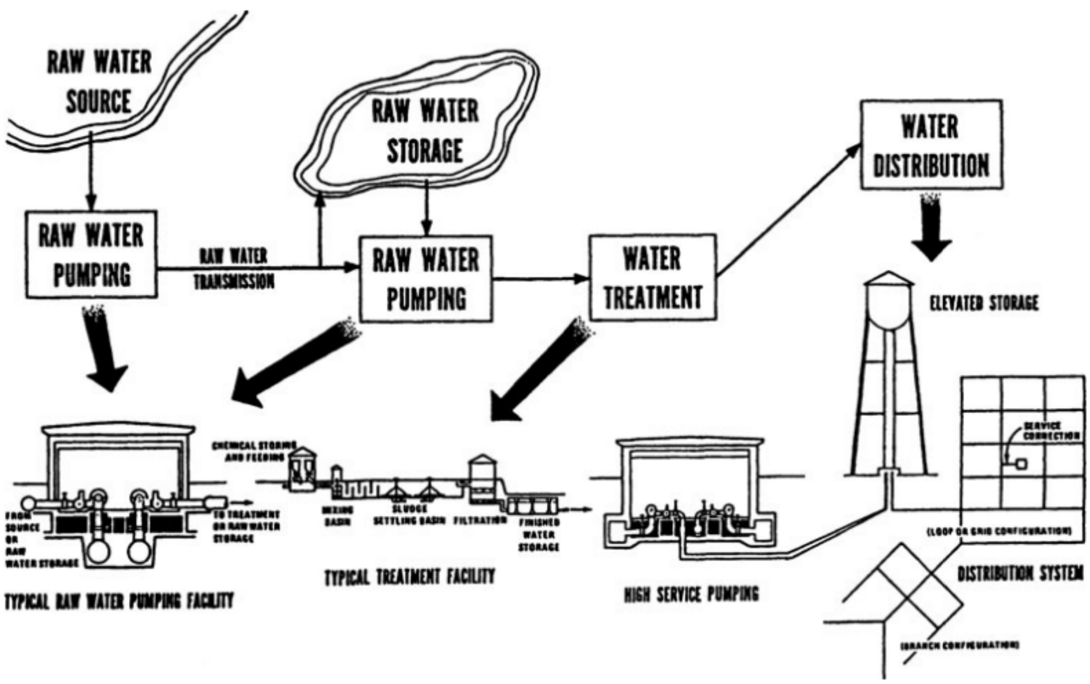


Figure 2: Illustrated the Functional Components of a Water Utility

Pipes are the largest capital investment in a distribution system. A steel pipeline that is cement coated and lined. Steel pipelines being installed that are polyethylene coated. Various types of joints and couplings to connect pipes are shown in Figure 3.

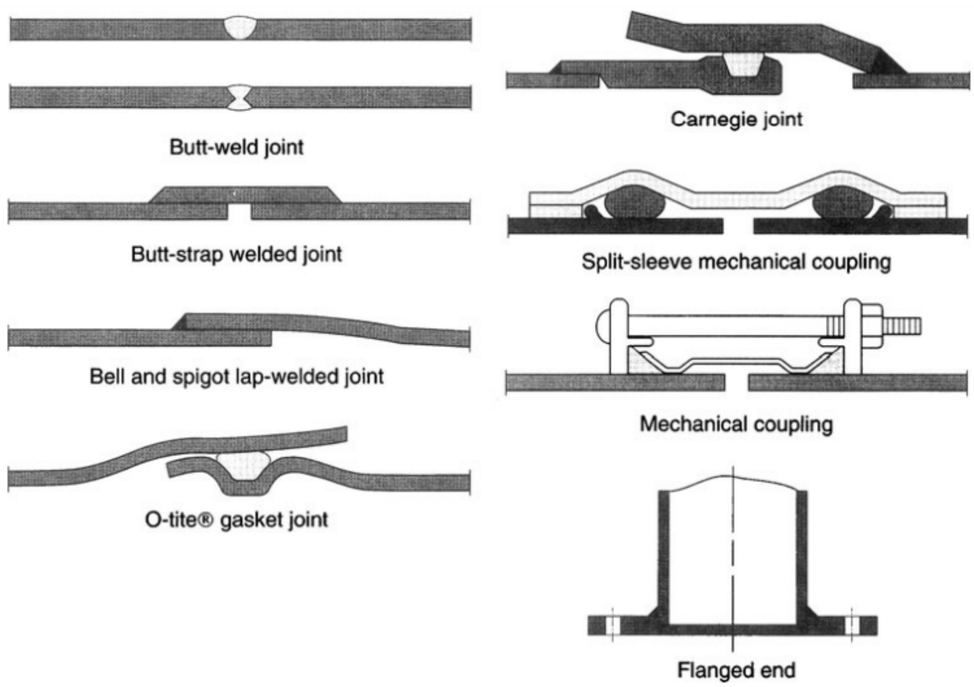


Figure 3: Represented the Variety of Joints and Couplings used for Water Pipe Systems.

A node refers to either end of a pipe. Two categories of nodes are junction nodes and fixed-grade nodes. Nodes where the inflow or the outflow is known are referred to as junction nodes. These nodes have lumped demand, which may vary with time. Nodes to which a reservoir is attached are referred to as fixed-grade nodes. These nodes can take the form of tanks or large constant-pressure mains.

Control valves regulate the flow or pressure in water distribution systems. If conditions exist for flow reversal, the valve will close and no flow will pass. The most common type of control valve is the pressure-reducing (pressure-regulating) valve (PRV), which is placed at pressure zone boundaries to reduce pressure. The PRV maintains a constant pressure at the downstream side of the valve for all flows with a pressure lower than the upstream head. When connecting high-pressure and low-pressure water distribution systems, the PRV permits flow from the high-pressure system if the pressure on the low side is not excessive[3].

The headless through the valve varies, depending upon the downstream pressure and not on the flow in the pipe. If the downstream pressure is greater than the PRV setting, then the pressure in chamber A will close the valve. Another type of check valve, a horizontal swing valve, operates under similar principle. Pressure-sustaining valves operated similarly to PRVs monitoring pressure at the upstream side of the valve. There are many other types of valves, including isolation valves to shut down a segment of a distribution system; direction-control valves to allow the flow of water in only one direction, such as swing check valves, rubber-flapper check valves, slanting check disk check valves, and double-door check valves; and air-release/vacuum-breaker valves to control flow in the main. Figure 4, show the typical application of a two-way altitude valve.

Distribution-system storage is needed to equalize pump discharge near an efficient operation point in spite of varying demands, to provide supply during outages of individual components, to provide water for firefighting, and to dampen out hydraulic transients. Distribution storage in a water distribution network is closely associated with the water tank. An elevated storage tank installation is illustrated in Figure 5. Tanks are usually made of steel and can be built at ground level or be elevated at a certain height above the ground. The water tank is used to supply water to meet the requirements during high system demands or during emergency conditions when pumps cannot adequately satisfy the pressure requirements at the demand nodes. If a minimum volume of water is kept in the tank at all times, then unexpected high demands cannot be met during critical conditions. The higher the pump discharge, the lower the pump head becomes. Thus, during a period of peak demands, the amount of available pump head is low [4].

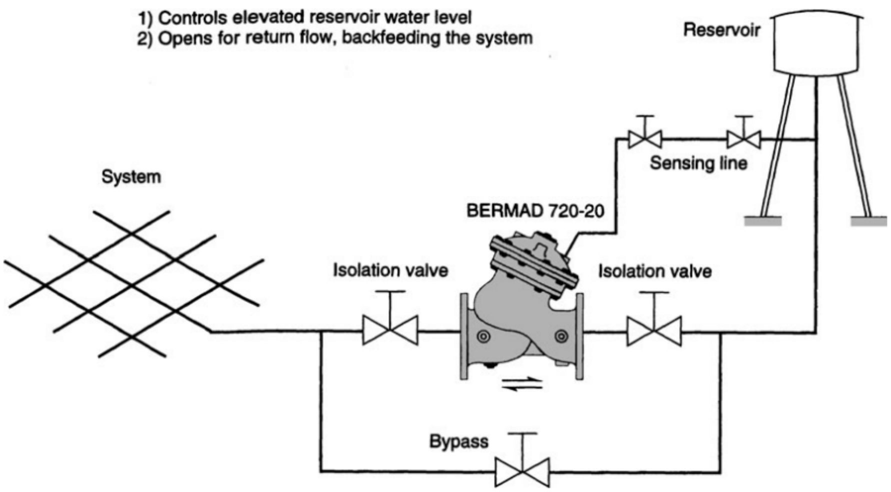


Figure 4: Represented the Two-way Altitude Valve.

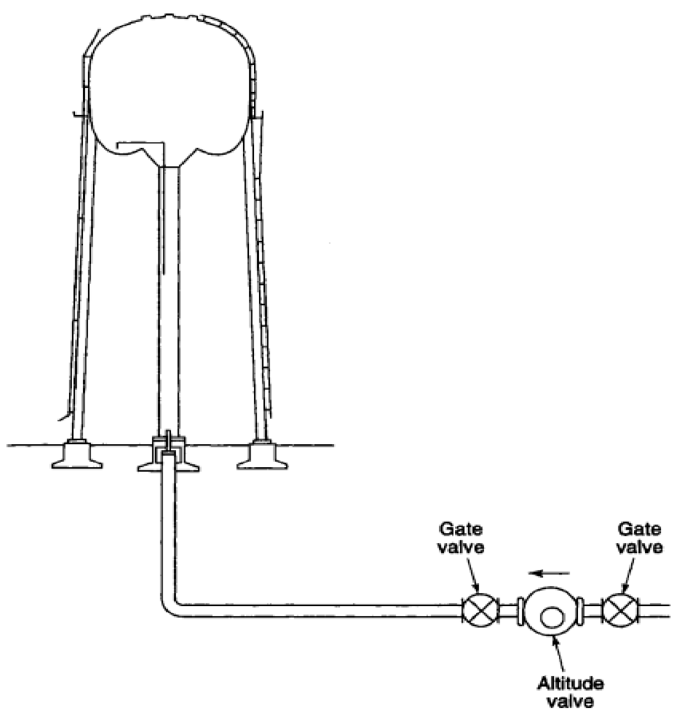


Figure 5: Represented the Typical Elevated Storage Tank Installations.

Pumps are used to increase the energy in a water distribution system. A pumping station in Mesa, Arizona, is shown in Figure 6. There are many different types of pumps (positive-displacement pumps, kinetic pumps, turbine pumps, horizontal centrifugal pumps, vertical pumps, and horizontal pumps). The most commonly used type of pump used in water distribution systems is the centrifugal pump. A pumping station with centrifugal pumps. Pumping stations house the pump, motors, and the auxiliary equipment. A pump at a well site in Mesa, Arizona which shows the Elmwood pumping station and storage reservoir in Mesa, Arizona.

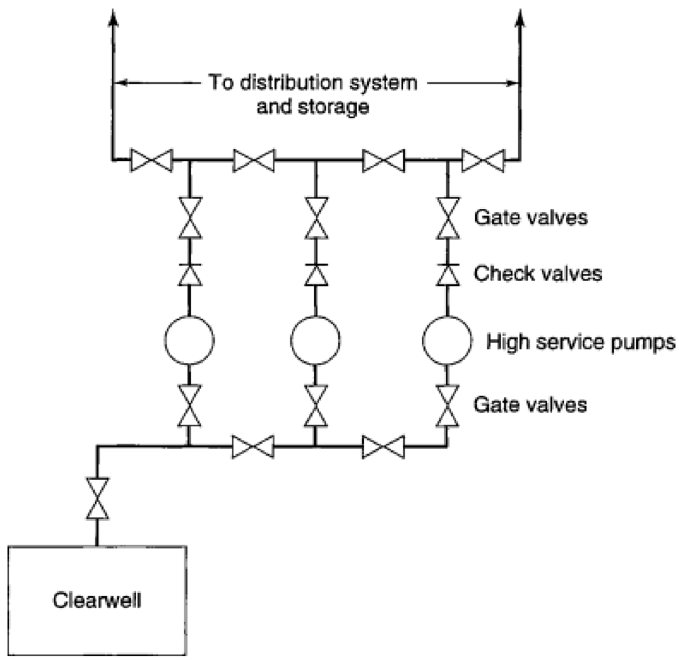


Figure 6: Represented the Schematic of a Typical Water Distribution System Pumping Station.

The metering (flow measurement) of water mains involves a wide array of metering devices. These include electromagnetic meters, ultrasonic meters, propeller or turbine meters, displacement meters, multiset meters, proportional meters, and compound meters. Electromagnetic meters measure flow by means of a magnetic field generated around an insulated section of pipe. Ultrasonic meters utilize sound-generating and sound-receiving sensors attached to the sides of the pipe. Turbine meters have a measuring chamber that is turned by the flow of water. Multijet meters have a multiblade rotor mounted on a vertical spindle within a cylindrical measuring chamber. Proportional meters utilize restriction in the water line to divert a portion of water into a loop that holds a turbine or displacement meter, with the diverted flow being proportional to the flow in the main line. Compound meters connect different sized meters in parallel[5].

System Components

Pumps

Centrifugal pumps are most commonly used in water distribution applications because of their low cost, simplicity, and reliability in the range of flows and heads encountered. As a result, the discussion on pumps is restricted to centrifugal pumps. A centrifugal pump is any pump in which fluid is energized by a rotating impeller, whether the flow is radial, axial, or a combination of both (mixed), using colloquial usage in the United States. In Europe, centrifugal pumps are strictly defined as radial flow pumps only. Here we use the U.S. usage. Centrifugal pumps are classified into three groups according to the manner in which the fluid moves through the pump as refer to Figure 7.

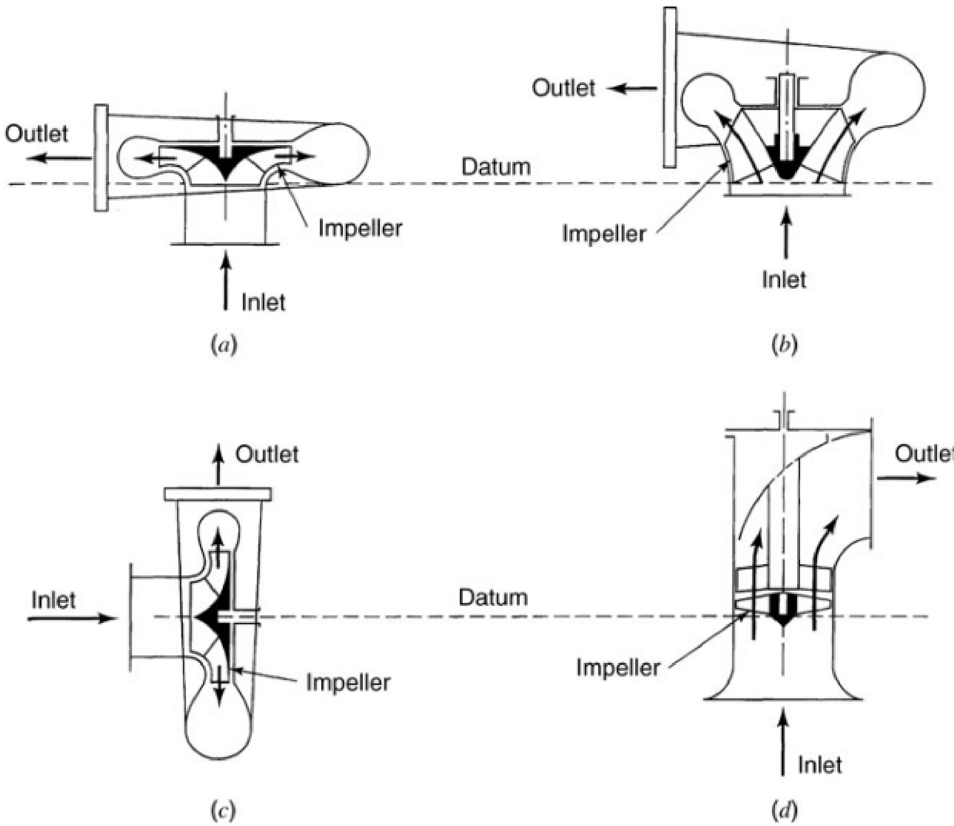


Figure 7: Illustrated the Typical flow paths in centrifugal pump. (a) Radial flow, vertical; (b) Mixed flow; (c) Radial flow, horizontal; (d) Axial flow

Pump Characteristics

A pump head-characteristic curve is a graphical representation of the total dynamic head versus the discharge that a pump can supply. These curves, which are determined from pump tests, are supplied by the pump manufacturer. The head-characteristic curve for various impeller diameters along with the efficiency and brake horsepower curves. When two or more pumps are operated, the pump station losses, which are the head losses associated with the piping into and out of the pump, should be subtracted from the manufacturer's pump curve to derive the modified head characteristic curve, as shown in Figure 8[6].

Two points of interest on the pump curve are the shutoff head and the normal discharge or rated capacity. The shutoff head is the head output by the pump at zero discharge, while the normal discharge or rated capacity is the discharge or head where the pump is operating at its most efficient level. Variable-speed motors can drive pumps at a series of relative speeds, which would result in a set of pump curves for the single pump, as illustrated in Figure 9. Typically, to supply a given flow and head, a set of pumps is provided to operate in series or parallel and the number of pumps working depends on the flow requirements. This makes it possible to operate the pumps near their peak efficiency.

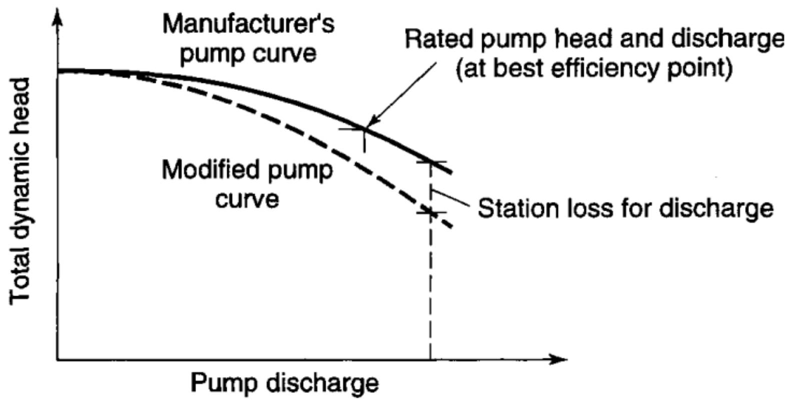
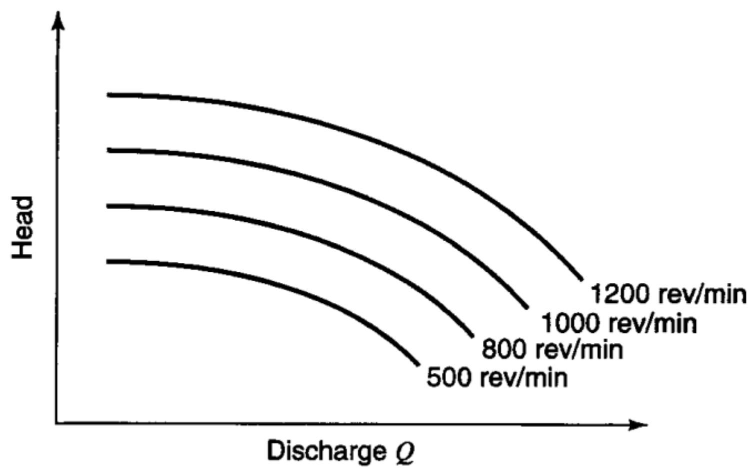


Figure 8: Illustrated the Modified Pump Curve.



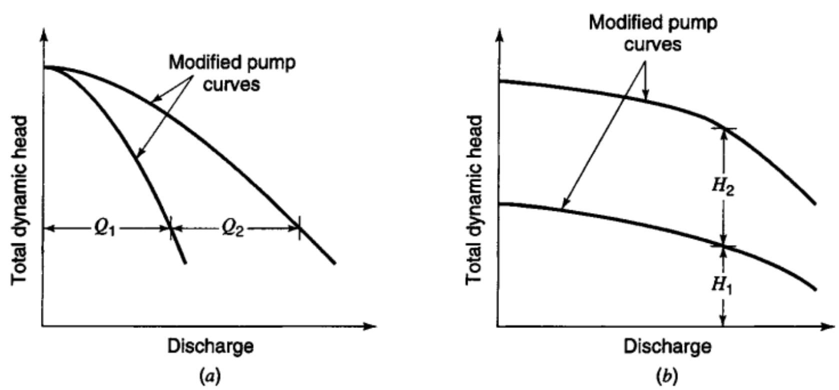


Figure 10: Represented the Pumps Operating (a) in parallel and (b) in series.

Figure 9: Represented the Pump Performance Curves for Variable Speed Pumps.

Multiple-pump operation for one or more pumps in parallel or in series requires the addition of the modified head-characteristic curves. For pumps operating in parallel, the modified head-characteristic curves are added horizontally with the respective heads remaining the same (see Figure 10(a). For pumps operating in series, the modified head-characteristic curves are added vertically, with the respective discharges remaining the same Figure 10(b). Pump manufacturers also provide curves relating the brake horsepower (required by pump) to the pump discharge. The brake horsepower (bhp) is calculated[7].

Pipes and Fittings

Water distribution piping can be of several types, including ductile iron pipe, steel, polyvinyl chloride pipe, asbestos cement pipe, reinforced concrete pressure pipe, and others.

The American water works association publishes C-series standards that provide standards for pipe construction, installation, and performance. Operating ranges of a pump can be developed by establishing a minimum acceptable efficiency and setting upper and lower limits on the allowable impeller diameters. Figure 11 illustrates the operating range of a pump based on these criteria. The following are several factors that must be considered in the selection of both exposed and buried pipe and fittings[8]:

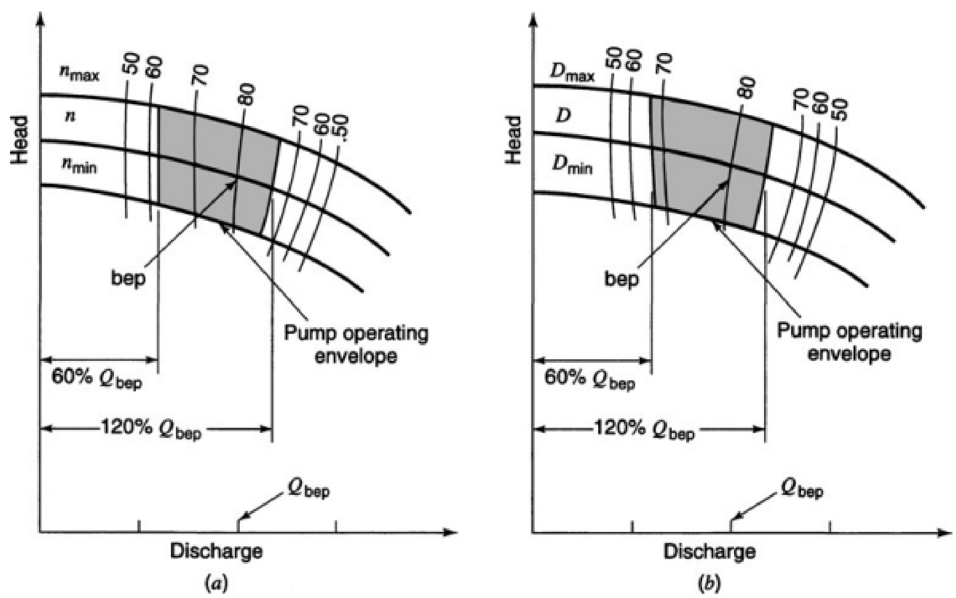


Figure 11: Represented the Pump Operating Envelopes based on the Percentage of Capacity at the Best Efficiency Capacity. (a) Rotational Speed; (b) Impeller Diameter

Control valves are used to regulate flow or pressure by operating partly open, creating high head losses and pressure differentials. These include pressure-reducing valves (PRV) and pressure sustaining valves (PSV). PRVs are used to monitor downstream pressures and PSVs are used to monitor pressures upstream of the valve. Flow control valves are used to maintain flow at a preset rate through throttling.

System Configuration and Operation

Water distribution systems are made up of networks of discrete components: pipes, fittings, pumps, valves, and storage tanks. The configurations of these systems vary significantly. These systems are typically very large and complex, especially for a large number of consumers spread over a wide service area. Hundreds to thousands of pipes may be required to distribute water to users throughout the system. Storage tanks and pumping stations are required to provide flexibility in demands as a function of time and location. The time variation in demand is illustrated in Figure 12.

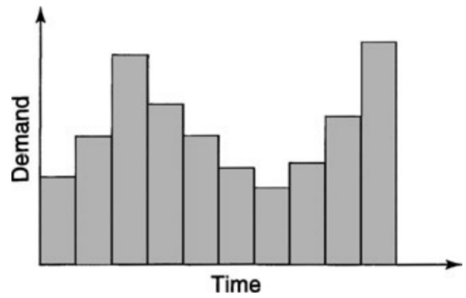


Figure 12: Illustrated the Demand Curve.

Large systems may include several pressure zones where pumps, valves, and tanks maintain required service pressures. requirements can be identified. Piezometric surface plots and contour pressure plots are a convenient means for reviewing and analyzing either new or existing water distribution system operations.

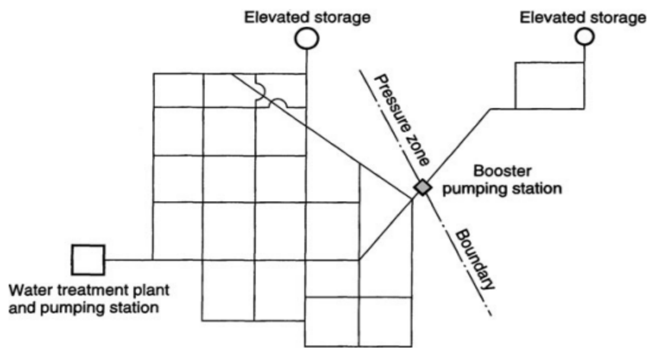


Figure 13: Illustrated the Schematic of Example System.

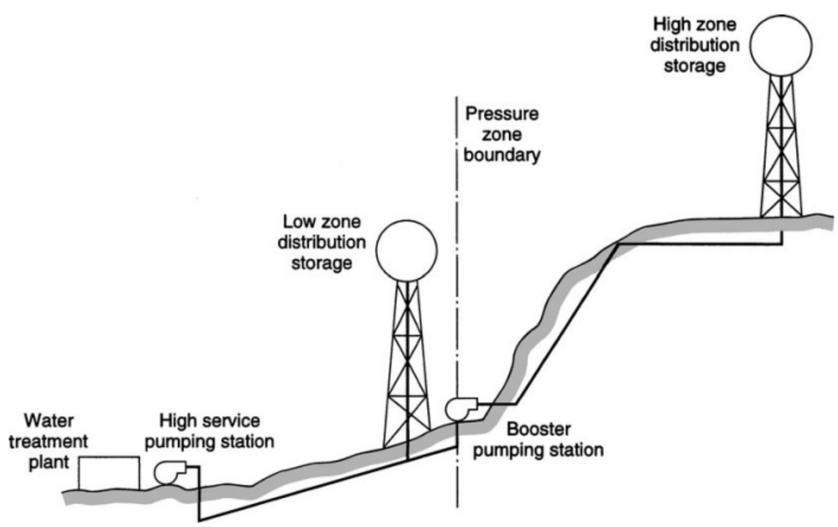


Figure 14: Illustrated the Typical Two-pressure-zone System.

Figures 13 and 14 illustrate an example system that includes two pressure zones served from a single treatment plant. In this system the one pressure zone is served by pumps at the treatment plant and an elevated storage tank. The other pressure zone is served by a booster pumping station and an elevated storage tank[9].

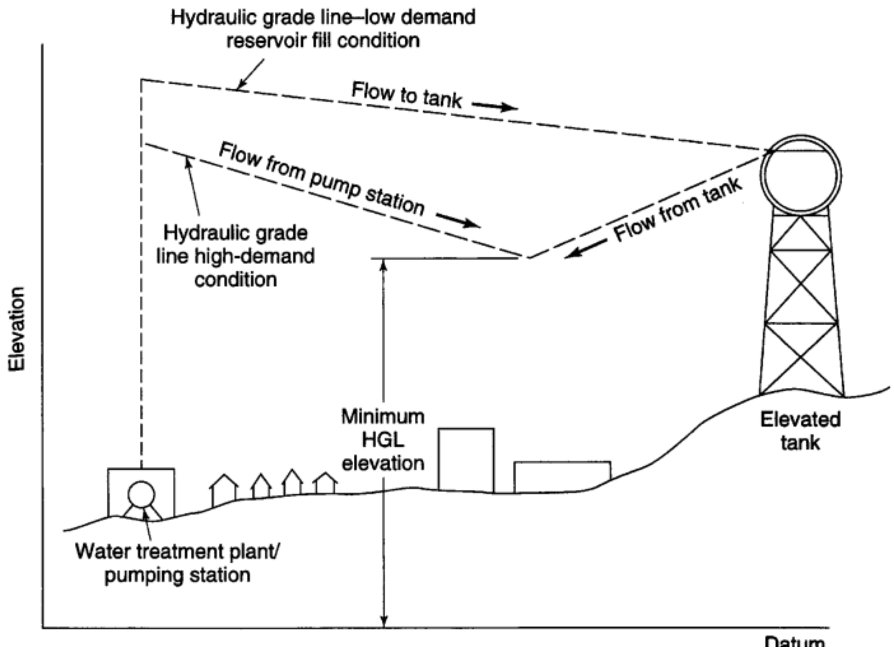


Figure 15: Illustrated the Hydraulic Grade Line Under Two Demand Conditions.

The piezo metric surface (surface of hydraulic grade line, HGL) is one way to visualize water distribution-system hydraulics for various water-distribution-system configurations. Figure 15 illustrates the hydraulic grade line for a simple system under two operating conditions:

i. A low demand condition

ii. A high-demand condition.

During the low-demand conditions, water is pumped from the pumping station to satisfy demand and to fill the elevated tank. During the high demand condition, the pumping station cannot supply the required demand, so water is supplied to the network by both the pumping station and the elevated storage tank. During low-demand conditions, the HGL is highest at the pumping station and slopes downward to meet the free surface at the elevated storage tank. The HGL slope indicates the energy required to pump water to the elevated storage tanks. During high demand, the HGL drops to a minimum in the highest-demand area[10].

For more complex systems the piezo metric surface, represented by contour plots of the HGL elevation, and contour plots of the pressure can be very helpful in analyzing the configuration and design of a system. Areas of a water distribution system that are subject to low pressures under various demand conditions can be identified. The portions of a water distribution system with high friction losses can be identified from these plots. Also, facilities that limit the ability of a system to meet demand and pressure requirements can be identified. Piezometric surface plots and contour pressure plots are a convenient means for reviewing and analyzing either new or existing water distribution system operations[11].

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CHAPTER 5

CLIMATE CHANGE AND SUSTAINABLE DEVELOPMENT FOR WATER RESOURCE

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Significantly however, the impact of climate change on water availability and management has generally never been featured in such discourse, or given the level of importance deserved. In this issue, we give focus to water and its role in our future development, with a particular emphasis on water as a development issue in Caribbean Small Island Developing States (SIDS).The UN's World Water Development Report 2015 puts water at the core of sustainable development, it being an essential element of services which support poverty reduction, economic growth and environmental sustainability. Water is of course pivotal to global food security, as an integral resource sustaining agriculture, and is critical to energy security and industrial development, since it is used for cooling power production and related industrial technologies. Water availability is also integral to improving social well-being and equity, and to fostering inclusive growth. Given its key role in the maintenance of environmental health, this resource is central to the growth and well-being of societies. Although water was not identified as a specific target of the Millennium Development Goals (MDGs), various achievements under the MDGs have resulted in improved access to drinking water for approximately 2.5 billion persons. Notwithstanding this significant milestone, global water demand is projected to increase by 55 per cent by 2050, driven by increased population and urbanization, as well as the application of more water intense food and energy security policies[1].

The macroeconomic growth of newly emerging countries through globalization is also expected to increase this demand, as changing diets and consumption patterns raise the levels of global per capita water use. From a policy standpoint, water and sanitation comprise a number of critically interrelated components which impact overall development. These include elements such as water resources, water governance, water-related diseases, wastewater pollution and water quality, drinking water, and sanitation and hygiene. It is all of these factors which led to a clear enunciation of water and sanitation as Goal 6 of the newly adopted Sustainable Development Goals (SDGs), the ultimate aim of which is to ensure availability and sustainable management of water and sanitation for all by the year 2030. While for Caribbean SIDS, progress has already been Access to clean water, sanitation and hygiene plays a central role in achieving development and, as such, is recognized as a human right that affects the lives and livelihoods of millions of persons.

The World Health Organization (WHO, 2012) estimates that investment in water and sanitation services has the potential for substantial returns, in the order of US $5 to US $28 per dollar invested. Conversely, a lack of access negatively affects health and wellbeing, which ultimately brings additional financial costs. In this regard, major global platforms including the Millennium Development Goals (MDGs), the Samoa Pathway and the Sustainable Development Goals (SDGs) have underscored the importance of water in alleviating poverty and in promoting sustainable development.

Water Remains Scarce Resource

Access to water is fundamental to economic and social development. However, such developments in turn demand increased use of water and bring environmental impacts. Climate change, population growth, degrading water quality and extreme hydrological events that is floods and droughts present serious challenges to national efforts to provide sustainable water services. Even though the link between hydrologic extremes and economic losses has been confirmed by many researchers, efforts to implement programs to address water-related disasters and water-related climate change impacts are not as widespread as they should be. Accelerated global development trends and population growth are exerting pressure on an already scarce resource. Population growth and development are accompanied by urbanization, food and energy security policies, and improved living standards that inevitably lead to sharp increases in water consumption and pollution of sources. Competing demands combined with management challenges will certainly exacerbate water scarcity and increase the risk of localized conflicts[2].

Water is Key to Social Development

A recorded 332.5 million cubic miles of water exist, but only 3 percent constitutes freshwater resources. Much of this (approximately 68 percent) is trapped in glaciers, with a further 30 percent stored as underground resources. Readily accessible global freshwater resources therefore are estimated at about 22,300 cubic miles; approximately 1/150th of the one percent of total water resources. Even while discounting the pressure of climate change and development, water is scarce. Nevertheless, freshwater resources are readily available in rivers and lakes, and are utilized by many sectors across society- including agriculture; energy production; recreation and manufacturing-, with the unfortunate result of a virtual tug-o-war among its users. In this context, water can be classed as a resource and a sector. It is key to social development, environmental integrity and economic growth. As a sector, water requires infrastructure development and operational funds. As a resource it cuts across sectors, demanding a more integrated approach to management. Financing, monitoring and infrastructure have all been identified as high priority water management issues facing decision-makers.

Caribbean Perspective

Caribbean states face three major obstacles that hinder the optimal management of water. These are:

- **a.** Governance,
- **b.** Infrastructure
- **c.** Wastewater management.

The water sector is seriously fragmented, which results in inefficient use of scarce resources, both human and financial. Typically, a number of agencies are responsible for separate but complementary components of the sector like potable water, sewerage, disposal, creating silos and often contributing to a weak enforcement of the existing regulations, many of which are inadequate and seriously outdated[3]. In the case of infrastructure, priority has been given to increasing access to potable water, with a focus on network expansion rather than on network upgrade, maintenance and/or rehabilitation. This has resulted in inattention to the need to upgrade infrastructure, resulting in significant levels of water leakage of between 50% and 70%.

This has been a major contributor to the waste of this vital resource and to the inefficiency of the sector. Fragmented governance and outdated infrastructure also combine to exacerbate existing challenges. Due to its weight, water transmission and distribution consumes large amounts of energy, and in the Caribbean, inefficient energy consumption represents 30 per cent of the operational budgets of water suppliers. This is directly related to the lack of funds for investments since many suppliers show below-cost recovery revenues, which means that tariffs only cover operation and maintenance costs. Energy efficient transmission and distribution devices could create savings between 30% and 40%; this is particularly relevant considering the sub region's high levels of indebtedness and dependence on imported fossil fuels.

Climate change aside, the challenges affecting water availability and quality include population expansion, growing urbanization and increasing demand. Over the last 10 years, global groundwater resources have been falling largely because of the increased rate of abstraction. This is a logical progression in response to increasing population growth and related development activities.Residential water demand has increased alongside growing population figures and ranks among the largest category of water users. Population and economic growth also translate into increased deforestation as forests are cleared for development, contributing to drought and flooding events. Growing populations also drive the need for irrigated agriculture, an activity responsible for more than 56 per cent of withdrawals from underground sources. This kind of agriculture is a major source of pollution for countries with mainly limestone topography like the Dominican Republic and Jamaica. It is increasingly evident that growing numbers of people in limited space without the adequate management practices can compromise water quality and quantity. These competing pressures interact to create complex manifestations that exacerbate the threats facing water resources (Box 1). When climate change is added to this equation the impact can be significant, as it affects the cycle, availability, quantity and quality of water resources, including the variability and frequency of precipitation[4].

Water Availability

Evidence shows that climate change is heating the atmosphere and increasing overall evaporation rates. This in turn increases the volume of water held in the air, causing heavier rainfall in many areas and drought in others. By way of example, studies by ECLAC (2013), suggest that the Caribbean region has already begun to show significant hydrological variation, with an intensification of precipitation during the winter months (December to March), and a decrease during the rainy season. Measures of anomalies in annual precipitation, from the 1960's to 2000's show overall downward trends for Barbados, Dominica, Grenada, Saint Kitts and Nevis, Saint Lucia and Saint Vincent and the Grenadines. High temperatures also cause an increase in water demand and a reduction in groundwater resources. The growing trend of reduced aquifer recharge shows the following scenarios. In the first instance, faster evaporation rates result in reduced water tables. Increased frequency and intensity of storms prevents proper soil infiltration and increases runoff.

In coastal areas, rising sea levels raise water tables, but delay effective aquifer recharge. Elevated temperatures encourage faster surface drying, which reduces the existence ofwater in the near-surface interface of soil, directly impacting agricultural production. When there is less downward movement of water through the soil, the opportunity for groundwater recharge severely diminishes. This worrying situation is not readily rectified by more rainfall, mainly because the infiltration process is hampered by the high temperatures. For low-lying coral based islands like

Barbados, British Virgin Islands, Cayman Islands and the Dutch Caribbean reduced precipitation is already a reality. Furthermore, there is another perspective that must be added to the discourse to appreciate the complexity of water availability. The water cycle distributes rainfall unevenly across space and time, contributing to the variability of global water storage. This may cause greater downpours and more flash floods leading to tremendous destruction of infrastructure, [5] environmental damage and loss of life. This variability in time and space is a factor that deserves great consideration when developing appropriate water management systems.

Unaccounted Water Loss and the Effects on Climate Change

At a regional level, the implications of this variability determine water quality and quantity, which in turn hinge on size, geology, topography, climate and patterns of socioeconomic development. Many countries in the region have restricted water resources because of their geological and physical features. Depending on the financial situation of the country, rainwater harvesting and desalination may be the only possible solutions, especially in smaller and drier islands. Limited water availability is an issue for Aruba, Barbados to a lesser extent, the British Virgin Islands, Cayman Islands and Curacao. For countries like Barbados, Antigua and Barbuda, and the Bahamas, their struggles are centred on addressing underground water resources that have been exhausted or contaminated from either pollutants or saltwater. Another concern is the high level of unaccounted water loss. The region recorded a staggering 50-60 per cent loss. This is particularly noteworthy, considering that the Caribbean is the region with the lowest water availability per capita among all Small Island Developing States (SIDS).

The Global Water Partnership identifies Integrated Water Resources Management

A process which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

There are four main principles that govern IWRM reform:

- Principle 1: Freshwater is a finite and vulnerable resource, essential to sustain life, development and the environment.
- Principle 2: Water development and management should be based on a participatory approach involving users, planners and policy makers at all levels.
- Principle 3: Women play a central role in the provision, management and safeguarding of water.
- Principle 4: Water has an economic value in all its competing uses and should be recognized as an economic good as well as a social good[6].

With specific reference to Principle 3, it is clear that gender should be addressed comprehensively to ensure that the views and contributions from both men and women are treated equitably in shaping the development agenda. IWRM underscores that access to clean water and sanitation is a basic right that should be afforded to all. IWRM changes the status quo, eschewing a disjointed approach to water resources management in favor of an integrated one. Its foundation is based on the concept that water resources are essential to the wellbeing of the ecosystem. Given the threat which climate change poses to the long term water availability in SIDS countries, a broad based strategic framework for IWRM is necessary to ensure future water security.

Such a framework should include the following:

1. **Implementation of the following adaptive strategies:**
    a. **Infrastructural:** build coastal and flood water guards to regulate sea-level rise and flooding, and devise techniques that increase water use efficiency such that drip agriculture).
    b. **Behavioral:** raise awareness in order to modify production and consumption behaviors such that efficient irrigation potable water to be used as needed.
    c. **Managerial:** change farm practices, for example by growing drought resistant crops that adapt to the changing weather, and demand management policies such as pricing, metering and classification of water use groups.
    d. **Government Policy:**adjust planning guidelines, building codes and utilization of renewable sources of energy (e.g. solar, wind, geothermal)[7].
2. **Modification of current water management strategies throughout the region through:**
    a. Improvement, rehabilitation and maintenance of infrastructure.
    b. Desalination, especially in water scarce countries.
    c. Rainwater harvesting.
    d. Harnessing the potential benefits of greywater as an alternative to increase the availability of water and to address the global challenge of wastewater management.
3. Strengthening of water resource management through assessments of water resources, economic assessments of the sector, water forecasting and industrial reform, capacity building, and establishment of water monitoring networks.
4. Development, design and implementation of water policies, which include integrated water resource management (IWRM), national water information systems to increase availability and accessibility of sector information.
5. Elaboration of sustainable land management practices and mainstreaming of development planning.

Recent evidence provides a good indicator of the likely impact of prolonged water deficits in the Caribbean on the basis of the 2019/2020 Caribbean Drought experience.

1. **Caribbean Drought of 2019-2020 Key Characteristics:**
    - Began during the 2009 rainy season in particular the month of October
    - Regional awareness through Caribbean Drought and Precipitation Monitoring Network (CDPMN); prior to this no official action
    - In 2010, stations in Barbados, Dominica, Grenada, Jamaica, Saint Vincent, Saint Lucia and Trinidad, recorded their lowest ever February rainfall totals

- Stations in Anguilla, Dominica, Grenada Saint Vincent and Trinidad recorded their lowest ever 3 month (January to March, 2010) totals
- Stations recorded their lowest six month (October 2009 to March 2010) totals.
- These included stations in Barbados, Grenada, Guyana, Saint Vincent, Saint Lucia and Tobago
- Over 24 years of record at Point Saline Airport in Grenada; 2009 lowest annual total
- Drought subsided in April, 2010 in northeast Caribbean and in May, 2010 in the southeast

2. **Impacts of the 2009-2010 Drought:**

- Water rationing in some Caribbean States.
- Water courses greatly depleted.
- Major crop losses; 25 % loss in onion crop, 30 % loss in tomato crop in Antigua.
- Increases in food prices; prices of tomatoes rose from $2.35/ pound in Feb 2010 to $6.00/ pound in Mar 2010.
- Hydro power contribution in Saint Vincent dropped from 28.69% in Feb 2009 to 12.01% in Feb 2010
- In one of Guyana’s Regions cost US $16,000 per day to deliver water (pumping and creation of canals) to one of its 10 regions; pumping saline water to about 150 acres of rice lands.
- Record numbers of bush fires in all Caribbean; in Dominica, 160 fires (mainly bush fires) during the 1st quarter of 2010, the entire year 2009 realised 103 fires.
- Severe landslides when rains returned.

According to the United Nations Department of Economic and Social Affairs (UNDESA), in 2014, 54 per cent of the global population lived in cities and it is expected that by 2050 this number will increase to two- thirds of the population. Urbanization is a significant demographic trend in most countries, particularly in developing countries. By the year 2050, two-thirds of the world’s population will be living in cities.

A growing, increasingly prosperous and rapidly urbanizing global population will demand more food, more energy and more water resources to meet its needs. These demands from industrial development and rapid population growth encourage investments in water and sanitation infrastructure. Currently, an average person uses more than double the water than a hundred years before, and urbanization is keeping domestic water use on an upward trend, accounting for 11% of total water withdrawal worldwide. However, pollution and over exploitation are seriously affecting the natural hydrological processes, and the world is projected to face a 40 per cent water deficit by 2030 under the business-as-usual scenario[8].

The Impact of Urbanization on the Hydrological Cycle and Ecosystems

Continuous exchange of water between the atmosphere, land and water bodies. It consists of processes such as precipitation, evaporation, infiltration and condensation. An urbanized area consists of large areas of impervious surfaces that disrupt the infiltration of water into the soil which results in the disruption of the recharge of groundwater, exacerbating flood risks. In urban areas there is the occurrence of a number of scenarios that affect the hydrological cycle. For example, the interception of rainfall is reduced due to removal of trees, the rate of evapotranspiration is much lower, surface run-off discharge is greater, the rate of infiltration and recharge is reduced, the amount of water that can be stored is lowered, there are increased runoff volumes and peak flows in rivers, and surface runoff occurs more frequently. Urban development significantly increases the amount of storm water and the frequency of extreme hydrological events experienced by the city's catchments. The increased runoff causes more intense local flooding, while droughts during dry weather are more severe and longer. Aquatic habitats are also affected by urbanization. This may occur in the form of increased discharges that erode stream beds and banks, which may cause the straightening of a stream by the process of channelization. There is also the loss of stream bank tree cover, which may be lost during floods or due to human activity. Additionally, increased contaminants in water and increased fine sediment in stream bed can also take place. Furthermore, there is a growing concentration of pollution into the rivers due to the runoff from land which affects the quality of water available for use. When urban development occurs, protection of biodiversity and the conservation and restoration of ecosystem services tend to not be the main priorities; therefore organisms in ecosystems are affected due to the destabilization of ecological processes between the food chains of different organisms which can restrict the provision of ecosystem services. Ultimately, this results in overall degradation of the aquatic habitat[9].

WATER SUPPLY, QUALITY AND DEMAND

Since much of the water consumed by cities generally comes from outside its limits, and the pollution generated tends to flow downstream, the impact of cities on water resources goes beyond their boundaries. Cities also import significant amounts of food, consumer goods and energy, which require large amounts of water at the point of production, transportation and sale. This virtual demand of cities greatly exceeds direct water use. Rapid urbanization, increased industrialization, and improving living standards generally combine to increase the overall demand for water in cities. It is projected that by 2050 global water demand may increase by 55 per cent, largely because of the growing demand from manufacturing, thermal electricity generation and domestic use, all of which mainly result from growing urbanization in developing countries. According to the U.N. Department of Economic and Social Affairs, around 1.2 billion people, or almost onefifth of the world's population, live in areas of physical water scarcity, and another 1.6 billion face economic water shortage in countries that lack the necessary infrastructure to extract water from rivers and aquifers. In many urbanized areas the availability of surface water and groundwater sources has been reduced (Figure 2). Therefore, cities have to go farther or dig deeper to access water. In some cases they will have to depend on innovative solutions or more advanced technologies, such as reverse osmosis for desalination, or reclaimed water, to meet their water demands.

The United Nations Environment Programme and Human Settlements Programme (UNEP/ UN-Habitat, 2010) define wastewater as a combination of one or more of: domestic effluent consisting of blackwater (excreta, urine and faecal sludge) and greywater (kitchen and bathing wastewater); water from commercial establishments and institutions, including hospitals; industrial effluent, stormwater and other urban run-off; agricultural, horticultural and aquaculture effluent, either dissolved or as suspended matter

This variety of contaminants and pollutants is produced primarily by the domestic/ urban, industrial and agricultural sectors, with the latter accounting for 70 per cent of total fresh water consumption. Extraction of water for food production and its resulting diffuse water pollution are likely to be exacerbated by population growth, considering that by 2050 the agriculture sector will need to produce 60 per cent more food globally, and 100 per cent more in developing countries. Inadequate treatment of wastewater can have detrimental effects on water quality. Most impacts are caused by (i) chemical contamination and (ii) microbial pollution. Chemical contamination is caused by excess nutrients (nitrates and phosphates), which can stimulate eutrophication and result in algal blooms, dissolved oxygen depletion, biodiversity loss, increased turbidity, invasion of alien and competitive species, and an overall reduction in water quality. Furthermore, “the deterioration in water quality resulting from eutrophication is estimated to have already reduced biodiversity in rivers, lakes and wetlands by about one- third globally” (UN- Water, 2015).

Microbial pollution is associated with high concentrations of excreted pathogens. As a result, it is estimated that 1.45 million people a year die due to diarrhoeal illness, of which 58 per cent is caused by inadequate water, sanitation and hygiene. It is critical to note that 43 per cent of the deaths occur in children aged five and under (UN- Water, 2015). The broad definition of wastewater, which includes domestic, commercial, industrial and agricultural end products, highlights the complex and multisectoral nature of the challenge. It also recognizes the importance of coordinated and integral approaches to address a complex issue within a sector with multiple and competing uses and users.

WASTEWATER AS A RESOURCE

As cities and populations have grown, countries and international organizations have strived to devote resources to guaranteeing access to water and sanitation to citizens worldwide. However, most efforts have been dedicated to granting access to safe drinking water and appropriate sanitation systems, without complementary actions to manage the end products of water and sanitation provision. MDG targets on improved sanitation have focused resources on increasing service coverage in terms of access to improved toilet facilities, but with far less attention paid towards ensuring that waste streams are adequately collected and treated prior to discharge into the environment. As a result, the majority of waste waters, septage and faecal sludges are discharged without any form of treatment into the environmen (World Water Council, 2012). This problem is particularly serious in developing countries, where UNWater (2015) estimates that only eight per cent of wastewater is treated. The treatment capacity of developing countries is below the global average of 20 per cent, and considerably lower than the capacity of high-income countries, set at 70 per cent, reflecting disparities among and within countries[10].

Additionally, the World Water Council (2012) expects urban populations to almost double in the next 40 years, rising from 3.4 billion to over six billion people. Furthermore, most of this growth and the rapid changes that it entails are already taking place in developing countries, which have limited capacity to address these issues, withmany cities currently lacking adequate wastewater management. The Millennium Development Goals proved that access to water and wastewater management are multisectoral issues that pose cross- cutting challenges due to the variety of stakeholders and institutions involved. The Post2015 Development Agenda aims at solving the most pressing issues of our time: poverty eradication; safe and sufficient food; sustainable energy; population growth; urbanization; and adequate management of water and environmental resources.

Building on lessons learned and understanding that water plays a fundamental role in almost all the global challenges we face, UN-Water identified five inter-linked areas that must be addressed in an integral manner to achieve sustainable access and management (Figure 1). Science, technology and innovation will play a key role in moving towards green economies, as they help to understand the complexities of sustainable use of water. Adaptive measures to improve water and wastewater management are crucial to use water efficiently and to provide access to all. There is also a need for new technologies for using different sources of water, such as rainwater and fog harvesting, grey water reuse and untreated river water. However, water is not distributed equally among societal sectors and across geographical boundaries. Additionally, water culture, and economic, legislative and environmental aspects vary within and among countries. Therefore, water management should be locally appropriate and new approaches and technologies must consider existing socio-cultural settings.

Figure 1: Illustrated the Components of Proposed Global Goal For Water.

ACHIEVING ADEQUATE WATER MANAGEMENT

The ecosystem-based approach should be complemented with a rights-based approach to promote participation from all agents, prioritize nondiscriminatory access to water and ensure accountability. In order to achieve adequate water management, it is also necessary to address key issues such as sectoral governance, access to financial resources, coherent regulatory and monitoring frameworks, and improvement of data quality. Data and innovative monitoring techniques are crucial to understand the state of water resources and design cohesive policies. Equitable, participatory and accountable approaches should be accompanied by appropriate policy and legal frameworks, and institutional and human capacities and structures. In this context, the Sustainable Development Goals (SDGs) and the Samoa Pathway have incorporated water management as a fundamental component of sustainable development. Both instruments focus on critical areas such as: (i) integrated management, (ii) sustainable management, (iii) water efficiency, (iv) wastewater management, and (v) institutional and human capacities. Ultimately, these measures will contribute to accomplishing SDG 6 "ensure availability and sustainable management of water and sanitation for all." SDG 6 expands the MDG focus on drinking water and basic sanitation to now cover the entire water cycle, including the management of water, wastewater and ecosystem resources.

CURRENT SITUATION IN THE CARIBBEAN

According to UNEP/UNHabitat, the world is facing a water crisis (quality and quantity) due to continuous population growth, which intensifies industrialization and food production, increases living standards and consumption, and tends to result in poor water use strategies, socioeconomic conflicts and unplanned urbanization. Intensive use is often accompanied by pollution which undermines the ecosystems' ability to regulate and restore themselves, in addition to their capacity to provide water-related services. The Caribbean is not exempt from these challenges, and countries have long recognized that pollution from diverse productive activities has negative impacts on marine ecosystems, which are one of the subregion's most valuable resources for economic and social development. The degradation of the marine ecosystems in the Caribbean is primarily driven by the discharge of untreated wastewater and is a consequence of rapidly expanding urban populations, suboptimal urban planning, and inadequate or absent sewage treatment facilities (CReW, UNEP, CWWA). According to GEF-CReW and UNEP, 85 per cent of wastewater entering the Caribbean Sea remains untreated and 51.5 per cent of households lack sewer connections. In contrast, only 17 per cent of households are connected to acceptable collection and treatment systems. Wastewater discharge has been a large contributor to the loss of over 80 per cent of living coral in the Caribbean in the past 20 years. Additionally, UNEP (2004) has shown that pollution by sewage has caused some serious problems in the subregion, such as: (i) increased fish mortality; (ii) eutrophication; (iii) threats to corals, swamp ecosystems and seagrass beds; (iv) biological diversity loss; (v) red tides; and (vi) threats to human health that affect local populations and touristic activity. Several regional and international organizations agree that there are three main challenges that have led to ineffective wastewater treatment and its associated problems: a. Inadequate policy and legal frameworks, including enforcement and monitoring. b. Insufficient funding. c. Low priority given to the development of the wastewater sector. In this context, and considering that the millennium Ecosystem. Assessment (2005) reported that 60 per cent of global ecosystem services are being degraded or used unsustainably, an ecosystem-based approach to wastewater management should consider the full wastewater cycle, from source to final disposal, and include both freshwater and marine waters[11].

WASTEWATER MANAGEMENT

In light of the complexities surrounding wastewater management and considering the incessantly growing demand of water for various uses and users, it is possible to understand the enormous pressure on the resource. Currently, management in most countries does not consider all the elements of the wastewater cycle. Technologies are often developed without taking national infrastructure fully into account, and supporting data is not always adequate or available, resulting in sewers and treatment plants being under- or over–utilized, and wastewater streams being combined. In terms of impacts on the ecosystems, poor management has resulted in overloaded natural processes, affecting water purification and maintenance of soil structure.

Wastewater management refers to systems that “work with rather than against natural ecosystem processes” (UNWater 2015). The ultimate goal of wastewater management is to reduce the level of pollutants before reusing or disposing the wastewater into the environment. In order to accomplish this, countries must put in place administrative structures responsible for the design and operation of wastewater management systems. It is necessary to understand the situation and role of both the receiving environment and the production and consumption processes before designing sustainable infrastructure and systems that respond to a particular societal organization. While there are different types of wastewater management approaches, their suitability will vary and depend on certain characteristics, such as population size and density, institutional and technical capacity, carrying capacity of the ecosystem, and level of development, among others. Complementarily, there is a new paradigm which emphasizes the usefulness of wastewater as a resource, shifting away from framing it merely as a problem. If adequate standards are put in place, wastewater can complement water supply in environmental applications, urban reuse and industry, but the agriculture sector is the main user of reclaimed water. Wastewater can be harnessed as a drought resistant source of water in agriculture, as well as in non-agricultural lands (parks, golf courses), as a source of nutrients, reducing the use of chemical fertilizers; and as a source of energy, since the bacterial decomposition process produces biogas. Regardless of the selected approach, there are two critical elements that authorities should consider. First, management must be continued, as systems have to be periodically maintained to avoid failures. This includes appropriately trained staff, allocation of resources, and adequate regulatory frameworks that include incentives, sanctions, and monitoring and inspections. On the other hand, systems should be locally appropriate and reflect the local environment, culture and resources.

THE ROLE OF GOVERNMENTS

Governance and infrastructure also affect the unsustainable levels of extraction in a subregion where water is naturally scarce. Even though water availability is limited and many countries already face deficits, the supplydemand gap is not necessarily due to insufficient resources, but weak infrastructure and institutional frameworks. Finally, growing populations, weak urban planning and inadequate sectoral governance combine to exacerbate the problems associated with wastewater disposal. It is estimated that 85 per cent of wastewater enters the Caribbeansea untreated, becoming the primary driver of marine degradation in the subregion (CReW 2010). It is evident that, in spite of climate change, water is under tremendous stress. Access to water and wastewater management are thus increasingly becoming global challenges that could result in serious environmental problems, posing grave threats to human health and wellbeing, and negatively impacting sustainable development.

WATER QUALITY

With the onset of glacier melt, sea level rise is already clearly evident, as oceans accommodate the increased volume of water. Salt water intrusion intonear coastal freshwater resources turns these reserves brackish. This occurs often in drought conditions, when groundwater resources are very low, drawing in saltwater to replace depleted reserves. Countries like Cuba, Hispaniola Island, Jamaica, and Trinidad and Tobago, have experienced some level of saltwater intrusion along their coastlines. Flooding events caused by both climatic and non-climatic conditions have varying levels of impact and the potential flood damage depends on rainfall intensity, frequency and volume of water. The pathogens and impurities from ruptured sewer mains alsorepresent a major source of contamination for freshwater reserves.

Additionally, heavy torrential rains bring garbage, silt, pollutants, animal waste and other impurities, increasing the microbial load of the water supply. A high microbial load in the waterways encourages algae blooms, which deplete oxygen levels, thereby disrupting aquatic ecosystems and eventually affecting human health. Such events retard the natural purification process of oceans and rivers, and contribute to overall water quality degradation. The tourism based economies in the Caribbean place tremendous value on ensuring the adequate supply of potable water. Managing high water consumption levels and significant wastewater volumes is critical to the maintenance of a viable tourism sector. Atelling example of water consumption by the tourism industrythat is not sustainable can be found in the Bahamas, where daily consumption levels are estimated at between 400 to 1,000 litres per capita, almost three times the residential demand. In Saint Vincent and the Grenadines, water demand in the tourism industry is four times that of domestic household consumption.

THE IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

There are still development challenges to be overcome in order to guarantee the sustainable development future of the sub region. These challenges are likely to be further exacerbated by the concomitant effects of climate change. Consider for example, climate projections for the Caribbean which suggest the likelihood of more intense rainfall over shorter time periods, resulting in periods of both excessive rainfall and drought. This phenomenon has implications for the subregion’s ability to implement both flood management infrastructure as well as drought mitigation systems, in order to shore up the public water supply, and to provide water for economic sectors such as tourism and agriculture.

Such challenges influenced by climate change directly impact the availability of natural water resources of Caribbean SIDS. As noted by the Caribbean Institute of Meteorology and Hydrology, climate change is anticipated to have major impacts on the islands’ two main water sources - ground water and surface water. In the case of ground water, changing rainfall intensity due to climate change could reduce ground water recharge during periods of extremely heavy rainfall, since much of this water dissipates through runoff. At the same time, drought conditions could also result in extreme water extraction from aquifers both through use and surface evaporation, ultimately affecting both water availability and ground water quality. In the case of surface water, climate change can induce high levels of evaporation from surface reservoirs, rapid run-off during heavy rainfall and filtration to ground water sources. The Caribbean is also facing challenges related to wastewater management and growing intersectoral water competition, as it struggles to provide improved housing and other public infrastructure while sustaining economic growth. With respect to public infrastructure, improved water distribution systems will be necessary to reduce the high level of water lost through leakage. The management of wastewater as a water recycling strategy is also critical in this regard. Water use efficiency in the tourism sector will also require attention, given the implications for both financial and environmental sustainability for the region’s most dynamic economic sector. It is my hope that the articles presented in this issue will provide the necessary food for thought to stimulate an awakening to the very real, urgent water challenges confronting us in the context of the broader development aspirations of the subregion.

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CHAPTER 6

ADVANCES IN WATER RESOURCES MANAGEMENT DUALISTIC WATER CYCLE THEORY

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With the economy development and the population increase, the water cycle has been changed from the natural model to the "natural artificial" dualistic model. The natural water cycle is consisted of precipitation, canopy interception, evapotranspiration, infiltration, surface runoff, overland flow, river flow and groundwater flow etc., and its driving forces are natural ones including radiation, gravity and wind etc. The "natural–artificial" dualistic water cycle includes not only the above The hydropower energy base in construction or in plan before 2050 natural hydrological processes but also the artificial social processes of water taking, water conveyance, water distribution, water utilization, water consumption and drainage etc., and its driving forces includes both the natural ones and the artificial ones.

In details, the "dualistic" characteristics are summarized as the following three aspects: first, the idealization of the driving force, that is, the internal driving force of basin water cycle in the modern environment has changed from the former centralized natural driving to "natural artificial" dualistic-driving, including both driving force of gravity, capillary force and the evaporation of solar radiation and artificial input driving forces as electrical, mechanical, and chemical energy; second, the idealization of the cycle structure, that is the modern complete water cycle is coupled by the natural cycle of "atmosphere slope underground river" and artificial collateral cycle of "water in taking water transporting–water consumption–water drainage"; third, the idealization of the cycle parameters, that is, the overall response of basin water cycle under changed environment to precipitation input is not only subject to the hydrological and geological parameters of the natural land surface, soil and groundwater, but also the development and utilization of water resources and related socio-economic parameters. It is the focus to solve the basin water resources and environmental issues that to conduct a comprehensive and systematic analysis of the dualistic water cycle and the rules of its associated process of evolution[1].

In addition, the world can be also understood to be made up of society–economy system and ecology environment system, which have mutual interaction role and feedback mechanisms between them. Within the two large systems, there exists materials and energy exchange partly through the carrier of water, which make water have five big attributes of "resources, ecology, environment, economy and society". Among them, "resources" attributes is the basic attribute of water, other attributes are due to the interaction between water and the two systems as illustrated in Figure 1. These attributes of water has strong relationship with the objectives of dualistic water cycle simulation and regulation.For the influence of intense human activity and climate variation, the water cycle process presents more and more obvious "natural and artificial" dualistic driving forces, which brings many water problems such as water scarcity, food and water-logging, worsening water environment and degradation of water ecology system. In order to mitigate water crisis and enhance the society and economy healthy development, it is necessary to identify the evolution disciplines of water cycle and the driving mechanism. Relying on the reasonable application of complex water resources system operation theory, we can exert fully the economic, social, environmental and ecological benefits of water resources to achieve economy and society sustainable development and the harmony between human and nature. Based on these requirements, we propose the theoretical framework of dualistic water cycle simulation and regulation as in Figure 2.

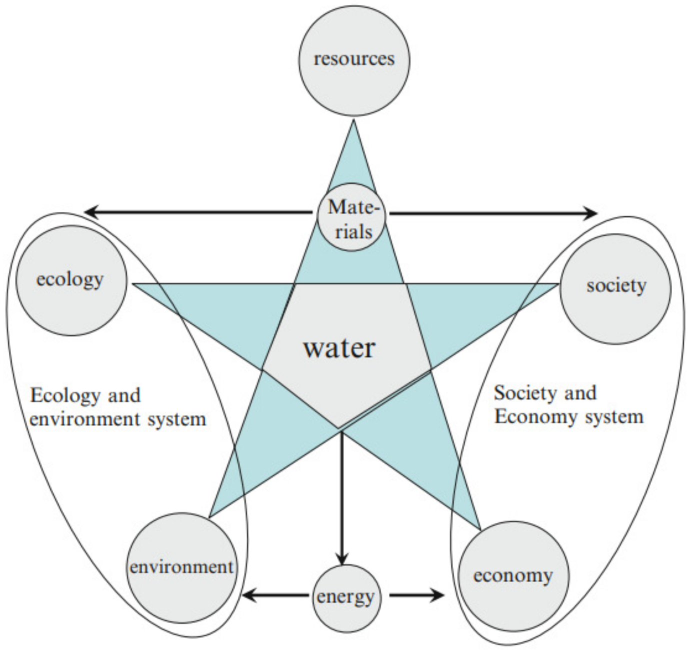

Figure 1: Illustrated the relationship between Water and Society, Economy, Ecology, Environment System.

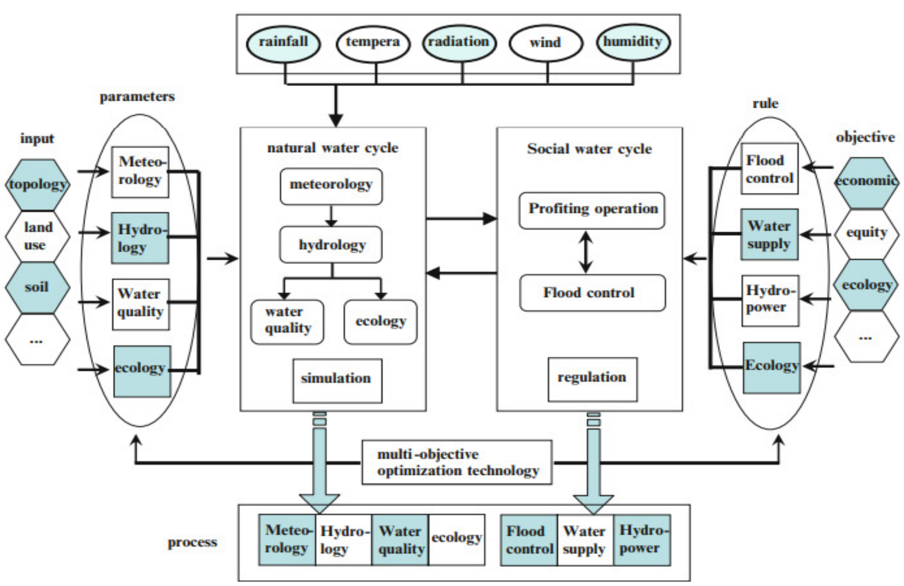

Figure 2: Illustrated the Theoretical Framework of Dualistic Water Cycle Simulation and Regulation.

The watershed water cycle is composed of "natural water cycle" and "artificial water cycle", whose intense interaction is mainly achieved by the operation of hydraulic projects. The artificial water cycle can be divided into two parts: flood control and profiting operation. For reservoir operation, profiting operation takes into account water supply, hydropower generation, ecology and navigation. The coupling simulation foundation of "natural and artificial" water cycle system is the physical mechanism of dualistic water cycle and the derivative effect theory of water resources. The model system of dualistic water cycle simulation and regulation is shown in Figure 3.

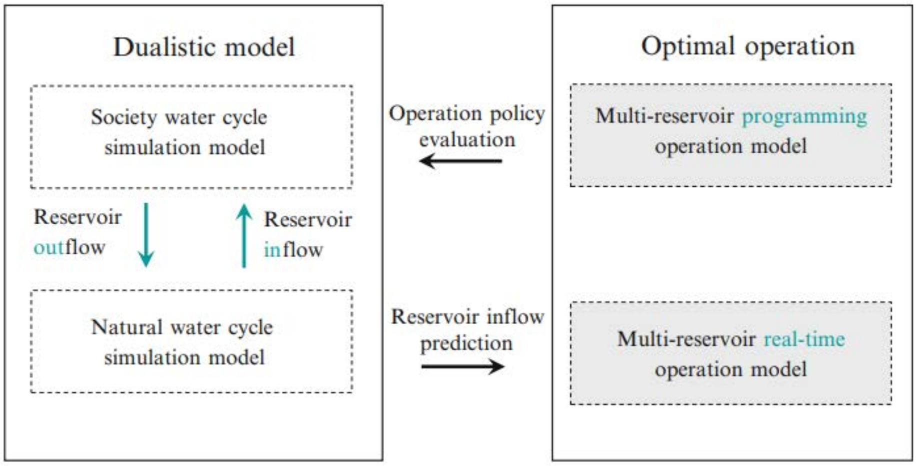

Figure 3: Illustrated the Model System of Dualistic Water Cycle Simulation and Regulation

For multi-reservoir system, the connection of dualistic model and optimal operation model is that the dualistic model can provide reservoir inflow prediction for optimal operation model and evaluate the effectiveness of system operating policy. The core theory of dualistic water cycle simulation and regulation model includes two aspects: watershed dualistic water cycle multi-process simulation theory and multi-objective operation theory for complex multi-reservoir system as shown in Figure 4.

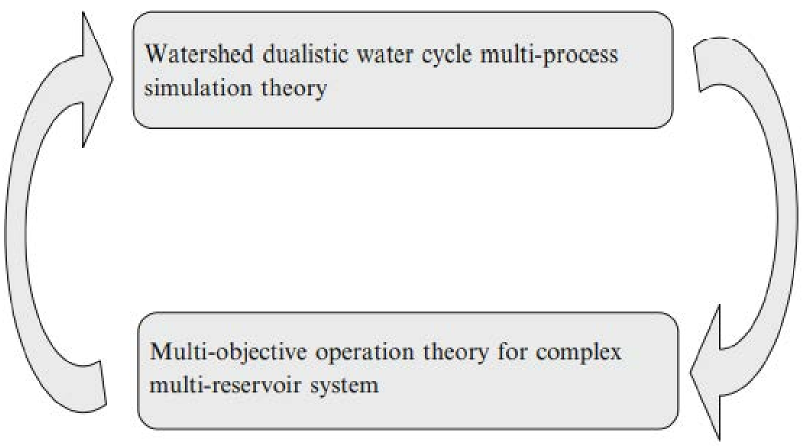

Figure 4: Represented the Core Theory of Dualistic Water Cycle Simulation and Regulation Model

The simulation part gives the description of dualistic water cycle system Reservoir inflow Reservoir outflow Dualistic model Society water cycle simulation model Natural water cycle simulation model Optimal operation Multi-reservoir programming operation model Multi-reservoir real-time operation model Reservoir inflow prediction Operation policy evaluation The model system of dualistic water cycle simulation and regulation Watershed dualistic water cycle multi-process simulation theory Multi-objective operation theory for complex multi-reservoir system. The core theory of dualistic water cycle simulation and regulation model 12 H. Wang et al. from the perspective of model and the operation part can achieves the consideration of human interruption for the social water cycle process. The optimal operation of hydraulic projects can make water resources serve fully for the economy and social development and mitigate their impact on natural water cycle system[2].

Coupling Technology for Dualistic Model

The dualistic model system can taking into comprehensive consideration the natural evolution factors, high-intensity human activities and urbanization, regulation and control of hydraulic projects, etc., and can be used to describe the water cycle and water ecosystems evolution, reveals the different transformation processes of mountainous and plain areas, surface and underground, urban and rural. Because on the core model platform, by making detailed simulation of the water cycle under different historical and planning conditions, master the key and the possible effects and corresponding countermeasures from the all aspects of evolution and the process of water cycle and regulation process, so that can guide scientists in solving the problems of water resources and water ecosystems, and provide supporting tools for achieving comprehensive management objectives of the basin water resources[3].

Dualistic Model System Outline

The dualistic model system is developed independently by China Institute of Water resources and Hydropower Research (IWHR), referred to as Dualistic Model. The model is formed by the coupling of Water and Energy transfer Processes model (WEP), Rules-based Objected-oriented Water Allocation Simulation Model (ROWAS) and Decision Analysis for Multi-Objective System (DAMOS), the overall structure is shown in Figure 5. Dualistic model system is the software system developed specifically for the dualistic model, including the system platform of dualistic model data management functions and model calculation function. The data management function includes various types of attribute and spatial data, hydrological data, water environment data and socio-economic data, etc.; model calculation function includes the pre-processing, multi-model coupling, post-processing functions required by the model calculation.

Characteristics of the Dualistic Model

Dualistic system model is a huge software project. The system has the following characteristics:

1. There are many models and the complex structure, so it is difficult to develop the system. Every individual model of the dualistic model is realized by different programming languages and programming methods, such as: DAMOS model adopts common optimization software GAMS to achieve the description and solution to the optimal allocation of multi-objective water resources. ROWAS model adopts C++ to achieve a

long series of simulation to the water resources supply and demand balance, and WEP model adopts FORTRAN language to achieve the simulation to the "natural–artificial" coupling water cycle process, water environment process and underground water process.

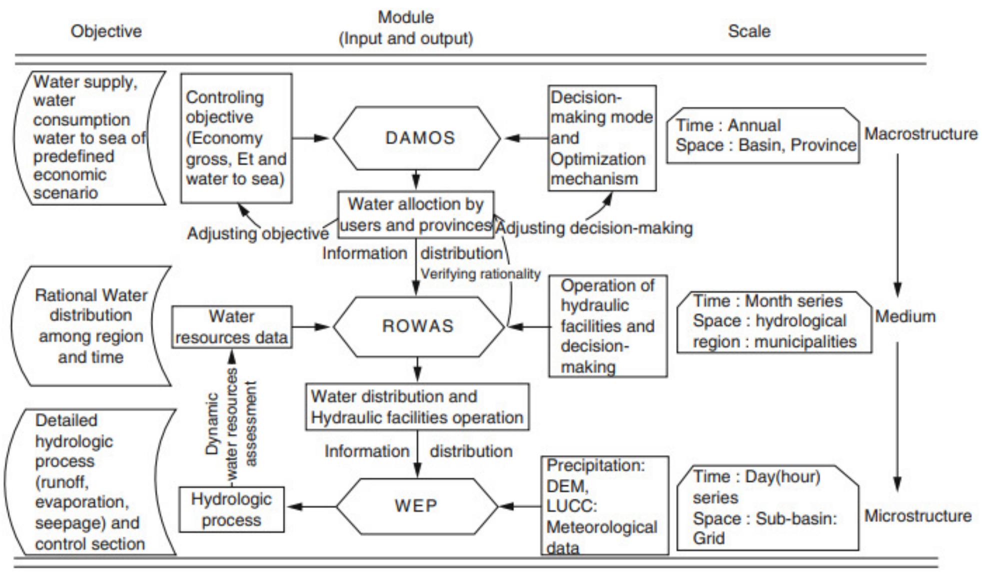

Figure 5: Illustrated the Dualistic Model Structure.

It is necessary to couple the three models into an organic whole in order to develop the dualistic model system. It requires an appropriate transformation to every model so that every model can be integrated into the final dualistic model system. For example: develop general-purpose optimization modeling and solving framework, the DAMOS model developed by using GAMS is realized by using Java language, and the perfect integration with the application system is achieved. At the same time, data is managed in different modes for different models (DAMOS model and WEP model adopt text mode to conduct data management, and ROWAS model adopts the mutual management of text and database), to solve this practical problem, in order to couple the models into an organic whole, the system conduct unified management to the required input and output data of every model, and build the unified data management module of multiple models on the unified database platform[4].

2. Integrate a variety of software technology, and enjoy a high degree of innovation. In order to adapt to the requirement of the highly complex dualistic model calculation and data management, the dualistic model system adopts the rich client/server model to conduct system development. The development mode integrates the merits of both the fat client/server (C/S) and thin client/server (B/S), and can guarantee all functions of the dualistic model system, the user can call a variety of complex models to do calculations on the system interface, without calling the other interfaces and platform.

At the same time, it can support a richer user interaction and achieve a better user response. The client end adopts the open source Eclipse RCP framework, using pure Java language for development, the database server adopts SQL Server2000, and Hibernate data access is adopted between client-servers. Java is adopted for develop so as to integrate better with practical application system, and lay a certain foundation for the future development of WEB-version based dualistic model system. At the same time, the dualistic model system integrates a wide range of software technologies, including optimization software GAMS, database software MS SQL Server, database connection components Hibernate, space display components Supermap, as well as spatial data management components ArcGIS SDE and a number of open sources GIS components MapWindow, etc.

Function of Dualistic Model System

1. Data management function: to facilitate system development and simplify the user's familiarization to the system interface, we have adopted a general purpose management interface for data input and output data management. The system data management is interactively reflected in the graphs, charts and other forms.
2. Model calculation: The dualistic model system will support calculation function of DAMOS, ROWAS, WEP model, and packaging and transformation is made according to characteristics of each model respectively. Taking DAMOS model as an example, since DAMOS model adopts GAMS optimization software package in the development, but GAMS is not suitable for application system development, so the system has developed a general-purpose water resources optimization model constructing and solving package, and then rewrite the DAMOS model using the software package[5].
3. In addition, the dualistic model system not only supports the calculation of the three models, but also supports the data coupling between the three models, so as to achieve automatic data exchange between the models and achieve the fully automated dualistic model. The time scale of DAMOS model is the annual value of many years, the spatial scale is province, while the time scale of ROWAS model is a long series of months, the spatial scale is the calculation unit of three-stage district and city, the time scale of WEP model is day, and the spatial scale is the contour band within sub-basins. To a new calculation program, in the time scale of the next several decades, DAMOS model first makes optimization to the industrial structure, planting structure, water utilization, sewage pollution control, and engineering measures of every planning level year. These optimization results are provided to ROWAS model and WEP model for them to do simulation on different levels. Besides, ROWAS model will also send feedback to DAMOS model, mainly water supply and water supply guarantee rate. Information of water utilization process, drainage process and project scheduling is received after ROWAS makes water supply and demand balance calculation. This information is further passed to the WEP model for it to do simulation at even smaller time scale and spatial scale. Of course, WEP model will also send feedback to ROWAS model, mainly the resources volume information, such as: the surface inflow, ground water status, etc. Because the time scale and spatial scale of the three models are different, so data distribution needs to be made on time scale and spatial scale. To this end, we developed the data distribution procedures of the coupling between the various models.

Developing Distributed Hydrological Model for Inflow Prediction

The physically-based distributed hydrological model, which couples simulations of natural hydrological processes and water use processes, was developed to characterize water resource variations in basins seriously affected by human impacts. To be applicable to a large river basin, and to overcome the implausible number of calculations caused by small grids and anamorphic simulations caused by overly rough grids, the modeling scheme adopts calculation units of contour bands within sub-basins, in which terrain, river network, vegetation, soil, and land use data are based on spatial information data on a 1 km grid. After the simulation is undertaken, many problems can still be found related to the application of the distributed hydrological models. Some models are too complicated to operate easily or too difficult to be modified, others are limited to small basins because of the heavy burden of computation or data preparation. Three disadvantages:

- Low modularization,
- Low generalization of pre-processing programs,
- Low automation, are possibly the key reasons for the limitations described above for WEP-L.

The AutoWEP modeling scheme was therefore developed with strong generalization and expandability, pre-processing modules were improved, and an automatic parameter identification module was developed. This section describes the main improvements and modeling approach developed for AutoWEP, which can be used for inflow prediction. To convert the WEP-L modeling method to one that can great simplify the modeling and calibration processes, enable users to reduce repetitive steps in building distributed hydrological models, upgrade the efficiency of modeling, and reach an ideal simulation precision, a completely new modeling algorithm called AutoWEP was developed. This involved re-establishing coding structure, revising input/output parameters, and pre-processing programs. New functions were added including parameter sensitivity analysis and automatic calibration of parameters. The main improvement in the Auto WEP algorithm is the addition of the “AUTO” modules, which improves the modeling and calibration of the WEP modeling method, making it more efficient. The Auto-WEP modeling process is shown in Figure 6[6].

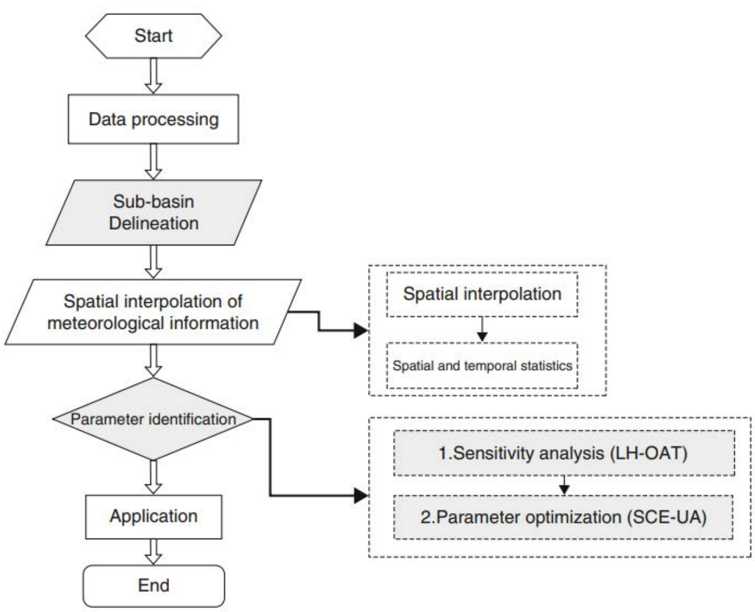

Figure 6: Illustrated the Modeling Process of AutoWEP Model

Dualistic Hydrology Simulation and Regulation System for Upper Reaches of Yangtze River

In the upper reaches of Yangtze River, many large reservoirs have been built or are being constructed or planned. Three Gorges reservoir is one of the most important reservoirs in upper reaches of Yangtze River, not only because of its huge capacity but also its special location. Three Gorges reservoir locates at the boundary of upper reaches of Yangtze River. The natural water cycle process after the regulation of the multi-reservoir system presents obvious dualistic characteristics. For satisfying the strategy requirement of sustainable utilization of water resources in Yangtze River watershed, we develop a dualistic hydrology simulation and regulation system for upper reaches of Yangtze River, which takes the dualistic hydrology simulation and multi-reservoir system operation theory as the theoretical basis. As shown in Figure 7, the system is devised from the perspective of multi-scale, multi-process and multilevel for simulating and regulating water resources system of Yangtze River upper reaches.

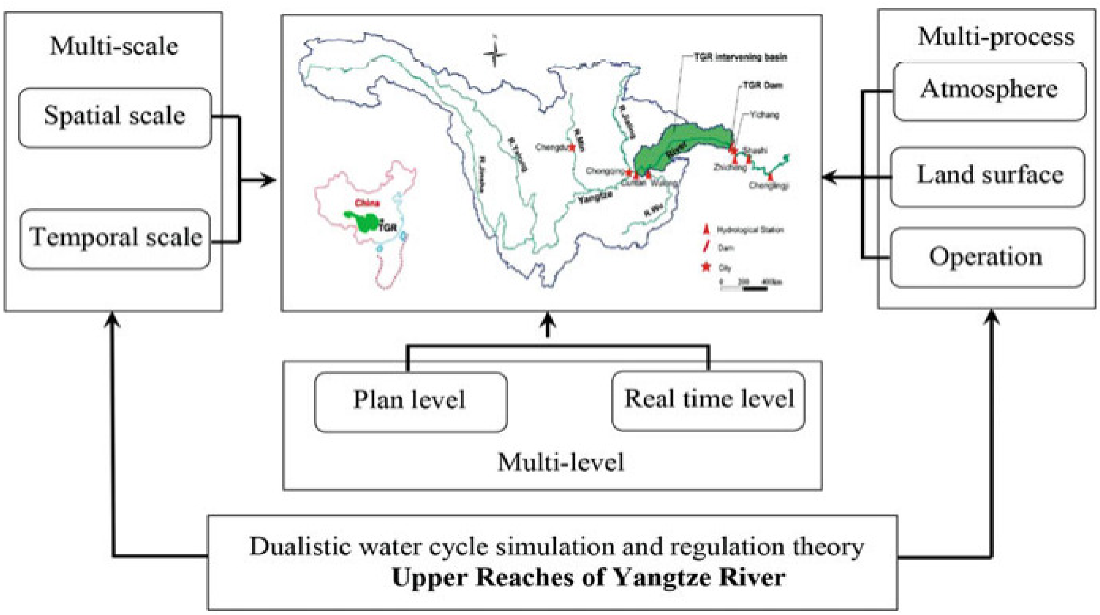

Figure 7: Illustrated the Dualistic Simulation and Regulation System for Upper Reaches of Yangtze River.

The dualistic hydrology simulation and water resources regulation problem of upper reaches in Yangtze River need to carry out the research work from temporal and spatial multi-scales. Not only the whole watershed but also some important and specific study areas need to be studied respectively to analyze the hydrological variation characteristics with scale change. As described in Figure 8, the hydrological time series of month scale, day scale and hour scale need to be modeled and generated for the real time operation and plan operation of the multi-reservoir system in upper reaches of Yangtze River[7].For achieving the whole process and all element simulation of the water cycle, the system needs to be able to model the water cycle and its accompanying process. As shown in Figure 9, the atmosphere process, the land surface process and operation process all can be taken into consideration in the system. In details, the atmosphere numerical simulation and forecast model includes global climate model (GCM), weather research and forecasting model (GCM) and Mesa-scale model.

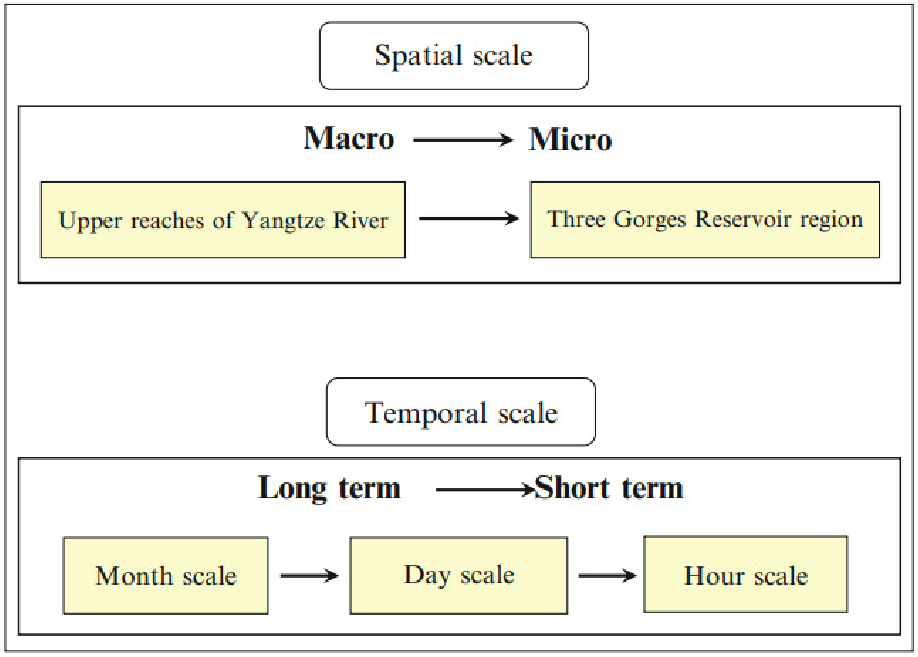

Figure 8:Represented the Multi-scale modeling technology for upper reaches of Yangtze River.

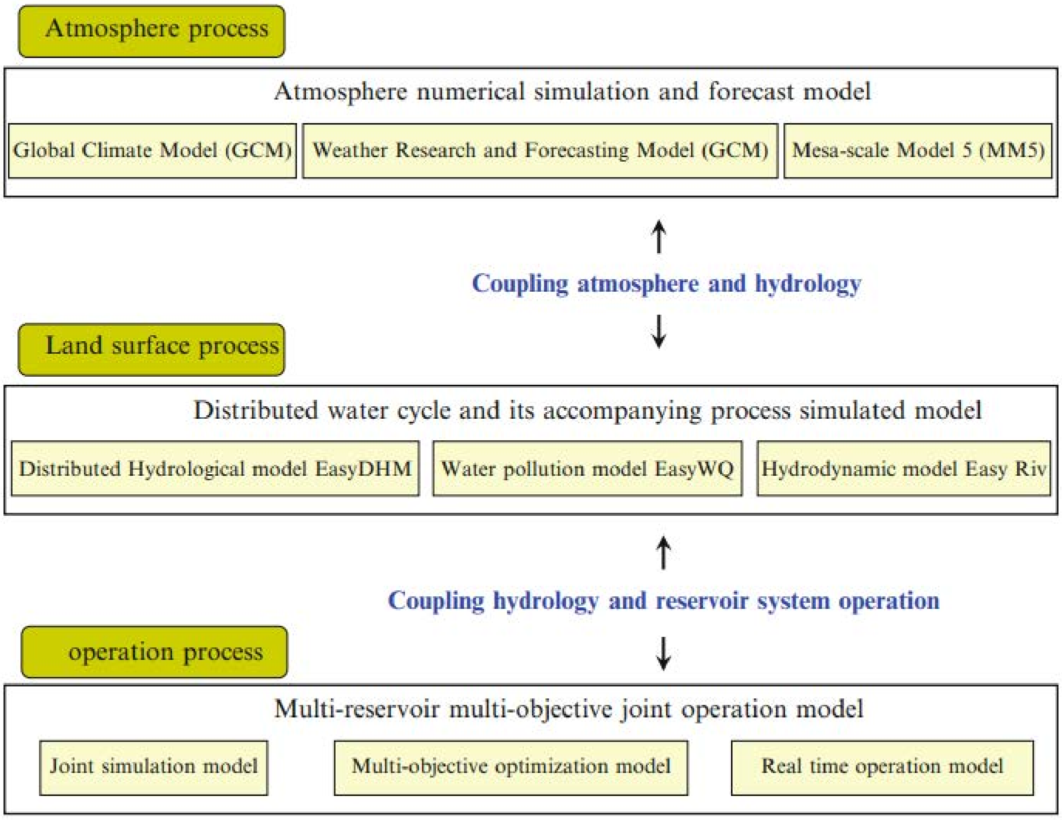

Figure 9: Illustrated the Multi-process Simulation of Upper Reaches of Yangtze River.

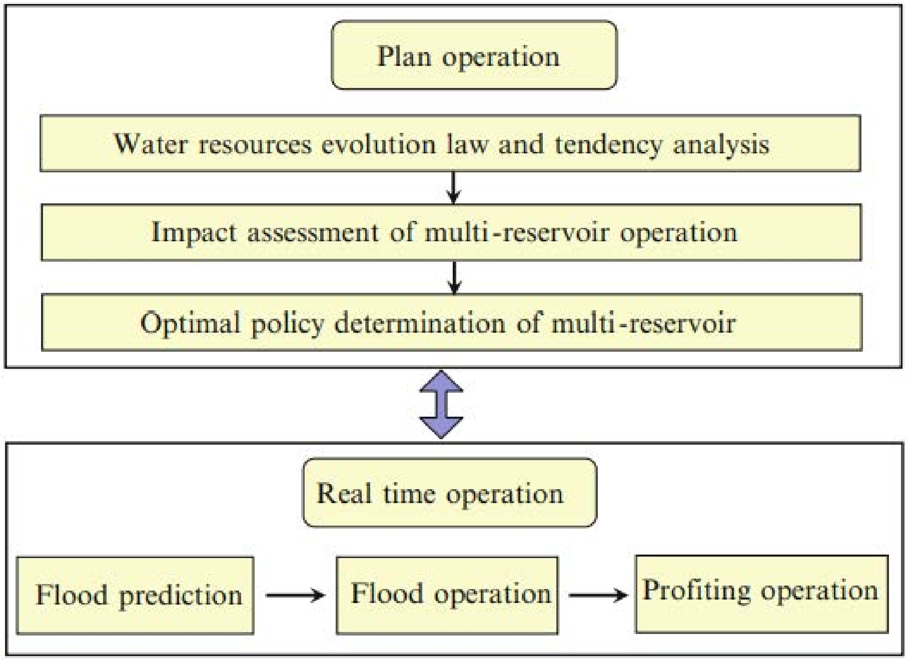

Figure 10: Illustrated the Multi-level operation of multi-reservoir system in upper reaches of Yangtze River.

The distributed water cycle and its accompanying process simulation model consists of distributed hydrological model EasyDHM, water pollution simulation model EasyWQ and hydrodynamic model EasyRiv. The multi-reservoir multi-objective joint operation model is constitutive of joint simulation model, multi-objective optimization model and real time operation model. The coupling technology between the different process simulations is important for the multiprocessor simulation of upper reaches of Yangtze River.

The joint operation model can be divided into two levels, real time operation and plan operation, to satisfy the different operation requirement of multi-reservoir system in upper reaches of Yangtze River. As described in Figure 10, the plan operation model is mainly used to analyze water resources evolution law, assess the impact of multi-reservoir operation and determine the optimal policy of the multireservoir system. The real time operation mainly serves for flood operation and short time scale profiting operation, which needs the inflow prediction information. The profiting operation refers to reservoir operation for the beneficial purpose such as hydropower generation, water supply, navigation or some other purposes[8]–[10].

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CHAPTER 7

WATER RESOURCES MANAGEMENT IN INDIA

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Management of water resources in India has been a challenge whose magnitude has risen manifolds over the past 50 years due to a variety of reasons, notably the rising demands and growing environmental degradation. Broadly, most of the challenges in water management in India can be categorized in the following groups:

a. Water availability, variability and increasing with drawals,
b. Environment and quality,
c. Project construction,
d. Water sharing disputes,
e. Water governance and institutions,
f. Challenges induced due to climate and land-use cover changes.

Here we discuss each of these challenges in detail. It is suggested that conservation of water and management of variabilities should be a cornerstone of water resources management in India. This note also suggests remedies to address the challenges and covers new initiatives by the Government of India.

Water Availability, Variability and Increasing

All the rivers of India can be grouped into four classes:

i. Himalayan rivers,
ii. Deccan rivers,
iii. Coastal rivers
iv. Rivers of the in land drainage basin. Figure 1 shows the major rivers of India.

According to the Figure 1 it displays the major rivers of India and the Himalayan Rivers receive contribution from rain, snow and glacier melt. The three main Himalayan River systems are the Indus, Ganga and Brahmaputra, which account for more than two-third of water in India. It is important to regulate the flow of the Himalayan Rivers so as to conserve water as well as save society and infra-structure from flood damages. Note that the three Himalayan Rivers are trans boundary.

These rivers or their major tributaries originate in India's neighboring countries. After flowing through India, these rivers enter Pakistan or Bangladesh. Thus, India is a down stream country in some cases and an upstream country in some others. Major rivers in the Deccan group are the Mahanadi, the Godavari, the Krishna, the Narmada, the Tapi and the Cauvery. All these rivers are rain fed and carry much les sediment compared to the Himalayan Rivers. Most peninsular rivers flow towards east and join the Bay of Bengal. Coastal rivers of India typically have small lengths and catchment areas. The rivers of West Coast have very high flow[1].

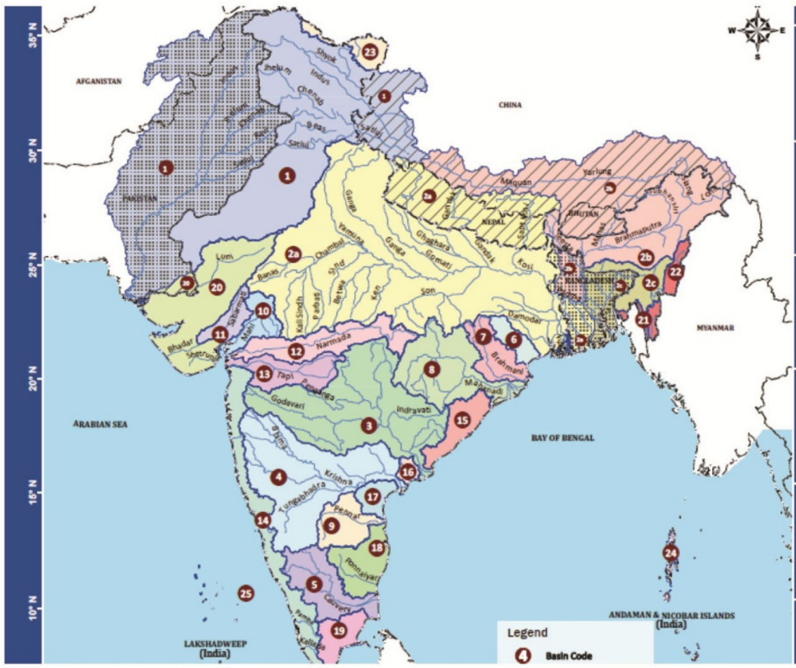

Figure 1: Represented the Important Rivers of India.

Annual precipitation in India has been estimated at about 4000 billion cubic meters (bcm) and the water resources potential is 1869 bcm. Due to topographical and other constraints, the utilizable water resource potential is690 bcm of surface water and 447 bcm of groundwater, totaling to 1137 bcm. Per capita annual water availability in India was about 1544 cubic m in 2011, which has now further fallen due to rise in population. The Falken mark Index is a commonly used measure of waters carcity[2] and a country with per capita annual renewable water below1700 $m^3$is said to be under water stress. Although this criterion is not directly applicable to India where life style and water usage are very different compared to countries in Europe and Americas, falling per capita water availability implies tighter constraints in water management. Three major issues concerning the variabilities in water resources in India are:

i. India has large temporal variability in water availability, leading to, among other issues, disasters such as floods and droughts.

ii. The regional mismatch between water availability and demands is high and the demands for various uses are increasing rapidly while the availability is nearly the same.

With drawal of water from surface and subsurface water bodies to meet growing demands is rising and becoming unsustainable[2].

VARIABILITY IN WATER AVAILABILITY

India faces large temporal variability in water availability, leading to, among other issues, disasters such as floods and droughts. Due to monsoon climate in India, more than 70% of the annual precipitation takes place in a limited period of about four months. Consequently, this is the period when the rivers carry more than 70%-75% of the annual flows, at times exceeding the capacity to safely pass this water. The remaining eight-month period accounts for the balance 25%-30% of river flows and many rivers do not flow for some summer months. Groundwater levels also show somewhat similar rise and fall, with some delay. Large variability in water availability gives rise to a host of problems, including floods and droughts. In addition to temporal variability, water availability in India also has huge variations with respect to location, resulting in surplus water in some river basins/regions and water scarcity in others, frequently at the same time. It will be better to address both types of variabilities together, since the tools are the same. Management of variabilities should be a cornerstone of water resources management in India. Jain3 has outlined the key elements of sustainable water resource management in the country.

Increasing gap between water availability and demands

Population is the key determinant in water demand. As the population of India is increasing, lifestyles are changing and economic activities are increasing, the demand for water is also rapidly rising. Agriculture sector accounts for more than 85% of the annual water demand in the country. As there is no major trend in annual rainfall in India, the gap between demand and supply of water is increasing. In many regions, the demand is already much more than the supply, leading to water scarcity.

Unsustainable water withdrawals

To meet the increasing water demands, progressively larger quantities of water are being withdrawn from surface and subsurface water bodies. Increasing withdrawals have adversely affected the health of many rivers in different reaches and some rivers in different stretches have stopped flowing round the year. This is highly detrimental to the river as well as the environment. Although groundwater use has provided the much-needed drinking water and food security to India, due to unsustainable extraction at many places, water tables are falling resulting in wells going dry, rising pumping cost, falling base flows in the rivers, and entry of harmful substances in the water supply. A large number of districts in India have reported groundwater contamination of some form or the other. These include contamination due to fluoride, iron, salinity, arsenic, etc. Excessive withdrawal from groundwater also results in land subsidence, which may lead to a number of other harmful consequences. In the near future, India is likely to face a situation where water availability in an average year would be nearly the same or less than the demands. The situation will become really precarious in the years of below-normal monsoon[3].

Suggested Remedies

While attempting to solve the water crisis, it is important to look at the water resources in totality (i.e. water resource = surface water + groundwater), rather than managing surface water and groundwater separately. Three distinct actions are required: reduce demands, conserve water and move water across geographies. First, all options should be exercised to check water demands in general, particularly in regions facing water scarcity. Demands from the agriculture sector account for more than 80% of the total demands in India and this sector provides the largest opportunity for water-saving. Estimates show that water use efficiencies in agriculture are very low in India; surface and groundwater use efficiencies hover around 40% and 50%. Clearly, there is a huge scope to improve these efficiencies. As the current irrigation water use in the country is about 550–600 bcm, about 20% rise in these efficiencies would yield enough water to substantially meet the demands from environment and municipal sectors. Savings of this order are possible by adopting sprinklers, drips and other water saving measures. Farmers should be incentivized to save water by improving water use efficiency (per drop, more crop), particularly in the regions where water availability is low.

Conserving flood flows

As noted earlier, India has a monsoon climate and the rivers carry more than 70% of the annual flows during four monsoon months. Hence it is essential to conserve flood flows and use them to meet the demands in the lean season to a larger extent. In places with limited groundwater, management of river flows in accordance with crop water requirements is necessary to ensure food security for the nation, since the water and land productivity of rained agriculture is much lower compared with irrigated agriculture. Water can be stored on or below the surface. Actions are needed at various levels. At the macro level, it is important and essential to conserve surplus monsoon or flood flows, either in the storages on the ground or below ground, since the flows in the remaining months are inadequate to meet the various demands. To store water on the surface, storage reservoirs have to be developed. Good sites for storages are limited in the country and numerous problems arise due to the submergence of forests, displacement of population, threat to biodiversity, environmental issues, etc. To conserve water below the surface, suitable hydro-geology is a must and facilities for large-scale managed aquifer recharge (MAR) need to be created. Thus, it can be seen that both options have some merits as well as demerits. It will be unwise to out rightly reject any option. Keeping in view the problem and feasible options, an alternative option has to be implemented, clearly knowing that any solution will entail some costs and some adverse consequences. Further, no action is not a good decision either since left to themselves, problems rarely get solved. It is also essential that groundwater withdrawals are regulated particularly in the zones where annual withdrawals are more than the annual recharge to arrest monotonic decline of the water table[4].

To make plans for artificial recharge, it would be necessary to estimate the amount of water available for recharge and the recharge potential of aquifers. Currently, only macro-scale information on recharge potential of aquifers is available, whereas the recharge activities need to be planned at local levels. Hence, it is necessary to identify and obtain the aquifer data at local scale, and delineate recharge sites by collecting and analyzing geological data. Also, there is a need to identify the desaturated aquifers and determine their water-holding capacity. Similarly, the amount of water that can be utilized for recharge needs to be estimated at local levels. Properly calibrated hydrologic models can give such estimates.

Rough estimates show that the volume of flood flows in Indian rivers could be about 500 bcm. A major part of this could be conserved through large, medium and small projects, and in subsurface zone through induced recharge. At present, the storage capacity in basins with large water potential such as the Ganga, Brahmaputra, Indus, Godavari, Mahanadi, etc. is quite low. It would help to conserve more water in these basins in the monsoon season and use it to meet the demands during the remaining water year. Conservation of flood waters will also help in partially mitigating two water-related disasters, namely floods and droughts. At the micro level, villagers and farmers may construct/rejuvenate village and farm ponds to store rainwater to satisfy farm water demands. Conservation of water at local levels by check dams can also help in meeting the local water demands. However, if a large number of such structures are created, availability of water in the downstream areas is significantly reduced. Therefore, planning for such interventions should be coordinated at the river basin-scale, so that the impacts of interventions at upstream locations are known and factored in the river basin plans.

Loss of reservoir storage due to deposition of sediments is a concern for India since it reduces the ability to regulate river flows. About 0.8%–1% of the created storage of more than 300 bcm is lost every year due to sedimentation. Replacement of this space by construction of new projects is becoming progressively more difficult. Hence it is important to control the sediment inflows into the storages by treatment of catchment areas. Flushing out stored sediments using low-level outlets is another attractive proposition. For this purpose, spillway crests of several new projects are being kept at low levels. In the early stages of the wet season when high sediment inflows are expected, spillway gates can be raised to allow sediments to exit the reservoir without settling down. This arrangement helps in checking the loss of storage capacity due to siltation. Possibility of efficiently removing sediments deposited in existing reservoirs also needs to be explored.

Managing Floods

To satisfactorily manage floods, a range of actions is required. High flows likely to because damage may be temporarily stored in reservoirs and subsequently released at lower rates. A number of storage reservoirs have been created in India to control floods Hirakud, Rihand, Tehri, and so on. Since the development of storage projects is becoming progressively difficult and these cannot provide complete flood protection, we also need to develop robust systems for flood forecasting and warning so that people, livestock, and movable assets can be relocated to safe locations before a flood strikes. Flood forecasting also helps in better regulation of reservoirs and efficient use of limited flood control space in them. Robust long-period flow forecasting will also help in better management of inflow variability[5].

To check flood damages, it is essential that floodplains of rivers are used wisely residential and commercial buildings should not be built too close to a river. Besides carrying flood flows, floodplains also perform other useful functions. A part of flood flows recharges ground water and rejuvenates riparian vegetation. Hence, no development should be planned such that it impairs the beneficial functions of floodplains. Recall that the main reason behind huge damages during the Uttarakhand floods of 2013 was that many structures had been built on the floodplains and were washed away by flood waters.Since complete protection against floods is not possible, we need to make plans for flood management or flood governance. A combination of structural and nonstructural measures needs to be implemented to create resilient systems and reduce vulnerabilities. To that end, flood management should not be the responsibility of a single department. A number of government agencies, including Water Resources Department, Transport Department, disaster management authorities, local administration, police and NGOs have to work in close coordination. It would also be necessary that mock drills are carried out before the flood season so that the different organizations are aware of their responsibilities and duties, and work as a team if and when a flood strikes. Coordinated use of various measures would ensure resilient and sustainable flood governance. Riparian population needs to be involved in such measures as active partners, rather than passive onlookers.

Rationalizing Cropping Patterns

Analysis of data shows that in the past five or six decades, cropping patterns across the country have dramatically changed. Sugarcane which requires a large quantity of water is being cultivated at many regions of low rainfall where it was not grown earlier. Similarly, rice is also cultivated in many such places. Therefore, to control agriculture water demands, it is essential to review the cropping patterns, particularly at places where annual rainfall is below, say 600 mm, or annual pumping from groundwater exceeds recharge and yet high water-consuming crops such as sugarcane and paddy are being grown. However, a major change in cropping pattern will be difficult to implement. There are many reasons why farmers prefer sugarcane crop. It gives high returns, is easy to plant, does not require much care, and is relatively safe from diseases. Many farmers have some type of agreement with factories. So it is easy for them to sell the crop, although in many instances, payment does come easily. An option would be to replace high water-consuming crops by those that were grown traditionally in these places or by coarse grains and pulses. In drought-prone areas, drought resistant crops must be preferred. Deficit irrigation is another option to manage scarcity. It can help save about 10–15% of the agricultural water demands without much reduction in crop yield. Crop pricing mechanism has also played a role in the shift in cropping pattern. Free supply of electricity to farmers is partly responsible for over irrigation and wastage of water. It might be better to let the farmers pay for the energy consumed at normal rates and directly send subsidy to their bank accounts to partly cover related expenditure.

Long Distance Water Transfer

India also faces substantial spatial mismatch between demand and supply as the places where water is needed and those where it is available are frequently far apart. A viable and tested way to overcome spatial supply demand mismatch is by transferring water from surplus regions to deficit regions by way of long-distance water transfer or interlinking of rivers, as is popularly known in India. This requires construction of reservoirs to store surplus water and transfer links (canals or pipes) to move water. Interbrain water transfer involves both technical and non-technical problems. Costs of these schemes are rapidly rising and soon many such schemes may be difficult to justify in financial terms, even though there may not be any other alternative to provide adequate quantity of water at the desired reliability. Experiences with projects such as Ken–Betwa and others show that technical matters are comparatively easy to solve; difficulties lie in resolving water-sharing, political and funding issues. In addition to long-distance water transfer, short-distance water transfer may also to investigated since here the expenditure, gestation period and opposition will not be much less[6].

Recycle and Reuse

At present, very little quantity of water supplied is recycled and a considerable amount of water is wasted in urban water supply networks due to leakages and thefts. Estimates show that about 40% of water from municipal supply for drinking purposes is lost due to leakage or theft in some cities. There is huge potential of water saving by reducing these leakages (replacing worn-out pipes, valves and other components), and by recycle and reuse of water in municipal and industrial sector. For instance, the Arab states produce more than 10 km3 /yr of wastewater. Of this, about 55% is treated and 15% is reused in farms and landscaping irrigation, environmental protection, and industrial cooling. By recycling a higher amount of water in India, it is possible to considerably reduce the shortage of drinking water in most cities. Poorly planned urbanization is also responsible for water woes in some cities. It is reported that large open areas near Chennai, which were aquifers recharging and flood absorbing areas till a few decades back, have been paved in recent times. This has markedly reduced their recharging capacity, resulting in declining water availability and increased flooding.

Any resource that is provided free is commonly wasted, water being no exception. Hence it is important to charge the users for the water supplied, covering the cost of providing services, with expenditure for maintenance of facilities and some amount for future expansion. All the water supplied should be metered. Clean water to meet the basic needs can be provided to the weaker sections at subsidized rates and the quantity consumed over and above the basic requirements should be charged at slab rates which increase with increasing consumption to discourage wastage. Water resources development plans should be prepared for each river basin and these should clearly identify the projects including their location, size, etc. that will be constructed in each river basin. These plans should ensure that the cumulative impacts of all the projects are within acceptable range and the carrying capacity of a river basin is not exceeded.

Quality of Water and Environment

While good-quality water is a boon and helps in environmental and spiritual rejuvenation, poor-quality water is a curse. Due to dumping of untreated or partially treated wastes from municipal and industrial areas as well as return flow from agricultural areas, orchards and plantations carrying polluted water, water in many of our natural water bodies such as rivers, lakes and ponds is highly polluted. Estimates indicate that over 50% of urban India's sewage enters water bodies untreated. Dumping of industrial and other wastes in subsurface zone has resulted in contamination of the top 10–20 m of subsurface zone. Highly polluted water from hand pumps at many places is an evidence of this contamination. Some big and medium industries are doing appreciable service by carefully treating wastewater, but we also have industrial units which are injecting waste in aquifers to save sewage treatment costs. Needless to say, contaminated aquifers will be a curse for future generations[7].

Forty-five per cent of India's children are stunted and 6 lakh children under five die each year, largely because of inadequate water supply and poor sanitation. According to a WHO study, in 2002, unsafe water and poor sanitation contributed 7.5% of total deaths and 9.4% of total disability-adjusted life years in India. About 73 million working days are lost in India due to waterborne diseases each year. Many or almost all of these deaths can be prevented by providing clean drinking water to children and adequate sanitation. In terms of water quality index, India ranks near the bottom. Adequate sewage treatment capacity is to be created and made operational to treat the sewage generated. Strict monitoring and punitive actions are needed to restore water quality of natural bodies. Every new water resources development (WRD) project should be environment-friendly and existing projects should be retrofitted to also make them environment-friendly. To ensure that the rivers remain in a healthy condition and continue to provide ecosystem services, location-specific assessment of environmental flows needs to be carried out and implemented.

Environment Impacts

One of the reasons why WRD projects face opposition is the perception that such projects harm the environment. Adverse environmental impacts of WRD projects include submergence of lands, forests and residential areas, fragmentation of rivers, barriers to the movement of fishes and other aquatic life, etc. While constructing some projects in the past, large populations were moved from their places of living and there are claims that some of the displaced people did not get due compensation even after a long wait. Two important developments have taken place in India in this context. GoI enacted the Environment Impact Assessment Notification 2006. It laid down a robust procedure for assessment of environmental impacts of WRD projects and creating a management plan to mitigate them. To provide fair compensation to the projectaffected population, Indian Parliament passed The Right to Fair Compensation and Transparency in Land Acquisition, Rehabilitation and Resettlement Act, 2013. This Act has provisions to provide fair compensation to those people whose lands have been acquired to construct a project. Due to liberal provisions of this Act, now the opposition to WRD projects is much less. A critical issue that remains to be addressed concerns development works in an area where a project is proposed. If an area is identified to fall in the submergence zone of a project, no development work is taken up. In many cases, the time between this identification and actual construction could be 2–3 decades, and local population is deprived of any development in this long period. There are instances where people who were supporters of a project turned into opponents due to this reason. Clearly, decision making process for WRD projects needs to be expedited.

Long Gestation Periods in Planning and Construction of WRD Projects

The planning for WRD project typically begins with the preparation of a feasibility report. If this report is accepted, a detailed project report (DPR) is prepared and then a number of approvals such as technical clearance, forest clearance, environment clearance, investment clearance, interstate clearance, etc. are sought. At times, all these approvals take considerable time which may extend to several years. There are instances when a project was dropped after spending considerable time and effort in preparing the DPR and seeking clearances. There is nothing wrong in dropping a bad project, except that if such a decision is taken after spending substantial resources, all the resources which may be quite high go waste. In too many cases, by the time a project gets mandatory approvals and construction begins, its cost may already have increased manifold.

For obvious reasons, the entire process needs to be made more efficient. To that end, in the first step, a detailed feasibility report for a project may be prepared and carefully examined by a group representing key ministries and regulators. This group must have the authority to decide whether to continue with the project or not. Provisions must be made to see that all objections/concerns regarding the project and its impacts are addressed at this stage itself. If the decision is to continue with the project, in the second step, the objective should be to implement the project in the best possible way, and within the estimated time and budget. A design and implementation group should decide the best design and other parameters of the project and also look after the construction. Arrangements should be put in place to ensure that no project work is halted due to agitations, court cases, etc. at this stage[8].

Dispute Resolution and Decision Making Mechanisms

Inter-state water-sharing disputes pose a hindrance in water resources utilization in the country. Besides loss of precious resource, these also result in delays, cost overruns, and law and order problems. To avoid disputes related with inter-state issues, it would be helpful if all major rivers are gauged at the state borders so that all stakeholders know exactly how much water is entering into a given state. At present, we do not have a complete picture of water utilization at different places. Thus, it is difficult to identify places where water is being wasted and where savings are possible. Hence it would be helpful if water use is measured so that its wastage is checked.

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In order to create awareness among people and sensitize them to use water wisely, we need to launch a new mission similar to Swachha Bharat Abhiyan, with the same or higher vigour and involving all sections of society. Students need to be educated for conservation of water and keeping our water bodies clean; overexploitation of rivers should be stopped and adequate water should be allocated for river and environment rejuvenation.

Based on the experiences, there is near consensus that we need to evolve a national framework law as an umbrella statement. The basic premise is that water is a scarce resource which is also essential to sustain life and ecology. This law should encourage inter-state coordination for optimum development of water resources of the country, while realizing that a river basin is the best unit for water resources planning and management. Further, currently use of groundwater is haphazard and the users withdraw water from the aquifers according to their wish, without bothering about the adverse consequences to themselves and others. Although efforts are being made to regulate groundwater exploitation, much more needs to be done for sustainable use of groundwater resources. We also need to introduce the best practices being followed in other parts of the world by involving academicians, researchers and NGOs in various activities[9].

A matter of concern is that a large number of groundwater assessment units fall in the dark category, which means that the withdrawal is more than the recharge and the number of such blocks is increasing with time. This needs to be addressed by regulating withdrawals, checking water use and encouraging artificial recharge, particularly in dark blocks. To control unsustainable groundwater exploitation, all electro-mechanical extraction means need to be registered and monitored. Information pertaining to geology, hydrology and climate could be used to issue permits to withdraw defined quantities from groundwater. A decentralized framework for groundwater governance, which is based on sound scientific understanding, engagement of stakeholders of the resource and congruent regulatory instruments, is clearly required for addressing India's groundwater problem.

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Water Governance and Institutions

Keeping in view the magnitude, range and extent of water-related problems in the country, the institutions involved in WRD and management in India require significant transformation. The main reason is that practice of water management has undergone large changes over the past four decades or so, and the profession is gradually becoming more multidisciplinary. Besides having knowledge of hydrological principles, water professionals need to know about the environment, forestry, agriculture, geology, meteorology, soil science, sociology, economics, law, management and so on. It would be necessary to transform the existing organizations by inducting persons from key relevant backgrounds and some tasks may be accomplished by outsourcing.

For WRD, GoI has to play multiple key roles as a developer, evaluator and regulator, and this requires strengthening of institutions involved in the development and management of water. Many multidisciplinary teams will be needed that can provide expert technical support on divergent issues. A strong monitoring mechanism has to be developed by involving experts from the government sector, academic and R&D institutions and non-governmental organizations as well as individuals. A comprehensive review of water governance challenges in India has been provided[10].

At present, water is dealt with by a number of ministries. This frequently results in delay in decision-making, inter-sectoral conflicts and problems in governance. To avoid such situations, it would be helpful to develop a unified framework for decision making wherein all the key sectors are represented. In the Indian context, the key sectors are agriculture, drinking water, hydro power, environment, floods and climate change. There can be an apex body for national level planning and decision making. At the next level, committees may be constituted for management of river basins with representatives from these key sectors from co-basin states.

A beginning has been made in this direction. Recently, the Ministry of Jal Shakti was formed by merging the Ministry of Water Resources, River Development and Ganga Rejuvenation with the Ministry of Drinking Water and Sanitation. Further, a draft 'River Basin Management Bill' has been prepared which aims at creation of river basin management boards. This Bill needs approval of parliament before it comes into practice. It is hoped that the Bill would be approved soon and the creation of river basin authorities according to its provisions would help overcome many roadblocks in scientific management of Indian River basins. Another positive initiative for WRD is the proposal to establish a single tribunal to adjudicate interstate river water sharing disputes. Note that in the present dispensation, such disputes may take decades to resolve.

In the mid-1990s, GoI had constituted a National Commission for Integrated Water Resources Development and Management. The Commission had completed a comprehensive review and analysis of the water sector and submitted its report, which had many useful suggestions on how to address problems in WRD and management. In the intervening period of about 25 years, there has been a sea change in the ground situation with respect to the water sector in India. It is now time that a similar Commission is appointed for another review and to suggest the way forward at the national level.

Currently, no R&D institution or think-tank in the water sector has a multidisciplinary team and infrastructure to take up challenging tasks such as development and implementation of integrated water resources management plan for a large basin, say, for example, the Krishna basin. The reasons behind this should be brain stormed and remedial steps may be taken up so that the country has several such teams which can help in technically sound integrated WRD and management in India. Despite a number of challenges as well as opportunities to work in the water sector in India, the best students rarely think of joining this sector. It would be necessary and useful to attract talent to the water sector by providing service conditions and incentives which are at par with the other sectors. Mujumdar and Tiwari cover the status of science and technology vis-à-vis water management in India.

Climate Change

India is highly vulnerable to impacts of climate change on water resources due to its unique climate, geography and topography. Warming of the lower atmosphere will impact snowfall. glaciers and snow cover, and crop water requirements; increase in extreme weather will impact incidence of floods and droughts; rising sea levels will increase flooding in coastal areas and seawater intrusion; rising temperatures will impact the quality of water in rivers and lakes, and so on. Remedies suggested here will be helpful in lessening the vulnerabilities due to climate change and increase resilience of the society. In addition, more focused R&D is needed to identify what changes are expected, and where and how to initiate specific adaptations[11]. An encouraging signal is the commitment/plan of GoI to provide water security to the entire population by 2022–23 by way of adequate availability of water for living, agriculture, economic development, ecology and environment. The goals set include: providing piped drinking water to every rural household by 2024; provide irrigation to all farms and improve water-use efficiency or produce more crop per drop; encourage industries to utilize recycled/treated water and ensure zero discharge of untreated effluents from industrial units; ensure uninterrupted and clean flow in the Ganga and other rivers and their tributaries; create additional water storage capacity to ensure full utilization of the utilizable surface water resources potential of 690 bcm, ensure long-term sustainability of finite groundwater resources, and ensure proper operation and maintenance of water infrastructure with active participation of farmers/consumers. Work has restarted on many WRD projects that were stalled for a long time due to different reasons. Sanitation drive initiated by the government will also benefit the water sector immensely in future. River rejuvenation efforts are beginning to show some results. Attainment of identified goals is possible by developing and adopting appropriate technologies in the water sector and with greater involvement of public in WRD and management[12].

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CHAPTER 8

ANALYSIS TO PROBLEMS IN WATER RESOURCES ENGINEERING

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Over the centuries, surface and ground waters have been a source of water supplies for agricultural, municipal and industrial consumers. Rivers have provided hydroelectric energy and inexpensive ways of transporting bulk cargo between different ports along their banks, as well as water-based recreational opportunities, and have been a source of water for wildlife and its habitat. They have also served as a means of transporting and transforming waste products that are discharged into them. The quantity and quality regimes of streams and rivers have been a major factor in governing the type, health and biodiversity of riparian and aquatic ecosystems[1].

Floodplains have provided fertile lands for agricultural production and relatively flat lands for roads, railways and commercial and industrial complexes. In addition to the economic benefits that can be derived from rivers and their floodplains, the aesthetic beauty of most natural rivers has made lands adjacent to them attractive sites for residential and recreational development. Rivers and their floodplains have generated and, if managed properly, can continue to generate substantial economic, environmental and social benefits for their inhabitants. Human activities undertaken to increase the benefits obtained from rivers and their floodplains may also increase the potential for costs and damage when the river is experiencing rare or extreme flow conditions, such as during periods of drought, floods and heavy pollution.

These costs and impacts are economic, environmental and social in nature and result from a mismatch between what humans expect or demand, and what nature (and occasionally our own activities) offers or supplies. Human activities tend to be based on the ‘usual or normal’ range of river flow conditions. Rare or ‘extreme’ flow or water quality conditions outside these normal ranges will continue to occur, and possibly with increasing frequency as climate change experts suggest. River-dependent, human activities that cannot adjust to these occasional extreme conditions will incur losses. The planning of human activities involving rivers and their floodplains must consider certain hydrological facts. One of these facts is that flows and storage volumes vary over space and time. They are also finite. There are limits to the amounts of water that can be withdrawn from surface and groundwater bodies[2].

There are also limits to the amounts of potential pollutants that can be discharged into them without causing damage. Once these limits are exceeded, the concentrations of pollutants in these waters may reduce or even eliminate the benefits that could be obtained from other uses of the resource. Water resources professionals have learned how to plan, design, build and operate structures that, together with non-structural measures, increase the benefits people can obtain from the water resources contained in rivers and their drainage basins. However, there is a limit to the services one can expect from these resources. Rivers, estuaries and coastal zones under stress from overdevelopment and overuse cannot reliably meet the expectations of those depending on them. How can these renewable yet finite resources best be managed and used?

How can this be accomplished in an environment of uncertain supplies and uncertain and increasing demands, and consequently of increasing conflicts among individuals having different interests in the management of a river and its basin? The central purpose of water resources planning and management activities is to address and, if possible, answer these questions. These issues have scientific, technical, political (institutional) and social dimensions and thus, so must water resources planning processes and their products.

River basin, estuarine and coastal zone managers those responsible for managing the resources in those areas are expected to manage them effectively and efficiently, meeting the demands or expectations of all users and reconciling divergent needs. This is no small task, especially as demands increase, as the variability of hydrological and hydraulic processes becomes more pronounced, and as stakeholder measures of system performance increase in number and complexity. The focus or goal is no longer simply to maximize net economic benefits while ensuring the equitable distribution of those benefits. There are also environmental and ecological goals to consider.

Rarely are management questions one-dimensional, such as: ‘How can we provide more high-quality water to irrigation areas in the basin at acceptable costs?’ Now added to that question is how those withdrawals would affect the downstream water quantity and quality regimes, and in turn the riparian and aquatic ecosystems. Problems and opportunities change over time. Just as the goals of managing and using water change over time, so do the processes of planning to meet these changing goals. Planning processes evolve not only to meet new demands, expectations and objectives, but also in response to new perceptions of how to plan more effectively. This chapter is about how quantitative analysis, and in particular computer models, can support and improve water resources planning and management. This first chapter attempts to review some of the issues involved. It provides the context and motivation for the chapters that follow, which describe in more detail our understanding of ‘how to plan’ and ‘how to manage’ and how computer based programs and models can assist those involved in these activities[3].

Need for Planning and Management

Planning and management of water resources systems are essential due to following factors:

1. Severity of the adverse consequences of droughts, floods and excessive pollution. These can lead to:

a. Too little water due to growing urbanization, additional water requirements, in stream flow requirements etc. Measures should be taken to reduce the demand during scarcity times.

b. Too much water due to increased flood frequencies and also increase in water requirements due to increased economic development on river floodplains.

c. Polluted water due to both industrial and household discharges.

2. Degradation of aquatic and riparian systems due to river training and reclamation of floodplains for urban and industrial development, poor water quality due to discharges of pesticides, fertilizers and wastewater effluents etc.
3. While port development requires deeper rivers, narrowing the river for shipping purposes will increase the flood level.
4. River bank erosion and degradation of river bed upstream of the reservoirs may increase the flooding risks.
5. Sediment accumulation in the reservoir due to poor water quality. Considering all these factors, the identification and evaluation of alternative measures that may increase the quantitative and qualitative system performance is the primary goal of planning and management policies.

Planning and Management Approaches

Two approaches which lead to an integrated plan and management policy are:

i. From the top down or the command and control approach.
ii. From the bottom up or the grass-roots approach.

Top down Approach

Water resources professionals prepare integrated, multipurpose “master” development plans with alternative structural and non-structural management options. There is dominance of professionals and little participation of stakeholders. In this approach, one or more institutions have the ability and authority to develop and implement the plan. However, nowadays, since public have active participation in planning and management activities, top-down approaches are becoming less desirable or acceptable[4].

Bottom up Approach

In this approach there is active participation of interested stakeholders – those affected by the management of the water and land resources. Plans are being created from the bottom up rather than top down. Top down approach plans do not take into consideration the concerns of affected local stakeholders. Bottom up approach ensures cooperation and commitment from stakeholders. The goals and priorities will be common among all stakeholders by taking care of laws and regulations and by identifying multiple alternatives and performance criteria. Tradeoffs are made between conflicting goals or measures of performance.

Integrated Water Resources Management

According to global water partnership, integrated water resources management is a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of the vital ecosystems. An integrated water management model develops solutions by involving all the essential components into an optimization scheme. The resources are used in relation to social and economic activities and functions. There is a need for laws and regulations for the sustainable use of the water resources.

Dublin principles for a good water resources management as described by the United Nations Water Conference in 1977 are[5]:

- **a.** The "ecological principle" to treat water as a unitary resource within river basins, with particular attention to ecosystems.
- **b.** The "institutional principle" to respect the principle of subsidiarity through the involvement of government, civil society and the private sector.
- **c.** The "instrument principle" to recognize water as a scarce economic community by imposing various penalties for excessive usage.

A management policy must be developed only after considering the factors such as cost effectiveness, economic efficiency, environmental impact, ecological and health considerations etc[6], [7].

Planning and Management Aspects

Technical Aspects

It is first necessary to identify the characteristics of resources in the basin, including the land, the rainfall, the runoff, the stream and river flows and the groundwater Technical aspects of planning involves:

- **a.** Predicting changes in land use/covers and economic activities at watershed and river basin levels
- **b.** Estimation of the costs and benefits of any measures being and to be taken to manage the basin's water resource including engineering structures, canals, diversion structures
- **c.** Identification and evaluation of alternative management strategies and also alternative time schedules for implementing those measures

Economic and Financial aspects

Water should be treated as an economic commodity to extract the maximum benefits as well as to generate funds to recover the costs of the investments and of the operation and maintenance of the system. Water had been treated for long as a free commodity. Revenues recovered are far below the capital cost incurred. Financial component of any planning process is needed to recover construction costs, maintenance, and repair and operation costs. In management policies, financial viability is viewed as a constraint that must be satisfied; not as an objective whose maximization could result in a reduction in economic efficiency, equity or other non-monetary objectives[8].

Institutional Aspects

Successful project implementation needs an enabling environment. National, provincial and local policies, legislation and institutions are crucial for implementation of the decisions. The role of the government is crucial since water is:

- **a.** Not a property right
- **b.** A resource that often requires large investment to develop

c. A medium that can impulse external effects.

The main causes of failure of water resources development project are insufficient institutional setting and lack of a sound economic evaluation and implementation[9], [10].

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CHAPTER 9

ECONOMIC ANALYSIS OF WATER RESOURCES SYSTEM

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Although the term "engineering economics" might seem far removed from the business world, in reality every small-business owner is an engineering economist. For instance, any time you use a cost value comparison to decide between two alternatives for a project, capital purchase or potential investment, you're practicing engineering economics. It is important to understand the basics of engineering economics because no matter how sound a project, capital purchase or investment may seem, it will fail if it is not economically feasible. Engineering economics principles focus on the process used to make an economics-based decision, not on the decision itself. Engineering economics plays an important role for business owners because it helps identify the steps required to make well-thought out decisions such as whether to lease or purchase office space, invest in new computers or update existing ones, or provide customer service in-house or outsource the customer service department.

Seven Principles

Each of the seven principles of engineering economics moves you a step closer toward making an economics-related decision. The first two principles making a list of alternatives and identifying the differences between each alternative set up the thought process. The next three principles focus on evaluation criteria.

These include establishing consistent evaluation criteria, developing common performance measurements and considering all relevant monetary and non-monetary criteria. The final two principles focus on analysis. These include weighing risks against potential rewards and performance monitoring[1].

i. **Develop the Alternatives**

The final choice (decision) is among alternatives. The alternatives need to be identified and then defined for subsequent analysis.

ii. **Focus on the Differences**

Only the differences in expected future outcomes among the alternatives are relevant to their comparison and should be considered in the decision.

iii. **Use a Consistent Viewpoint**

The prospective outcomes of the alternatives, economic and other, should be consistently developed from a defined viewpoint (perspective).

iv. **Use a Common Unit of Measure**

Using a common unit of measurement to enumerate as many of the prospective outcomes as possible will make easier the analysis and comparison of alternatives.

v. Consider All Relevant Criteria

Selection of a preferred alternative (decision making) requires the use of a criterion (or several criteria).

vi. Make Uncertainty Explicit

Uncertainty is inherent in projecting or estimating the future outcomes of the alternatives and should be recognized in their analysis and comparison.

vii. Revisit Your Decisions

Improved decision making results from an adaptive process; to the extent practicable, the initial projected outcomes of the selected alternative should be subsequently compared with actual results achieved[2].

Engineering Economic Analysis Procedure

i. Problem recognition, definition, and evaluation
ii. Define the goal or objectives
iii. Define the feasible alternatives
iv. Collect all relevant data/information
v. Evaluate each alternative
vi. Select the "best" alternative
vii. Implement and monitor the decision

Principles in Action

The way you put the principles of engineering economics into action depends on what kind of decision you must make. For example, potential economic alternatives for an out-of-date computer network might include updating the current system or building a new system from scratch. During this process you might analyze how each alternative will affect the cost, expected performance and useful lifetime of the system to decide which alternative will provide the most value to the company. Evaluation criteria might include factors such as the purchase and installation costs, annual operating costs, maintenance costs and both principal and interest payments if you plan on using outside financing. Compare the risks of each alternative against potential economic and non-economic rewards. After making a decision, compare actual results to expectations.

Capital

In economics, capital consists of anything that can enhance a person's power to perform economically useful work. Capital goods, real capital, or capital assets are already-produced, durable goods or any non-financial asset that is used in production of goods or services. Adam Smith defines capital as "That part of a man's stock which he expects to afford him revenue". The term "stock" is derived from the Old English word for stump or tree trunk. It has been used to refer to all the moveable property of a farm since at least 1510. How a capital good is maintained or returned to its pre-production state varies with the type of capital involved. In most cases capital is replaced after a depreciation period as newer forms of capital make continued use of current capital non profitable. It is also possible that advances make an obsolete form of capital practical again[3].

Capital is distinct from land or non-renewable resources in that capital can be increased by human labour. At any given moment in time, total physical capital may be referred to as the capital stock which is not to be confused with the capital stock of a business entity.

In a fundamental sense, capital consists of anything that can enhance a person's power to perform economically useful work a stone or an arrow is capital for a caveman who can use it as a hunting instrument, and roads are capital for inhabitants of a city. Capital is an input in the production function. Homes and personal autos are not usually defined as capital but as durable goods because they are not used in a production of saleable goods and services.

In Marxian political economy, capital is money used to buy something only in order to sell it again to realize a financial profit. For Marx capital only exists within the process of economic exchange it is wealth that grows out of the process of circulation itself, and for Marx it formed the basis of the economic system of capitalism. In more contemporary schools of economics, this form of capital is generally referred to as "financial capital" and is distinguished from "capital goods".

Narrow and Broad Uses

Classical and neoclassical economics regard capital as one of the factors of production alongside the other factors: land and labour. All other inputs to production are called intangibles in classical economics. This includes organization, entrepreneurship, knowledge, goodwill, or management (which some characterize as talent, social capital or instructional capital). This is what makes it a factor of production:

i. The good is not used up immediately in the process of production unlike raw materials or intermediate goods. (The significant exception to this is depreciation allowance, which like intermediate goods, is treated as a business expense.)
ii. The good can be produced or increased (in contrast to land and non-renewable resources).

These distinctions of convenience have carried over to contemporary economic theory. There was the further clarification that capital is a stock. As such, its value can be estimated at a point in time. By contrast, investment, as production to be added to the capital stock, is described as taking place over time ("per year"), thus a flow[4].

Marxian economics distinguishes between different forms of capital:

i. Constant capital, which refers to capital goods.

ii. Variable capital which refers to labour-inputs, where the cost is "variable" based on the amount of wages and salaries are paid throughout the duration of an employee's contract/employment.

iii. Fictitious capital, which refers to intangible representations or abstractions of physical capital, such as stocks, bonds and securities (or "tradable paper claims to wealth").

Earlier illustrations often described capital as physical items, such as tools, buildings, and vehicles that are used in the production process. Since at least the 1960s economists have increasingly focused on broader forms of capital. For example, investment in skills and education can be viewed as building up human capital or knowledge capital, and investments in intellectual property can be viewed as building up intellectual capital. These terms lead to certain questions and controversies discussed in those articles.

Modern types of Capital

Detailed classifications of capital that have been used in various theoretical or applied uses generally respect the following division:

i. **Financial Capital**

It represents obligations, and is liquidated as money for trade and owned by legal entities. It is in the form of capital assets, traded in financial markets. Its market value is not based on the historical accumulation of money invested but on the perception by the market of its expected revenues and of the risk entailed.

ii. **Natural Capital**

It is inherent in ecologies and which increases the supply of human wealth.

iii. **Social Capital**

It in private enterprise is partly captured as goodwill or brand value, but is a more general concept of inter-relationships between human beings having money-like value that motivate actions in a similar fashion to paid compensation.

iv. **Instructional Capital**

It defined originally in academia as that aspect of teaching and knowledge transfer that is not inherent in individuals or social relationships but transferrable. Various theories use names like knowledge or intellectual capital to describe similar concepts but these are not strictly defined as in the academic definition and have no widely agreed accounting treatment.

v. **Human Capital**

It is a broad term that generally includes social, instructional and individual human talent in combination. It is used in technical economics to define balanced growth which is the goal of improving human capital as much as economic capital[5].

Public and private sector accounting differ in goals, time scales and accordingly in accounting. The ownership and control of some forms of capital may accordingly justify differentiating it in an economic theory. A blanket term that attempts to characterize all that clearly physical capital that is considered infrastructure and which supports production in unclear or poorly accounted ways is public capital. This encompasses the aggregate body of all government owned assets that are used to promote private industry productivity, including highways, railways, airports, water treatment facilities, telecommunications, electric grids, energy utilities, municipal buildings, public hospitals and schools, police, fire protection, courts and still others. However, it is a problematic term insofar as many of these assets can be either publicly or privately owned.

Separate literatures have developed to describe both natural capital and social capital. Such terms reflect a wide consensus that nature and society both function in such a similar manner as traditional industrial infrastructural capital, that it is entirely appropriate to refer to them as different types of capital in themselves. In particular, they can be used in the production of other goods, are not used up immediately in the process of production, and can be enhanced (if not created) by human effort. There is also a literature of intellectual capital and intellectual property law. However, this increasingly distinguishes means of capital investment, and collection of potential rewards for patent, copyright (creative or individual capital), and trademark (social trust or social capital) instruments[6].

Interest and Interest Rates

Interest is the charge for the privilege of borrowing money, typically expressed as annual percentage rate (APR). Interest can also refer to the amount of ownership a stockholder has in a company, usually expressed as a percentage.Two main types of interest can be applied to loans: simple and compound.

- **a.** Simple interest is a set rate on the principle originally lent to the borrower that the borrower has to pay for the ability to use the money.
- **b.** Compound interest is interest on both the principle and the compounding interest paid on that loan. The latter of the two types of interest is the most common. Some of the considerations that go into calculating the type of interest and the amount a lender will charge a borrower include:
    - Opportunity cost or the cost of the inability of the lender to use the money they're lending out.
    - Amount of expected inflation
    - Risk that the lender is unable to pay the loan back because of default
    - Length of time that the money is being lent
    - Possibility of government intervention on interest rates
    - Liquidity of the loan being made

A quick way to get a rough understanding of how long it will take in order for an investment to double is to use the rule of 72. Divide the number 72 by the interest rate, 72/4 for instance, and you'll double your investment in 18 years. An interest rate is the amount of interest due per period, as a proportion of the amount lent, deposited or borrowed called the principal sum. The total interest on an amount lent or borrowed depends on the principal sum, the interest rate, the compounding frequency, and the length of time over which it is lent, deposited or borrowed[7].It is defined as the proportion of an amount loaned which a lender charges as interest to the borrower, normally expressed as an annual percentage. It is the rate a bank or other lender charges to borrow its money, or the rate a bank pays its savers for keeping money in an account. Annual interest rate is the rate over a period of one year. Other interest rates apply over different periods, such as a month or a day, but they are usually annualized.

The Time Value of Money

Evaluation criteria establish measures of economic worth that make it possible to decide between two possible cost or investment alternatives. The alternative that provides the greatest return for the least cost or investment is usually the best solution. Common measures of worth include calculations based on the time value of money, a concept that uses time, interest rates and the investment amount to determine which alternative is the wisest decision. These calculations might include the rate of return, cost-benefit ratio, cost capitalization and present, future and annual worth. Their value lies in forcing you to consider long-term benefits and costs -- not just an initial purchase price or investment.

Depreciation

In economics, depreciation is the gradual decrease in the economic value of the capital stock of a firm, nation or other entity, either through physical depreciation, obsolescence or changes in the demand for the services of the capital in question. The net increment to the capital stock is the difference between gross investment and depreciation, and is called net investment[8].

Differences between Tangible and Intangible Assets

Economic depreciation is different than the depreciation recognized for tangible assets as those assets are used to create revenue. While land does not depreciate, buildings and other tangible assets do recognize depreciation, which is the decline in value of a physical asset as the asset is used over time. Assume, for example, that a roofing company uses a truck to perform residential roofing work, and that the truck is used for seven years. As the truck is used each year to generate revenue, the company also posts depreciation expense for the decline in value of the asset. Intangible assets, such as a patent or other intellectual property, do not depreciate in value.

Factoring in Liquidity

Real estate's lack of liquidity makes the impact of economic depreciation more profound for the owner. Liquidity refers to the ability of an owner to sell an asset, and assets that sell on exchanges, such as stocks and bonds, are more liquid than real estate and other assets. If, for example, an investor wants to sell 100 shares of IBM common stock, that investor can check the bid price on a stock exchange and place a trade to sell the stock on any business day. Real estate, on the other hand, requires the seller to find a buyer, and the two parties must negotiate until the parties agree on a price. In addition, the sale normally requires an appraisal of the property, and a real estate sale can take months to complete.

Economic and Financial Evaluation

Financial management involves planning, allocation and control of financial resources of a company. Financial management is essential as it controls the financial operations of a company. For a construction company, the decision to bid for a project will depend on its financial status which in turn will be governed by financial management principles. The decision to bid for a project will depend on various factors namely whether the company have enough funds or require outside financing, whether to acquire the equipment through purchase or acquisition through renting or leasing, whether to carry out the entire work or subcontract a portion of the work etc. If the company uses its own funds for the project, it may have an adverse effect on its financial status as it will reduce the liquid asset thus affecting company's working capital[9].

The construction industry differs from other industries because of its unique characteristics and accordingly the financial management principles are applied for using the financial resources of the company. Generally, the construction companies receive the payments from the owners at specified time intervals as the construction work progresses and owners often retain certain amount subject to the satisfactory completion of the project. Thus the terms and conditions for receipt of payments from owners affect the cash flow of the construction companies and need the changes in allocation of financial resources.

Further construction companies often subcontract some portion of the work (as required) to the subcontractors, which in turn affect the cash flow. The financial management decisions include the decisions for investment, financing and distribution of earnings. For construction companies the investment decisions relate to investment in the business i.e. investment of funds in acquiring the assets (both current assets and long-term assets) to be utilized in the projects for the expected return along with the risk of cash flows associated with uncertain future conditions. The financing decisions depend on decision to investment the funds and the resources possessed by the construction companies.

In addition the financing decisions are also controlled by other factors namely source of financing (from banks or other financial institutions), cost of financing i.e. interest cost on the loan and the financing duration. The decision for distribution of earnings or profits of the company depends on the dividends to be paid to the stockholders and the retained earnings to be reinvested in the business to increase the return. Thus for any company or organization, financial management has to ensure the supply of funds in acquiring the assets and their effective utilization in business activities, to ensure the expected return on the investment considering the risk associated and optimal.

Benefit Cost Evaluation and Discounting Techniques

Quantifying alternatives for any item is the most important aspect of decision making for selecting the best option. For example, a construction company is planning to purchase a new concrete mixer for preparing concrete at a construction site. Let's say there are two alternatives available for purchasing the mixer[10], [11]:

a. An automatic concrete mixer

b. A semi-automatic concrete mixer.

Then the task is to find out best alternative that the company will purchase that will yield more profit. For this purpose one has to quantify both the alternatives by the following parameters:

- This initial cost that includes purchase price, sales tax, cost of delivery and cost of assembly and installation
- Annual operating cost
- Annual profit which will depend on the productivity i.e. quantity of concrete prepared
- The expected useful life
- The expected salvage values
- Other expenditure or income associated with the equipment
- Income tax benefit

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CHAPTER 10

THE HYDROLOGIC CYCLE AND INTERACTIONS OF GROUND WATER AND SURFACE WATER

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The hydrologic cycle describes the continuous movement of water above, on, and below the surface of the Earth. The water on the Earth's surface water occurs as streams, lakes, and wetlands, as well as bays and oceans. Surface water also includes the solid forms of water snow and ice. The water below the surface of the Earth primarily is ground water, but it also includes soil water. The hydrologic cycle commonly is portrayed by a very simplified diagram that shows only major transfers of water between continents and oceans, as in Figure 1. However, for understanding hydrologic processes and managing water resources, the hydrologic cycle needs to be viewed at a wide range of scales and as having a great deal of variability in time and space.

Precipitation, which is the source of virtually all freshwater in the hydrologic cycle, falls nearly everywhere, but its distribution is highly variable. Similarly, evaporation and transpiration return water to the atmosphere nearly everywhere, but evaporation and transpiration rates vary considerably according to climatic conditions. As a result, much of the precipitation never reaches the oceans as surface and subsurface runoff before the water is returned to the atmosphere. The relative magnitudes of the individual components of the hydrologic cycle, such as evapotranspiration, may differ significantly even at small scales, as between an agricultural field and a nearby woodland[1].

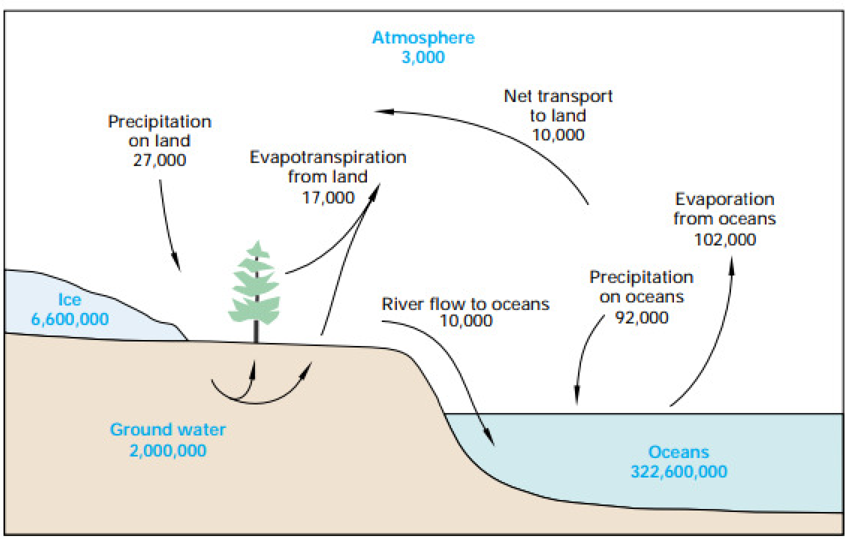

Figure 1: Shows Only Major Transfers of Water between Continents and Oceans

To present the concepts and many facets of the interaction of ground water and surface water in a unified way, a conceptual landscape is used. The conceptual landscape shows in a very general and simplified way the interaction of ground water with all types of surface water, such as streams, lakes, and wetlands, in many different terrains from the mountains to the oceans. The intent is to emphasize that ground water and surface water interact at many places throughout the landscape. Movement of water in the atmosphere and on the land surface is relatively easy to visualize, but the movement of ground water is not. Concepts related to ground water and the movement of ground water are introduced in Box A. As illustrated in Figure 2, ground water moves along flow paths of varying lengths from areas of recharge to areas of discharge. The generalized flow paths in Figure 3 start at the water table, continue through the ground-water system, and terminate at the stream or at the pumped well. The source of water to the water table (ground-water recharge) is infiltration of precipitation through the unsaturated zone.

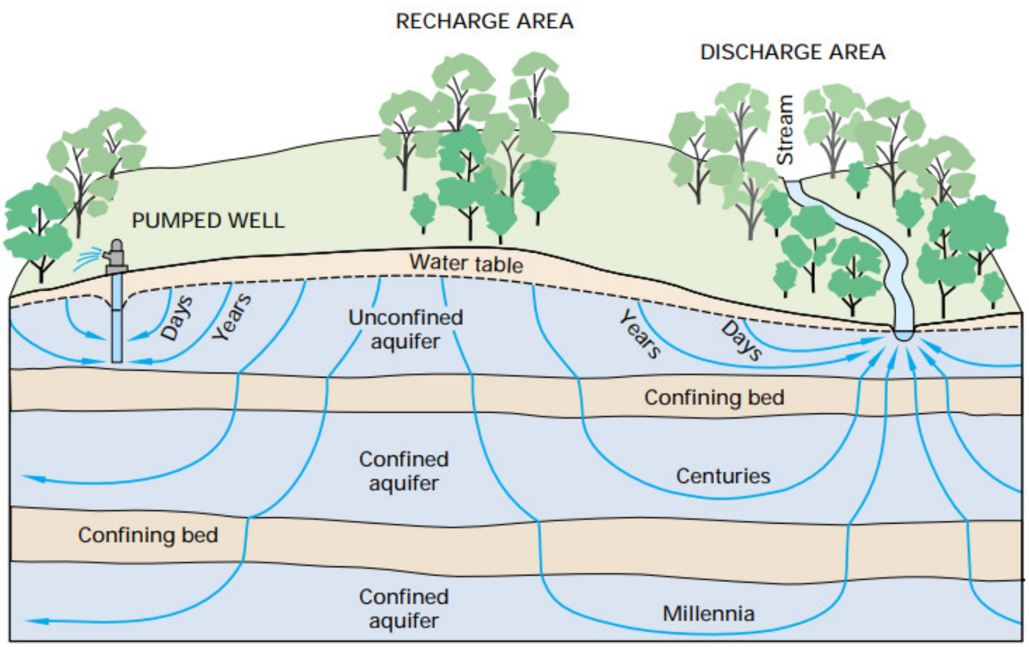

Figure 2: Represented the Ground-water flow paths vary greatly in length, depth, and travel time

In the uppermost, unconfined aquifer, flow paths near the stream can be tens to hundreds of feet in length and have corresponding travel times of days to a few years. The longest and deepest flow paths in Figure 3 may be thousands of feet to tens of miles in length, and travel times may range from decades to millennia. In general, shallow ground water is more susceptible to contamination from human sources and activities because of its close proximity to the land surface. Therefore, shallow, local patterns of ground-water flow near surface water are emphasized in this Circular[2].

Concepts of Ground Water, Water Table, and Flow Systems

Subsurface Water

Water beneath the land surface occurs in two principal zones, the unsaturated zone and the saturated zone as display in Figure 3. In the unsaturated zone, the voids that is, the spaces between grains of gravel, sand, silt, clay, and cracks within rocks contain both air and water. Although a considerable amount of water can be present in the unsaturated zone, this water cannot be pumped by wells because it is held too tightly by capillary forces. The upper part of the unsaturated zone is the soil-water zone.

The soil zone is crisscrossed by roots, voids left by decayed roots, and animal and worm burrows, which enhance the infiltration of precipitation into the soil zone. Soil water is used by plants in life functions and transpiration, but it also can evaporate directly to the atmosphere.

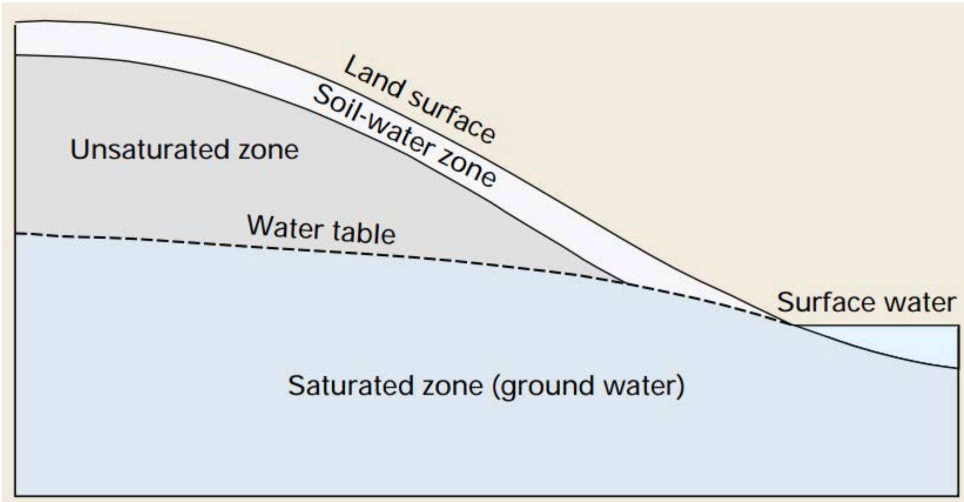

Figure 3: Represented the water table is the upper surface of the saturated zone.

In contrast to the unsaturated zone, the voids in the saturated zone are completely filled with water. Water in the saturated zone is referred to as ground water. The upper surface of the saturated zone is referred to as the water table. Below the water table, the water pressure is great enough to allow water to enter wells, thus permitting ground water to be withdrawn for use. A well is constructed by inserting a pipe into a drilled hole; a screen is attached, generally at its base, to prevent earth materials from entering the pipe along with the water pumped through the screen. The depth to the water table is highly variable and can range from zero, when it is at land surface, to hundreds or even thousands of feet in some types of landscapes. Usually, the depth to the water table is small near permanent bodies of surface water such as streams, lakes, and wetlands. An important characteristic of the water table is that its configuration varies seasonally and from year to year because groundwater recharge, which is the accretion of water to the upper surface of the saturated zone, is related to the wide variation in the quantity, distribution, and timing of precipitation[3].

The Water Table

The depth to the water table can be determined by installing wells that penetrate the top of the saturated zone just far enough to hold standing water. Preparation of a water-table map requires that only wells that have their well screens placed near the water table be used. If the depth to water is measured at a number of such wells throughout an area of study, and if those water levels are referenced to a common datum such as sea level, the data can be contoured to indicate the configuration of the water table as display in Figure 4.

In addition to various practical uses of a water-table map, such as estimating an approximate depth for a proposed well, the configuration of the water table provides an indication of the approximate direction of ground-water flow at any location on the water table. Lines drawn perpendicular to water-table contours usually indicate the direction of ground-water flow along the upper surface of the ground-water system. The water table is continually adjusting to changing recharge and discharge patterns. Therefore, to construct a water-table map, water-level measurements must be made at approximately the same time, and the resulting map is representative only of that specific time[4].

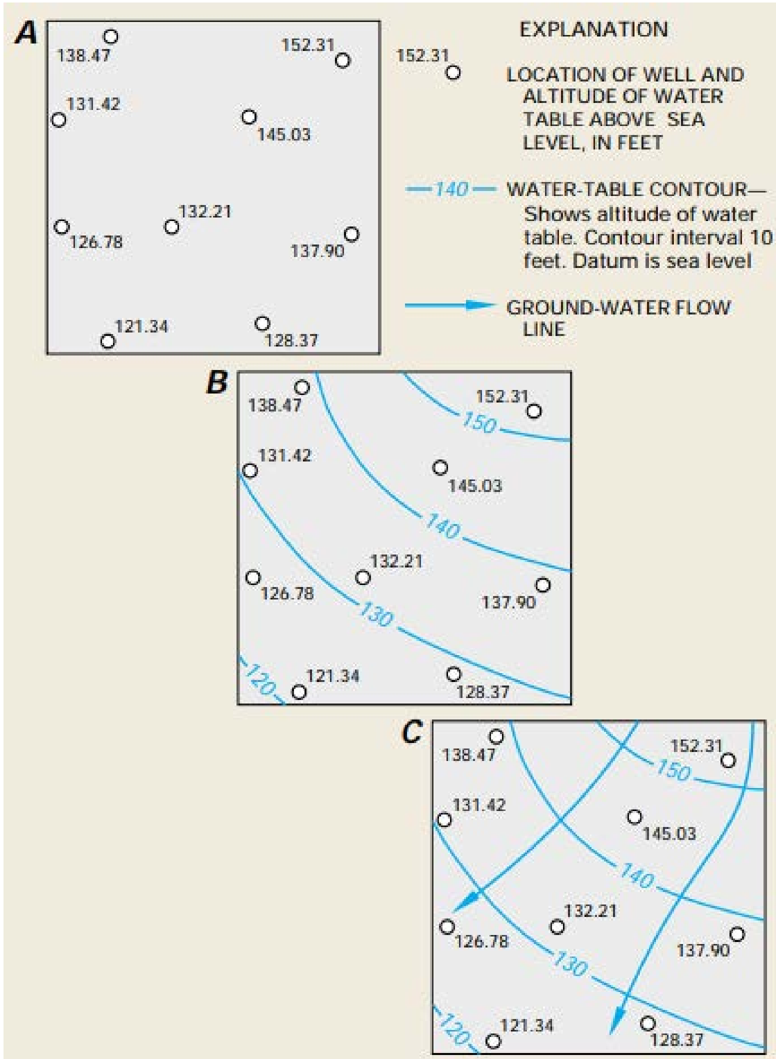

Figure 4: Illustrated the water table at individual wells (A), contour maps of the water-table surface can be drawn (B), and directions of ground-water flow along the water table can be determined (C) because flow usually is approximately perpendicular to the contours.

Ground-Water Movement

The ground-water system as a whole is actually a three-dimensional flow field; therefore, it is important to understand how the vertical components of ground-water movement affect the interaction of ground water and surface water. A vertical section of a flow field indicates how potential energy is distributed beneath the water table in the ground-water system and how the energy distribution can be used to determine vertical components of flow near a surface-water body. The term hydraulic head, which is the sum of elevation and water pressure divided by the weight density of water, is used to describe potential energy in ground-water flow systems. For example, Figure 5 shows a generalized vertical section of subsurface water flow. Water that infiltrates at land surface moves vertically downward to the water table to become ground water. The ground water then moves both vertically and laterally within the ground-water system. Movement is downward and lateral on the right side of the diagram, mostly lateral in the center, and lateral and upward on the left side of the diagram.

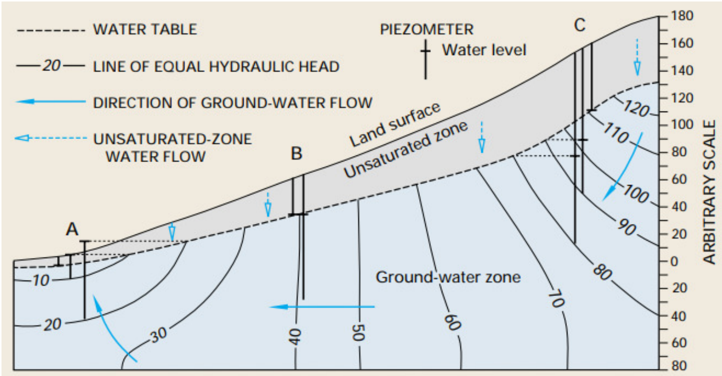

Figure 5: Illustrated the generalized vertical section of subsurface water flow.

Actual flow fields generally are much more complex than that shown in Figure 6. For example, flow systems of different sizes and depths can be present, and they can overlie one another. In a local flow system, water that recharges at a water-table high discharges to an adjacent lowland. Local flow systems are the most dynamic and the shallowest flow systems; therefore, they have the greatest interchange with surface water. Local flow systems can be underlain by intermediate and regional flow systems. Water in deeper flow systems have longer flow paths and longer contact time with subsurface materials; therefore, the water generally contains more dissolved chemicals. Nevertheless, these deeper flow systems also eventually discharge to surface water, and they can have a great effect on the chemical characteristics of the receiving surface water[5].

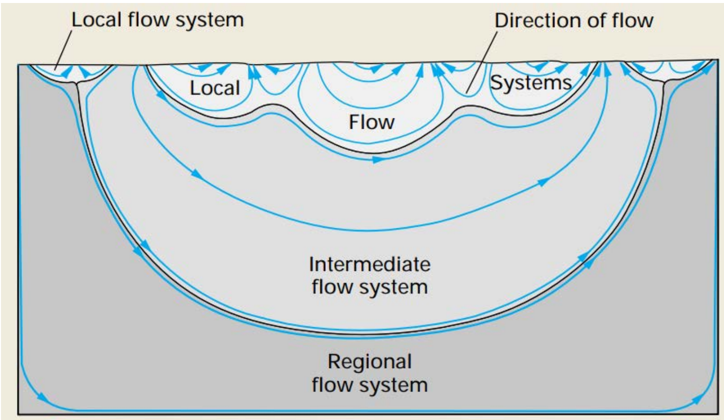

Figure 6: Illustrated the Ground-water flow systems can be local, intermediate, and regional in scale.

Ground-Water Discharge

The quantity of ground-water discharge (flux) to and from surface-water bodies can be determined for a known cross section of aquifer by multiplying the hydraulic gradient, which is determined from the hydraulic-head measurements in wells and piezometers, by the permeability of the aquifer materials. Permeability is a quantitative measure of the ease of water movement through aquifer materials. For example, sand is more permeable than clay because the pore spaces between sand grains are larger than pore spaces between clay particles.

Changing meteorological conditions also strongly affect seepage patterns in surface-water beds, especially near the shoreline. The water table commonly intersects land surface at the shoreline, resulting in no unsaturated zone at this point. Infiltrating precipitation passes rapidly through a thin unsaturated zone adjacent to the shoreline, which causes water-table mounds to form quickly adjacent to the surface water. This process, termed focused recharge, can result in increased ground-water inflow to surface-water bodies, or it can cause inflow to surface-water bodies that normally have seepage to ground water. Each precipitation event has the potential to cause this highly transient flow condition near shorelines as well as at depressions in uplands as display in Figure 7[6].

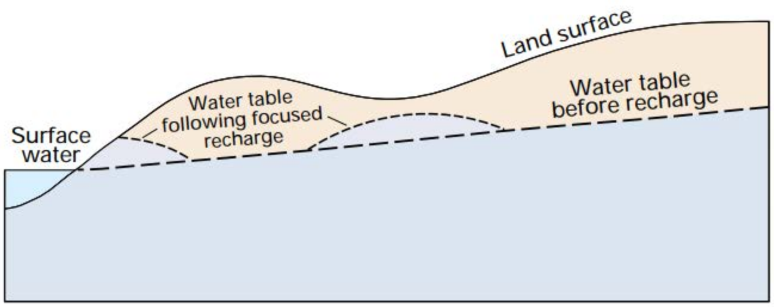

Figure 7: Represented the Ground Water Recharge Commonly is Focused Initially

Transpiration by near shore plants has the opposite effect of focused recharge. Again, because the water table is near land surface at edges of surface-water bodies, plant roots can penetrate into the saturated zone, allowing the plants to transpire water directly from the ground water system as display in Figure 8. Transpiration of ground water commonly results in a drawdown of the water table much like the effect of a pumped well. This highly variable daily and seasonal transpiration of ground water may significantly reduce ground-water discharge to a surface-water body or even cause movement of surface water into the subsurface.

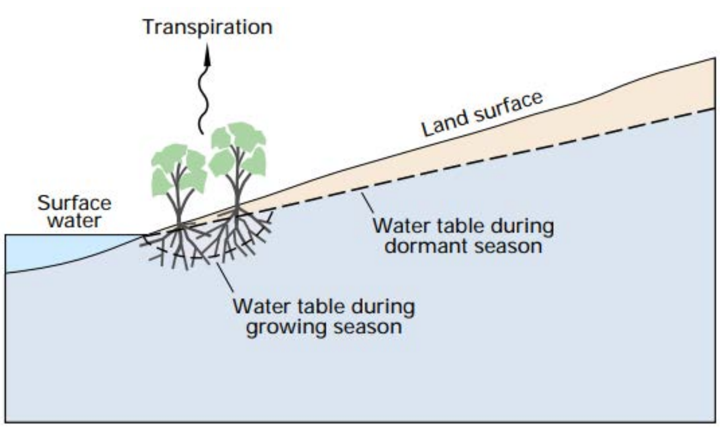

Figure 8: Illustrated the depth to the water table is small adjacent to surface-water bodies, transpiration directly from ground water.

In many places it is possible to measure diurnal changes in the direction of flow during seasons of active plant growth; that is, ground water moves into the surface water during the night, and surface water moves into shallow ground water during the day. These periodic changes in the direction of flow also take place on longer time scales: focused recharge from precipitation predominates during wet periods and drawdown by transpiration predominates during dry periods. As a result, the two processes, together with the geologic controls on seepage distribution, can cause flow conditions at the edges of surface-water bodies to be extremely variable. These "edge effects" probably affect small surface-water bodies more than large surface-water bodies because the ratio of edge length to total volume is greater for small water bodies than it is for large ones.

Interaction of Ground Water and Streams

Streams interact with ground water in all types of landscapes. The interaction takes place in three basic ways: streams gain water from inflow of ground water through the streambed gaining stream, as mention in Figure 9, they lose water to ground water by outflow through the streambed losing stream, as mention in Figure 10, or they do both, gaining in some reaches and losing in other reaches[7].

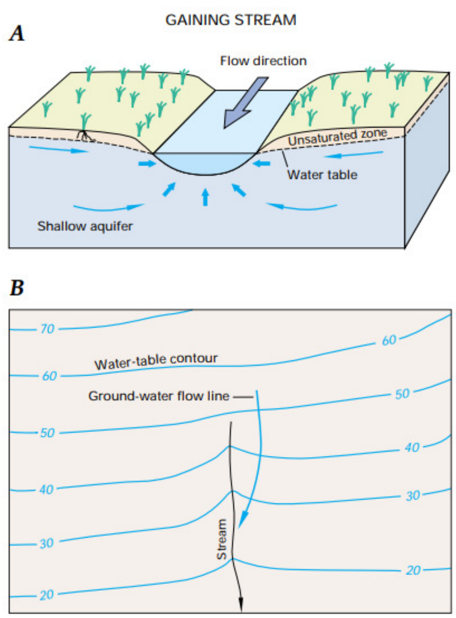

Figure 9: Represented the Gaining streams receive water from the ground-water system (A). This can be determined from water-table contour maps because the contour lines point in the upstream direction where they cross the stream (B).

For ground water to discharge into a stream channel, the altitude of the water table in the vicinity of the stream must be higher than the altitude of the stream-water surface. Conversely, for surface water to seep to ground water, the altitude of the water table in the vicinity of the stream must be lower than the altitude of the stream-water surface. Contours of water-table elevation indicate gaining streams by pointing in an upstream direction (Figure 9B), and they indicate losing streams by pointing in a downstream direction (Figure 10B) in the immediate vicinity of the stream. Losing streams can be connected to the ground-water system by a continuous saturated zone (Figure 9A) or can be disconnected from the ground-water system by an unsaturated zone. Where the stream is disconnected from the ground water system by an unsaturated zone, the water table may have a discernible mound below the stream if the rate of recharge through the streambed and unsaturated zone is greater than the rate of lateral ground-water flow away from the water-table mound. An important feature of streams that are disconnected from ground water is that pumping of shallow ground water near the stream does not affect the flow of the stream near the pumped wells[8].The ground-water system by an unsaturated zone. Where the stream is disconnected from the ground water system by an unsaturated zone, the water table may have a discernible mound below the stream as shown Figure 11.

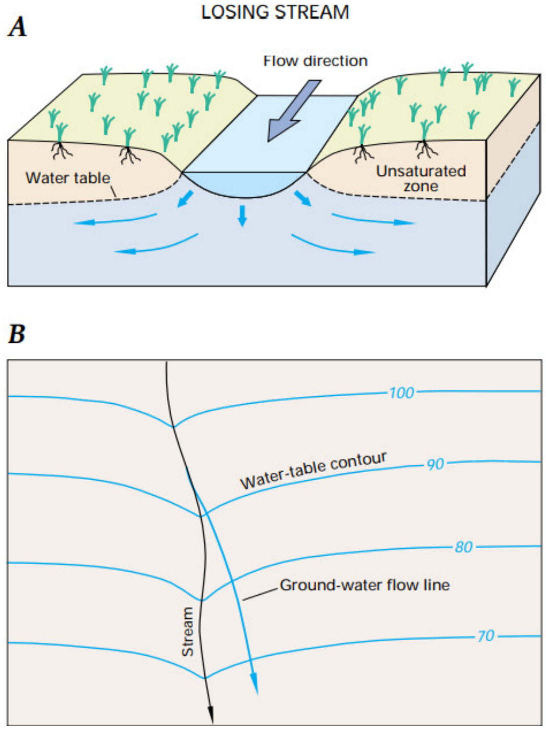

Figure 10: Illustrated the Losing streams lose water to the ground-water system (A). This can be determined from water-table contour maps because the contour lines point in the downstream direction where they cross the stream (B).

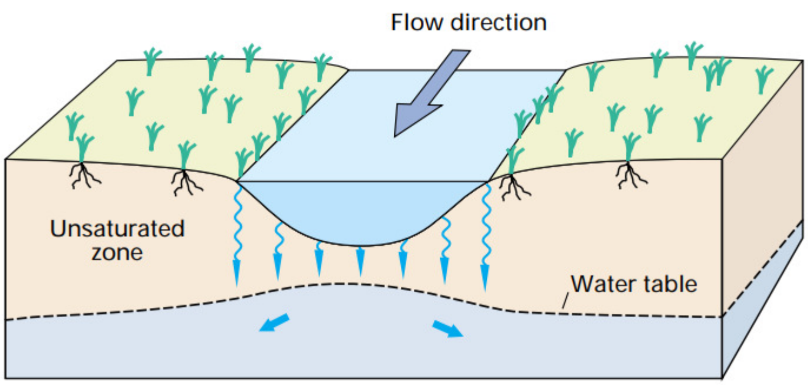

Figure11: Illustrated the disconnected streams are separated from the ground-water system by an unsaturated zone.

If the rate of recharge through the streambed and unsaturated zone is greater than the rate of lateral ground-water flow away from the water-table mound. An important feature of streams that are disconnected from ground water is that pumping of shallow ground water near the stream does not affect the flow of the stream near the pumped wells. In some environments, stream flow gain or loss can persist; that is, a stream might always gain water from ground water, or it might always lose water to ground water. However, in other environment, flow direction can vary a great deal along a stream; some reaches receive ground water, and other reaches lose water to ground water. Furthermore, flow direction can change in very short timeframes as a result of individual storms causing focused recharge near the stream bank, temporary flood peaks moving down the channel, or transpiration of ground water by streamside vegetation. A type of interaction between ground water and streams that takes place in nearly all streams at one time or another is a rapid rise in stream stage that causes water to move from the stream into the stream banks. This process, termed bank storage as display in Figure 12, usually is caused by storm precipitation, rapid snowmelt, or release of water from a reservoir upstream[9].

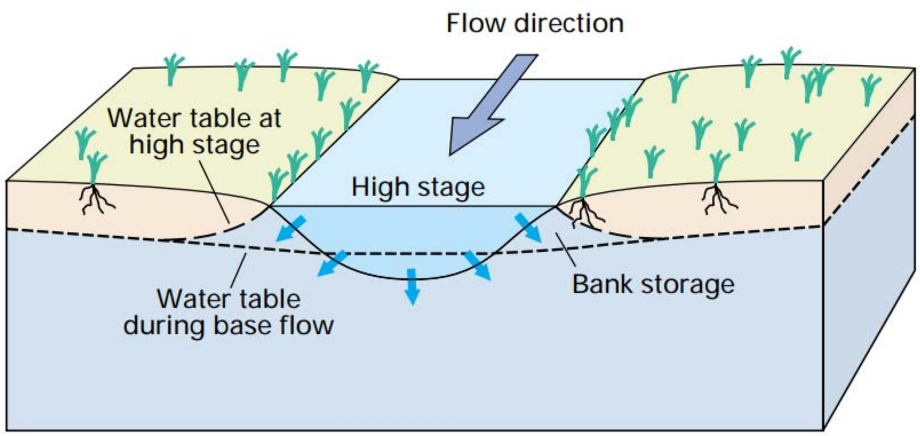

Figure 12: Represented the If stream levels rise higher than adjacent ground-water levels, stream water moves into the stream banks as bank storage.

As long as the rise in stage does not overtop the stream banks, most of the volume of stream water that enters the stream banks returns to the stream within a few days or weeks. The loss of stream water to bank storage and return of this water to the stream in a period of days or weeks tends to reduce flood peaks and later supplement stream flows. If the rise in stream stage is sufficient to overtop the banks and flood large areas of the land surface, widespread recharge to the water table can take place throughout the flooded area as display in Figure 13. In this case, the time it takes for the recharged floodwater to return to the stream by ground-water flow may be weeks, months, or years because the lengths of the ground water flow paths are much longer than those resulting from local bank storage. Depending on the frequency, magnitude, and intensity of storms and on the related magnitude of increases in stream stage, some streams and adjacent shallow aquifers may be in a continuous readjustment from interactions related to bank storage and overbank flooding. In addition to bank storage, other processes may affect the local exchange of water between streams and adjacent shallow aquifers[10].

The Ground-Water Component of Stream flow

Ground water contributes to streams in most physiographic and climatic settings. Even in settings where streams are primarily losing water to ground water, certain reaches may receive ground-water inflow during some seasons. The proportion of stream water that is derived from ground-water inflow varies across physiographic and climatic settings. The amount of water that ground water contributes to streams can be estimated by analyzing stream flow hydrographs to determine the ground-water component, which is termed base flow. Several different methods of analyzing hydrographs have been used by hydrologists to determine the base flow component of stream flow.

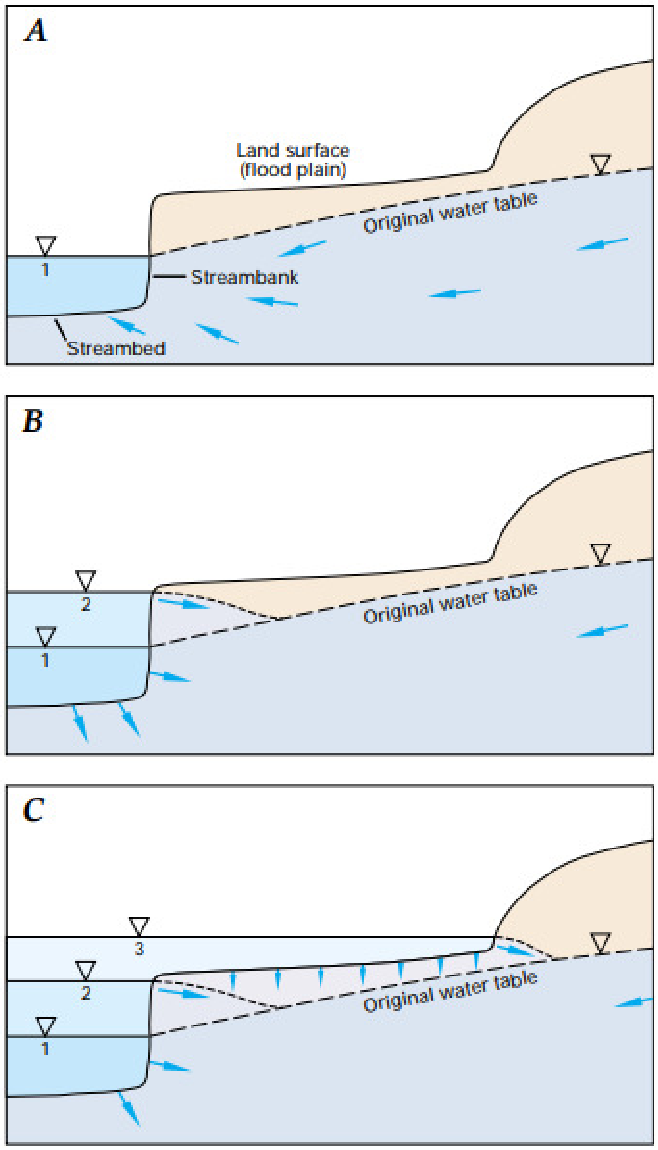

Figure 13: Illustrated the If stream levels rise higher than their stream banks

One of the methods, which provides a conservative estimate of base flow, was used to determine the groundwater contribution to stream flow in 24 regions in the conterminous United States. The regions, delineated on the basis of physiography and climate, are believed to have common characteristics with respect to the interactions of ground water and surface water. Fifty-four streams were selected for the analysis, at least two in each of the 24 regions. Streams were selected that had drainage basins less than 250 square miles and that had less than 3% of the drainage area covered by lakes and wetlands. Daily streamflow values for the 30-year period, 1961–1990, were used for the analysis of each stream. The analysis indicated that, for the 54 streams over the 30-year period, an average of 52% of the streamflow was contributed by ground water. Ground-water contributions ranged from 14 percent to 90 percent, and the median was 55%. As an example of the effect that geologic setting has on the contribution of ground water to streamflow, the Forest River in North Dakota can be compared to the Sturgeon River in Michigan. The Forest River Basin is underlain by poorly permeable silt and clay deposits, and only about 14% of its average annual flow is contributed by ground water; in contrast, the Sturgeon River Basin is underlain by highly permeable sand and gravel, and about 90 percent of its average annual flow is contributed by ground water[11].

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CHAPTER 11

THE EFFECT OF GROUND-WATER WITHDRAWALS ON SURFACE WATER

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Withdrawing water from shallow aquifers that are directly connected to surface-water bodies can have a significant effect on the movement of water between these two water bodies. The effects of pumping a single well or a small group of wells on the hydrologic regime are local in scale. However, the effects of many wells withdrawing water from an aquifer over large areas may be regional in scale. Withdrawing water from shallow aquifers for public and domestic water supply, irrigation, and industrial uses is widespread. Withdrawing water from shallow aquifers near surface-water bodies can diminish the available surface-water supply by capturing some of the ground-water flow that otherwise would have discharged to surface water or by inducing flow from surface water into the surrounding aquifer system. An analysis of the sources of water to a pumping well in a shallow aquifer that discharges to a stream is provided here to gain insight into how a pumping well can change the quantity and direction of flow between the shallow aquifer and the stream. Furthermore, changes in the direction of flow between the two water bodies can affect transport of contaminants associated with the moving water. Although a stream is used in the example, the results apply to all surface-water bodies, including lakes and wetlands. A ground-water system under predevelopment conditions is in a state of dynamic equilibrium—for example, recharge at the water table is equal to ground-water discharge to a stream as display in Figure 1 A. Assume a well is installed and is pumped continually at a rate, Q1.

After a new state of dynamic equilibrium is achieved, inflow to the ground-water system from recharge will equal outflow to the stream plus the withdrawal from the well. In this new equilibrium, some of the ground water that would have discharged to the stream is intercepted by the well, and a ground-water divide, which is a line separating directions of flow, is established locally between the well and the stream as displaying Figure 1 B. If the well is pumped at a higher rate, Q2, at a later time a new equilibrium is reached. Under this condition, the ground-water divide between the well and the stream is no longer present and withdrawals from the well induce movement of water from the stream into the aquifer as display in Figure 1 C. Thus, pumpage reverses the hydrologic condition of the stream in this reach from a ground-water discharge feature to a ground-water recharge feature. In the hydrologic system depicted the quality of the stream water generally will have little effect on the quality of the shallow ground water. However, in the case of the well pumping at the higher rate, Q2, the quality of the stream water, which locally recharges the shallow aquifer, can affect the quality of ground water between the well and the stream as well as the quality of the ground water withdrawn from the well. This hypothetical withdrawal of water from a shallow aquifer that discharges to a nearby surface-water body is a simplified but compelling illustration of the concept that ground water and surface water are one resource. In the long term, the quantity of ground water withdrawn is approximately equal to the reduction in streamflow that is potentially available to downstream users[1].

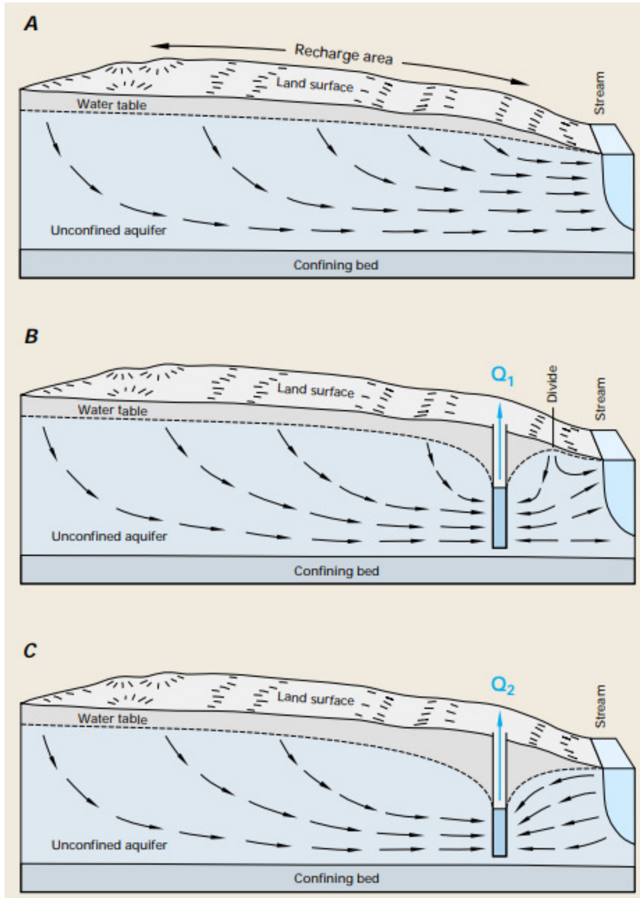

Figure 1: Represented the schematic hydrologic setting where ground water discharges to a stream under natural conditions (A), placement of a well pumping at a rate (Q1) near the stream will intercept part of the ground water that would have discharged to the stream (B). If the well is pumped at an even greater rate (Q2), it can intercept additional water that would have discharged to the stream in the vicinity of the well and can draw water from the stream to the well (C).

Where streamflow is generated in head waters areas, the changes in streamflow between gaining and losing conditions may be particularly variable as display in Figure 2. The headwaters segment of streams can be completely dry except during storm events or during certain seasons of the year when snowmelt or precipitation is sufficient to maintain continuous flow for days or weeks. During these times, the stream will lose water to the unsaturated zone beneath its bed. However, as the water table rises through recharge in the headwaters area, the losing reach may become a gaining reach as the water table rises above the level of the stream. Under these conditions, the point where ground water first contributes to the stream gradually moves upstream. Some gaining streams have reaches that lose water to the aquifer under normal conditions of streamflow. The direction of seepage through the bed of these streams commonly is related to abrupt changes in the slope of the streambed as mentioned in Figure 2 A or to meanders in the stream channel which is display in Figure 2 B. For example, a losing stream reach usually is located at the downstream end of pools in pool and riffle streams, or upstream from channel bends in meandering streams[2], [3]. The subsurface zone where stream water flows through short segments of its adjacent bed and banks is referred to as the hypothetic zone.

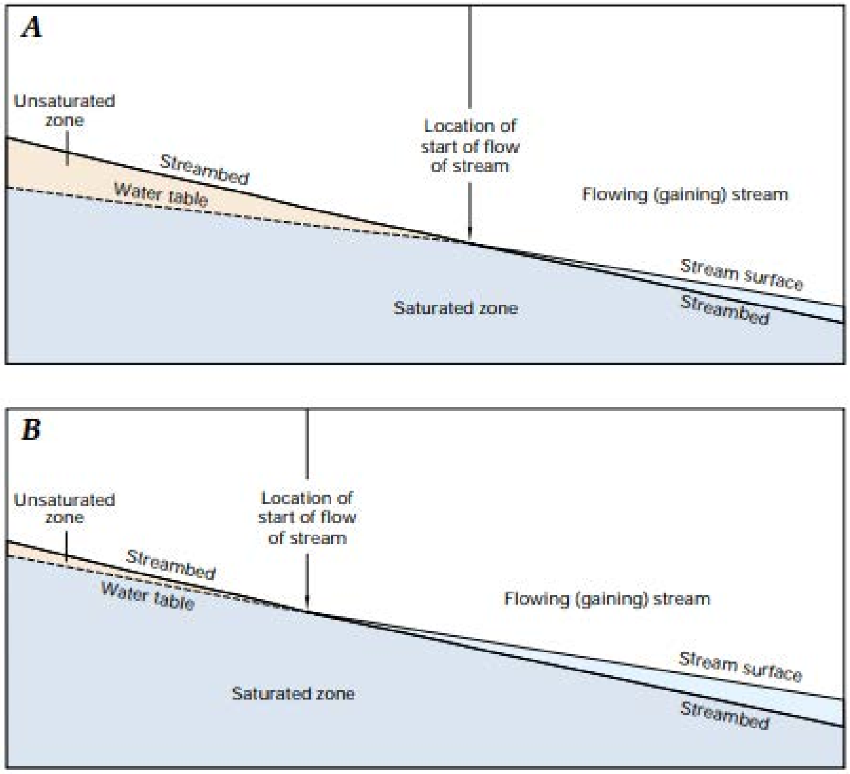

Figure 2: Illustrated the location where perennial streamflow begins in a channel can vary depending on the distribution of recharge in headwaters areas. Following dry periods (A), the start of streamflow will move up channel during wet periods as the ground-water system becomes more saturated (B).

The size and geometry of hyporheic zones surrounding streams vary greatly in time and space. Because of mixing between ground water and surface water in the hyporheic zone, the chemical and biological character of the hyporheic zone may differ markedly from adjacent surface water and ground water. Ground-water systems that discharge to streams can underlie extensive areas of the land surfaces display in Figure 3. As a result, environmental conditions at the interface between ground water and surface water reflect changes in the broader landscape. For example, the types and numbers of organisms in a given reach of streambed result, in part, from interactions between water in the hyporheic zone and ground water from distant sources[4].

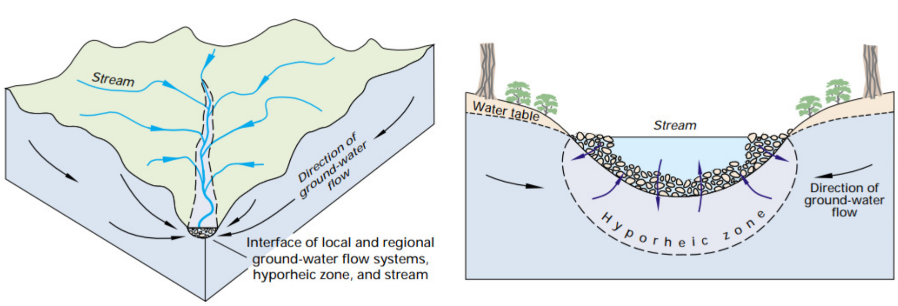

Figure 3: Illustrated the Streambeds and banks are unique environments because they are where ground water that drains much of the subsurface of landscapes interacts with surface water that drains much of the surface of landscapes.

Interaction of Ground Water and Lakes

Lakes interact with ground water in three basic ways: some receive ground-water inflow throughout their entire bed; some have seepage loss to ground water throughout their entire bed; but perhaps most lakes receive ground water inflow through part of their bed and have seepage loss to ground water through other parts as display in Figure 4. Although these basic interactions are the same for lakes as they are for streams, the interactions differ in several ways. The water level of natural lakes, that is, those not controlled by dams, generally does not change as rapidly as the water level of streams; therefore, bank storage is of lesser importance in lakes than it is in streams. Evaporation generally has a greater effect on lake levels than on stream levels because the surface area of lakes is generally larger and less shaded than many reaches of streams, and because lake water is not replenished as readily as a reach of a stream. Lakes can be present in many different parts of the landscape and can have complex ground-water flow systems associated with them. This is especially true for lakes in glacial and dune terrain, as is discussed in a later section of this Circular. Furthermore, lake sediments commonly have greater volumes of organic deposits than streams. These poorly permeable organic deposits can affect the distribution of seepage and biogeochemical exchanges of water and solutes more in lakes than in streams[5].

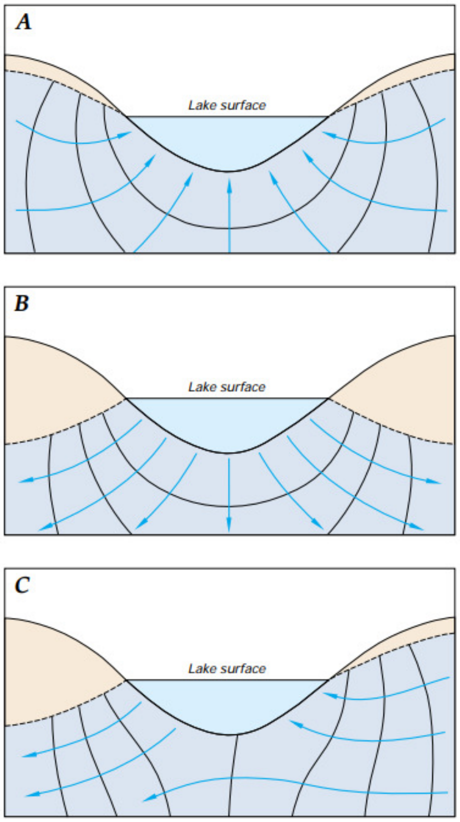

Figure 4: Illustrated the (A) Lakes can receive ground-water inflow, (B) lose water as seepage to ground water, (C) or both

Reservoirs are human-made lakes that are designed primarily to control the flow and distribution of surface water. Most reservoirs are constructed in stream valleys; therefore, they have some characteristics both of streams and lakes. Like streams, reservoirs can have widely fluctuating levels, bank storage can be significant, and they commonly have a continuous flushing of water through them. Like lakes, reservoirs can have significant loss of water by evaporation, significant cycling of chemical and biological materials within their waters, and extensive biogeochemical exchanges of solutes with organic sediments.

Interaction of Ground Water and Wetlands

Wetlands are present in climates and landscapes that cause ground water to discharge to land surface or that prevent rapid drainage of water from the land surface. Similar to streams and lakes, wetlands can receive ground-water inflow, recharge ground water, or do both. Those wetlands that occupy depressions in the land surface have interactions with ground water similar to lakes and streams.

Unlike streams and lakes, however, wetlands do not always occupy low points and depressions in the landscape; they also can be present on slopes (such as fens) or even on drainage divides (such as some types of bogs). Fens are wetlands that commonly receive groundwater discharge; therefore, they receive a continuous supply of chemical constituents dissolved in the ground water. Bogs are wetlands that occupy uplands or extensive flat areas, and they receive much of their water and chemical constituents from precipitation. The distribution of major wetland areas in the United States. In areas of steep land slopes, the water table sometimes intersects the land surface, resulting in ground-water discharge directly to the land surface. The constant source of water at these seepage faces permits the growth of wetland plants. A constant source of ground water to wetland plants is also provided to parts of the landscape that are down gradient from breaks in slope of the water table, and where subsurface discontinuities in geologic units cause upward movement of ground water. Many wetlands are present along streams, especially slow-moving streams.

Although these riverine wetlands commonly receive ground-water discharge, they are dependent primarily on the stream for their water supply[6], [7]. A major difference between lakes and wetlands, with respect to their interaction with ground water, is the ease with which water moves through their beds. Lakes commonly are shallow around their perimeter where waves can remove fine-grained sediments, permitting the surface water and ground water to interact freely. In wetlands, on the other hand, if fine-grained and highly decomposed organic sediments are present near the wetland edge, the transfer of water and solutes between ground water and surface water is likely to be much slower.

Another difference in the interaction between ground water and surface water in wetlands compared to lakes is determined by rooted vegetation in wetlands. The fibrous root mat in wetland soils is highly conductive to water flow; therefore, water uptake by roots of emergent plants results in significant interchange between surface water and pore water of wetland sediments. The water exchanges in this upper soil zone even if exchange between surface water and ground water is restricted at the base of the wetland sediments[8]–[10].

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CHAPTER 12

CHEMICAL INTERACTIONS OF GROUND WATER AND SURFACE WATER

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Two of the fundamental controls on water chemistry in drainage basins are the type of geologic materials that are present and the length of time that water is in contact with those materials. Chemical reactions that affect the biological and geochemical characteristics of a basin include

- **a.** Acid-base reactions,
- **b.** Precipitation and dissolution of minerals,
- **c.** Sorption and ion exchange,
- **d.** Oxidation-reduction reactions,
- **e.** Biodegradation,
- **f.** Dissolution and resolution of gases.

When water first infiltrates the land surface, microorganisms in the soil have a significant effect on the evolution of water chemistry. Organic matter in soils is degraded by microbes, producing high concentrations of dissolved carbon dioxide (CO2). This process lowers the pH by increasing the carbonic acid (H2CO3) concentration in the soil water. The production of carbonic acid starts a number of mineral-weathering reactions, which result in bicarbonate (HCO3 −) commonly being the most abundant anion in the water. Where contact times between water and minerals in shallow ground water flow paths are short, the dissolved-solids concentration in the water generally is low. In such settings, limited chemical changes take place before ground water is discharged to surface water[1].

In deeper ground-water flow systems, the contact time between water and minerals is much longer than it is in shallow flow systems. As a result, the initial importance of reactions relating to microbes in the soil zone may be superseded over time by chemical reactions between minerals and water geochemical weathering. As weathering progresses, the concentration of dissolved solids increases.

Depending on the chemical composition of the minerals that are weathered, the relative abundance of the major inorganic chemicals dissolved in the water changes. Surface water in streams, lakes, and wetlands can repeatedly interchange with nearby ground water.

Thus, the length of time water is in contact with mineral surfaces in its drainage basin can continue after the water first enters a stream, lake, or wetland. An important consequence of these continued interchanges between surface water and ground water is their potential to further increase the contact time between water and chemically reactive geologic materials.

Chemical Interactions of Ground Water and Surface Water in Streams, Lakes, and Wetlands

Ground-water chemistry and surface-water chemistry cannot be dealt with separately where surface and subsurface flow systems interact. The movement of water between ground water and surface water provides a major pathway for chemical transfer between terrestrial and aquatic systems. This transfer of chemicals affects the supply of carbon, oxygen, nutrients such as nitrogen and phosphorus, and other chemical constituents that enhance biogeochemical processes on both sides of the interface. This transfer can ultimately affect the biological and chemical characteristics of aquatic systems downstream.

Some Common Types of Biogeochemical Reactions Affecting Transport of Chemicals in Ground Water and Surface Water

Acid-base reactions involve the transfer of hydrogen ions (H+) among solutes dissolved in water, and they affect the effective concentrations of dissolved chemicals through changes in the H+ concentration in water. A brief notation for H+ concentration (activity) is pH, which represents a negative logarithmic scale of the H+ concentration. Smaller values of pH represent larger concentrations of H+, and larger values of pH represent smaller concentrations of H+. Many metals stay dissolved when pH values are small; increased pH causes these metals to precipitate from solution[2].

Precipitation and Dissolution of Minerals

Precipitation reactions result in minerals being formed (precipitated) from ions that are dissolved in water. An example of this type of reaction is the precipitation of iron, which is common in areas of ground-water seeps and springs. At these locations, the solid material iron hydroxide is formed when iron dissolved in ground water comes in contact with oxygen dissolved in surface water. The reverse, or dissolution reactions, result in ions being released into water by dissolving minerals. An example is the release of calcium ions (Ca++) and bicarbonate ions (HCO_3 −) when calcite ($CaCO_3$) in limestone is dissolved.

Sorption and Ion Exchange

Sorption is a process in which ions or molecules dissolved in water become attached to the surfaces or near-surface parts of solid materials, either temporarily or permanently. Thus, solutes in ground water and surface water can be sorbed either to the solid materials that comprise an aquifer or streambed or to particles suspended in ground water or surface water. The attachments of positively charged ions to clays and of pesticides to solid surfaces are examples of sorption. Release of sorbed chemicals to water is termed desorption.

When ions attached to the surface of a solid are replaced by ions that were in water, the process is known as ion exchange. Ion exchange is the process that takes place in water softeners; ions that contribute to water hardness calcium and magnesium are exchanged for sodium on the surface of the solid. The result of this process is that the amount of calcium and magnesium in the water declines and the amount of sodium increases. The opposite takes place when saltwater enters an aquifer; some of the sodium in the saltwater is exchanged for calcium sorbed to the solid material of the aquifer[3].

Oxidation-Reduction Reactions

Oxidation-reduction reactions take place when electrons are exchanged among solutes. In these reactions, oxidation loss of electrons of certain elements is accompanied by the reduction gain of electrons of other elements. For example, when iron dissolved in water that does not contain dissolved oxygen mixes with water that does contain dissolved oxygen, the iron and oxygen interact by oxidation and reduction reactions. The result of the reactions is that the dissolved iron loses electrons the iron is oxidized and oxygen gains electrons the oxygen is reduced. In this case, the iron is an electron donor and the oxygen is an electron acceptor. Bacteria can use energy gained from oxidation reduction reactions as they decompose organic material. To accomplish this, bacterially mediated oxidation-reduction reactions use a sequence of electron acceptors, including oxygen, nitrate, iron, sulfate, and carbon dioxide. The presence of the products of these reactions in ground water and surface water can be used to identify the dominant oxidationreduction reactions that have taken place in those waters. For example, the bacterial reduction of sulfate (SO_4^{2-}) to sulfide (HS^-) can result when organic matter is oxidized to CO_2.

Biodegradation

Biodegradation is the decomposition of organic chemicals by living organisms using enzymes. Enzymes are specialized organic compounds made by living organisms that speed up reactions with other organic compounds. Microorganisms degrade organic chemicals as a source of energy and carbon for growth. Microbial processes are important in the fate and transport of many organic compounds. Some compounds, such as petroleum hydrocarbons, can be used directly by microorganisms as food sources and are rapidly degraded in many situations. Other compounds, such as chlorinated solvents, are not as easily assimilated. The rate of biodegradation of an organic chemical is dependent on its chemical structure, the environmental conditions, and the types of microorganisms that are present. Although biodegradation commonly can result in complete degradation of organic chemicals to carbon dioxide, water, and other simple products, it also can lead to intermediate products that are of environmental concern. For example, deethylatrazine, an intermediate degradation product of the pesticide atrazine, commonly is detected in water throughout the corn-growing areas of the United States[4].

Dissolution and Absolution of Gases

Gases are directly involved in many geochemical reactions. One of the more common gases is carbon dioxide (CO_2). For example, stalactites can form in caves when dissolved CO_2exsolves (degasses) from dripping ground water, causing pH to rise and calcium carbonate to precipitate. In soils, the microbial production of CO_2 increases the concentration of carbonic acid (H_2CO_3), which has a major control on the solubility of aquifer materials. Other gases commonly involved in chemical reactions are oxygen, nitrogen, hydrogen sulfide (H_2S), and methane (CH_4). Gases such as chlorofluorocarbons (CFCs) and radon are useful as tracers to determine the sources and rates of ground-water movement.

Evolution of Ground-Water Chemistry from Recharge to Discharge Areas in the Atlantic Coastal Plain

Changes in the chemical composition of ground water in sediments of the Atlantic Coastal Plain provide an example of the chemical evolution of ground water in a regional flow system as shown in Figure 1. In the shallow regime, infiltrating water comes in contact with gases in the unsaturated zone and shallow ground water. As a result of this contact, localized, short-term, fast reactions take place that dissolve minerals and degrade organic material. In the deep regime, long term, slower chemical reactions, such as precipitation and dissolution of minerals and ion-exchange, add or remove solutes. These natural processes and reactions commonly produce a predictable sequence of hydro chemical faces. In the Atlantic Coastal Plain, ground water evolves from water containing abundant bicarbonate ions and small concentrations of dissolved solids near the point of recharge to water containing abundant chloride ions and large concentrations of dissolved solids where it discharges into streams, estuaries, and the Atlantic Ocean[5].

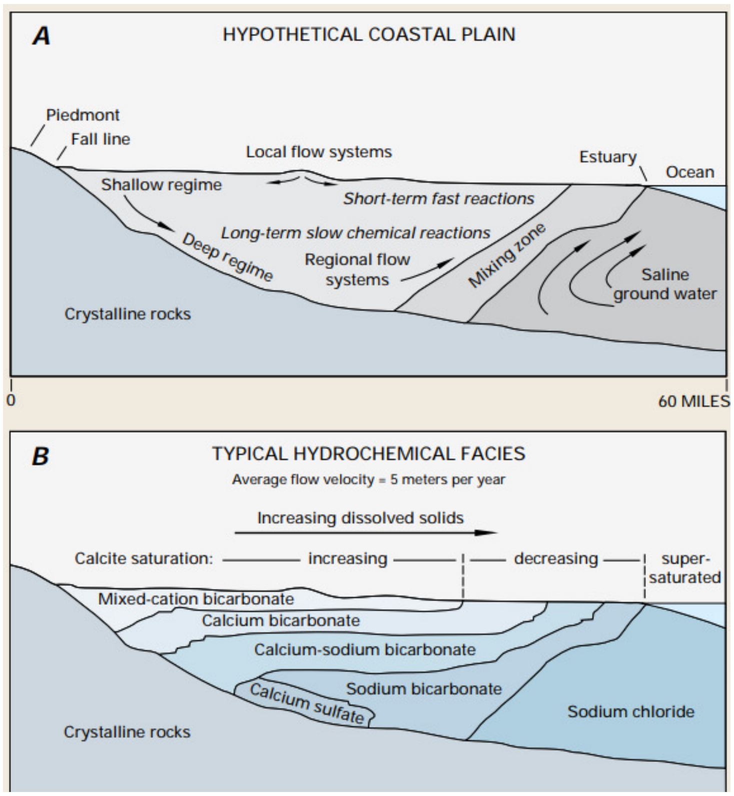

Figure 1: Represented the Atlantic Coastal Plain.

Many streams are contaminated. Therefore, the need to determine the extent of the chemical reactions that take place in the hyporheic zone is widespread because of the concern that the contaminated stream water will contaminate shallow ground water. Streams offer good examples of how interconnections between ground water and surface water affect chemical processes. Rough channel bottoms cause stream water to enter the streambed and to mix with ground water in the hyporheic zone. This mixing establishes sharp changes in chemical concentrations in the hyporheic zone. A zone of enhanced biogeochemical activity usually develops in shallow ground water as a result of the flow of oxygen-rich surface water into the subsurface environment, where bacteria and geochemically active sediment coatings are abundant as mention in Figure 2.

This input of oxygen to the streambed stimulates a high level of activity by aerobic (oxygen-using) microorganisms if dissolved oxygen is readily available. It is not uncommon for dissolved oxygen to be completely used up in hyporheic flow paths at some distance into the streambed, where anaerobic microorganisms dominate microbial activity. Anaerobic bacteria can use nitrate, sulfate, or other solutes in place of oxygen for metabolism. The result of these processes is that many solutes are highly reactive in shallow ground water in the vicinity of streambeds. The movement of nutrients and other chemical constituents, including contaminants, between ground water and surface water is affected by biogeochemical processes in the hyporheic zone. For example, the rate at which organic contaminants biodegrade in the hyporheic zone can exceed rates in stream water or in ground water away from the stream. Another example is the removal of dissolved metals in the hyporheic zone. As water passes through the hyporheic zone, dissolved metals are removed by precipitation of metal oxide coatings on the sediments[6].

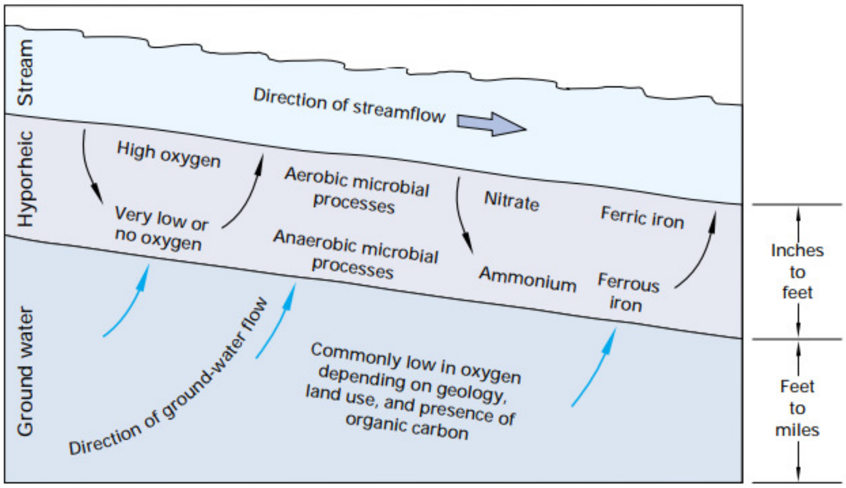

Figure 2: Illustrated the Enhanced Biogeochemical Activity.

Interface between Ground Water and Surface Water as an Environmental Entity

In the bed and banks of streams, water and solutes can exchange in both directions across the streambed. This process, termed hyporheic exchange, creates subsurface environments that have variable proportions of water from ground water and surface water. Depending on the type of sediment in the streambed and banks, the variability in slope of the streambed, and the hydraulic gradients in the adjacent ground-water system, the hyporheic zone can be as much as several feet in depth and hundreds of feet in width. The dimensions of the hyporheic zone generally increase with increasing width of the stream and permeability of streambed sediments.

The importance of the hyporheic zone was first recognized when higher than expected abundances of aquatic insects were found in sediments where concentrations of oxygen were high. Caused by stream-water input, the high oxygen concentrations in the hyporheic zone make it possible for organisms to live in the pore spaces in the sediments, thereby providing a refuge for those organisms. Also, spawning success of salmon is greater where flow from the stream brings oxygen into contact with eggs that were deposited within the coarse sediment. The hyporheic zone also can be a source of nutrients and algal cells to streams that foster the recovery of streams following catastrophic storms. For example, in a study of the ecology of Sycamore Creek in Arizona, it was found that the algae that grew in the top few inches of streambed sediment were quickest to recover following storms in areas where water in the sediments moved upward.

These algae recovered rapidly following storms because concentrations of dissolved nitrogen were higher in areas of the streambed where water moved upward than in areas where water moved downward. Areas of streambed where water moved upward are, therefore, likely to be the first areas to return to more normal ecological conditions following flash floods in desert streams. Hyporheic zones also serve as sites for nutrient uptake. A study of a coastal mountain stream in northern California indicated that transport of dissolved oxygen, dissolved carbon, and dissolved nitrogen in stream water into the hyporheic zone stimulated uptake of nitrogen by microbes and algae attached to sediment. A model simulation of nitrogen uptake indicated that both the physical process of water exchange between the stream and the hyporheic zone and the biological uptake of nitrate in the hyporheic zone affected the concentration of dissolved nitrogen in the stream[7].

The importance of biogeochemical processes that take place at the interface of ground water and surface water in improving water quality for human consumption is shown by the following example. Decreasing metal concentrations in drinking-water wells adjacent to the River Glatt in Switzerland was attributed to the interaction of the river with subsurface water. The improvement in ground-water quality started with improved sewage-treatment plants, which lowered phosphate in the river. Lower phosphate concentrations lowered the amount of algal production in the river, which decreased the amount of dissolved organic carbon flowing into the riverbanks. These factors led to a decrease in the bacteria-caused dissolution of manganese and cadmium that were present as coatings on sediment in the aquifer. The result was substantially lower dissolved metal concentrations in ground water adjacent to the river, which resulted in an unexpected improvement in the quality of drinking water.

Use of Environmental Tracers to Determine the Interaction of Ground Water and Surface Water

Environmental tracers are naturally occurring dissolved constituents, isotopes, or physical properties of water that are used to track the movement of water through watersheds. Useful environmental tracers include:

- **a.** Common dissolved constituents, such as major captions and anions;
- **b.** Stable isotopes of oxygen (^{18}O) and hydrogen (^{2}H) in water molecules;
- **c.** Radioactive isotopes such as tritium (^{3}H) and radon (^{222}Rn);
- **d.** Water temperature. When used in simple hydrologic transport calculations, environmental tracers can be used to:
    - Determine source areas of water and dissolved chemicals in drainage basins,
    - Calculate hydrologic and chemical fluxes between ground water and surface water,
    - Calculate water ages that indicate the length of time water and dissolved chemicals have been present in the drainage basin,
    - Determine average rates of chemical reactions that take place during transport. Some examples are described below:

Major captions and anions have been used as tracers in studies of the hydrology of small watersheds to determine the sources of water to streamflow during storms Figure 3. In addition, stable isotopes of oxygen and hydrogen, which are part of water molecules, are useful for determining the mixing of waters from different source areas because of such factors as:

a. Differences in the isotopic composition of precipitation among recharge areas,
b. Changes in the isotopic composition of shallow subsurface water caused by evaporation
c. Temporal variability in the isotopic composition of precipitation relative to ground water.

Radioactive isotopes are useful indicators of the time that water has spent in the ground-water system. For example, tritium (^3H) is a well-known radioactive isotope of hydrogen that had peak concentrations in precipitation in the mid-1960s as a result of above-ground nuclear-bomb testing conducted at that time. Chlorofluorocarbons (CFCs), which are industrial chemicals that are present in ground water less than 50 years old, also can be used to calculate ground-water age in different parts of a drainage basin[8].

Radon is a chemically inert, radioactive gas that has a half-life of only 3.83 days. It is produced naturally in ground water as a product of the radioactive decay of radium in uranium-bearing rocks and sediment. Several studies have documented that radon can be used to identify locations of significant ground-water input to a stream, such as from springs. Radon also has been used to determine stream water movement to ground water. For example, radon was used in a study in France to determine stream-water loss to ground water as a result of ground-water withdrawals as display in Figure 3 and Figure 4.

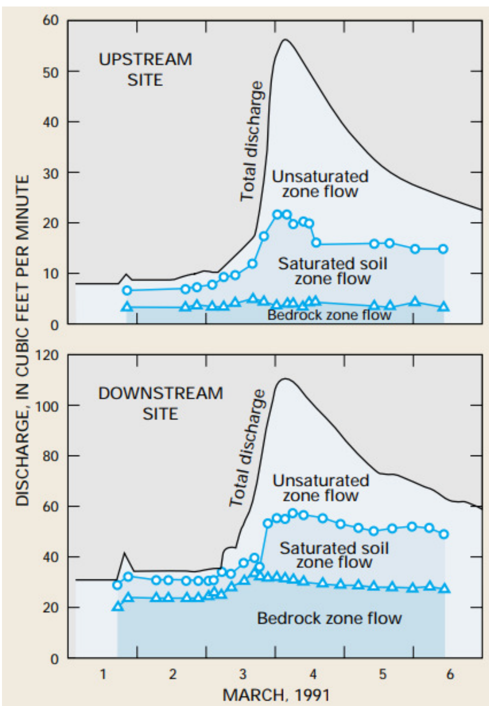

Figure 3: Represented the Sources of Water to Streamflow during Storms.

An example of using stream-water temperature and sediment temperature for mapping gaining and losing reaches of a stream. In gaining reaches of the stream, sediment temperature and stream-water temperature are markedly different. In losing reaches of the stream, the diurnal fluctuations of temperature in the stream are reflected more strongly in the sediment temperature.

Lakes and wetlands also have distinctive biogeochemical characteristics with respect to their interaction with ground water. The chemistry of ground water and the direction and magnitude of exchange with surface water significantly affect the input of dissolved chemicals to lakes and wetlands. In general, if lakes and wetlands have little interaction with streams or with ground water, input of dissolved chemicals is mostly from precipitation; therefore, the input of chemicals is minimal. Lakes and wetlands that have a considerable amount of ground-water inflow generally have large inputs of dissolved chemicals. In cases where the input of dissolved nutrients such as phosphorus and nitrogen exceeds the output, primary production by algae and wetland plants is large.

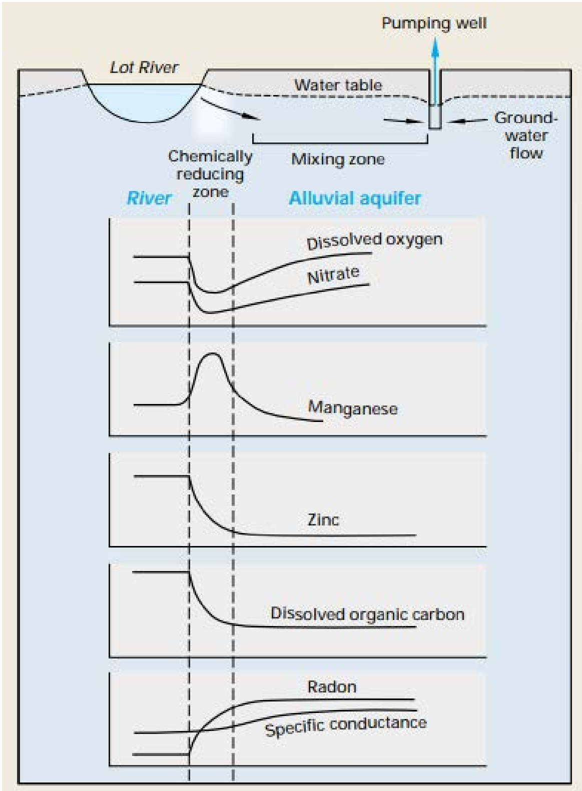

Figure 4: Represented the Ground-Water Withdrawals

When this large amount of plant material dies, oxygen is used in the process of decomposition. In some cases the loss of oxygen from lake water can be large enough to kill fish and other aquatic organisms. The magnitude of surface-water inflow and outflow also affects the retention of nutrients in wetlands. If lakes or wetlands have no stream outflow, retention of chemicals is high. The tendency to retain nutrients usually is less in wetlands that are flushed substantially by through flow of surface water. In general, as surface-water inputs increase, wetlands vary from those that strongly retain nutrients to those that both import and export large amounts of nutrients. Furthermore, wetlands commonly have a significant role in altering the chemical form of dissolved constituents. For example, wetlands that have through flow of surface water tend to retain the chemically oxidized forms and release the chemically reduced forms of metals and nutrients[9].

Interaction of Ground Water and Surface Water in Different Landscapes

Ground water is present in virtually all landscapes. The interaction of ground water with surface water depends on the physiographic and climatic setting of the landscape. For example, a stream in a wet climate might receive ground-water inflow, but a stream in an identical physiographic setting in an arid climate might lose water to ground water. To provide a broad and unified perspective of the interaction of ground water and surface water in different landscapes, a conceptual landscape is used as a reference. Some common features of the interaction for various parts of the conceptual landscape are described below. The five general types of terrain discussed are mountainous, riverine, coastal, glacial and dune, and karst.

Mountainous Terrain

The hydrology of mountainous terrain is characterized by highly variable precipitation and water movement over and through steep land slopes. On mountain slopes, macropores created by burrowing organisms and by decay of plant roots have the capacity to transmit subsurface flow downslope quickly. In addition, some rock types underlying soils may be highly weathered or fractured and may transmit significant additional amounts of flow through the subsurface. In some settings this rapid flow of water results in hillside springs. A general concept of water flow in mountainous terrain includes several pathways by which precipitation moves through the hillside to a stream as display in Figure 5.

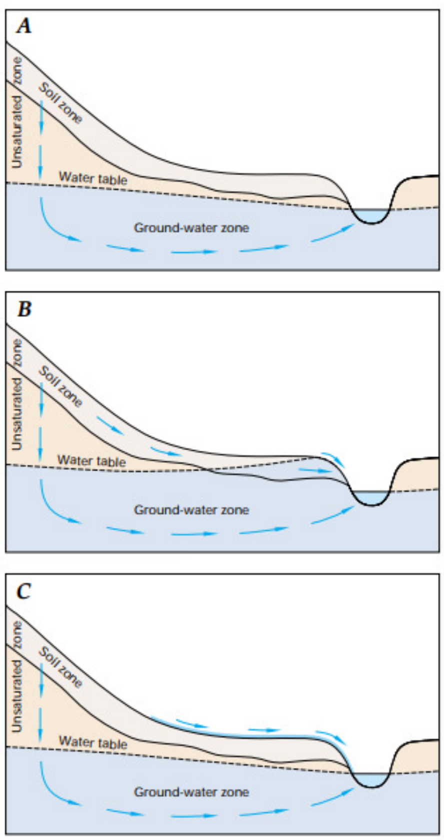

Figure 5: Represented the Hillside to a Stream.

Between storm and snowmelt periods, streamflow is sustained by discharge from the ground-water system. During intense storms, most water reaches streams very rapidly by partially saturating and flowing through the highly conductive soils. On the lower parts of hill slopes, the water table sometimes rises to the land surface during storms, resulting in overland flow. When this occurs, precipitation on the saturated area adds to the quantity of overland flow. When storms or snowmelt persist in mountainous areas, near-stream saturated areas can expand outward from streams to include areas higher on the hillslope. In some settings, especially in arid regions, overland flow can be generated when the rate of rainfall exceeds the infiltration capacity of the soil.

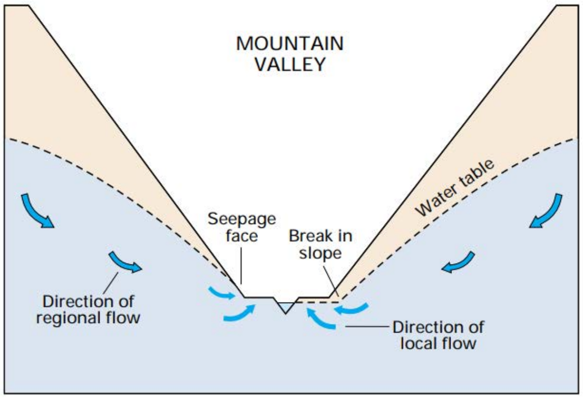

Figure 6: In mountainous terrain, ground water can discharge at the base of steep slopes

Near the base of some mountainsides, the water table intersects the steep valley wall some distance up from the base of the slope as mention in Figure 6. This results in perennial discharge of ground water and, in many cases, the presence of wetlands. A more common hydrologic process that results in the presence of wetlands in some mountain valleys is the upward discharge of ground water caused by the change in slope of the water table from being steep on the valley side to being relatively flat in the alluvial valley. Where both of these water-table conditions exist, wetlands fed by ground water, which commonly are referred to as fens, can be present. Another dynamic aspect of the interaction of ground water and surface water in mountain settings is caused by the marked longitudinal component of flow in mountain valleys[10].

The high gradient of mountain streams, coupled with the coarse texture of streambed sediments, results in a strong down-valley component of flow accompanied by frequent exchange of stream water with water in the hyporheic zone. The driving force for water exchange between a stream and its hyporheic zone is created by the surface water flowing over rough streambeds, through pools and riffles, over cascades, and around boulders and logs. Typically, the stream enters the hyporheic zone at the downstream end of pools and then flows beneath steep sections of the stream, returning to the stream at the upstream end of the next pool. Stream water also may enter the hyporheic zone upstream from channel meanders, causing stream water to flow through a gravel bar before reentering the channel downstream.

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CHAPTER 13

IN MOUNTAINOUS TERRAIN, GROUND WATER CAN DISCHARGE AT THE BASE OF STEEP SLOPES

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The steep slopes and rocky characteristics of mountainous terrain make it difficult to determine interactions of ground water and surface water. Consequently, few detailed hydrogeological investigations of these interactions have been conducted in mountainous areas. Two examples are given below. A field and modeling study of the Mirror Lake area in the White Mountains of New Hampshire indicated that the sizes of ground-water flow systems contributing to surfacewater bodies were considerably larger than their topographically defined watersheds. For example, much of the ground water in the fractured bedrock that discharges to Mirror Lake passes beneath the local flow system associated with Norris Brook. Furthermore, a more extensive deep ground-water flow system that discharges to the Pemigewasset River passes beneath flow systems associated with both Norris Brook and Mirror Lake. Studies in mountainous terrain have used tracers to determine sources of ground water to streams. In addition to revealing processes of water exchange between ground water and stream water, solute tracers have proven useful for defining the limits of the hyporheic zone surrounding mountain streams. For example, solute tracers such as chloride or bromide ions are injected into the stream to artificially raise concentrations above natural background concentrations. The locations and amounts of ground-water inflow are determined from a simple dilution model. The extent that tracers move into the hyporheic zone can be estimated by the models and commonly is verified by sampling wells placed in the study area[1].

A study in Colorado indicated that hyporheic exchange in mountain streams is caused to a large extent by the irregular topography of the streambed, which creates pools and riffles characteristic of mountain streams. Ground water enters streams most readily at the upstream end of deep pools, and stream water flows into the subsurface beneath and to the side of steep sections of streams. Channel irregularity, therefore, is an important control on the location of ground-water inflow to streams and on the size of the hyporheic zone in mountain streams because changes in slope determine the length and depth of hyporheic flow paths. The source and fate of metal contaminants in streams receiving drainage from abandoned mines can be determined by using solute tracers. In addition to surface drainage from mines, a recent study of Chalk Creek in Colorado indicated that contaminants were being brought to the stream by ground-water inflow. The ground water had been contaminated from mining activities in the past and is now a new source of contamination to the stream. This nonpoint groundwater source of contamination will very likely be much more difficult to clean up than the point source of contamination from the mine tunnel.

Riverine Terrain

In some landscapes, stream valleys are small and they commonly do not have well-developed flood plains. However, major rivers area V of the reference landscape, have valleys that usually become increasingly wider downstream. Terraces, natural levees, and abandoned river meanders are common landscape features in major river valleys, and wetlands and lakes commonly are associated with these features. The interaction of ground water and surface water in river valleys is affected by the interchange of local and regional ground-water flow systems with the rivers and by flooding and evapotranspiration. Small streams receive ground-water inflow primarily from local flow systems, which usually have limited extent and are highly variable seasonally. Therefore, it is not unusual for small streams to have gaining or losing reaches that change seasonally[2]. For larger rivers that flow in alluvial valleys, the interaction of ground water and surface water usually is more spatially diverse than it is for smaller streams.

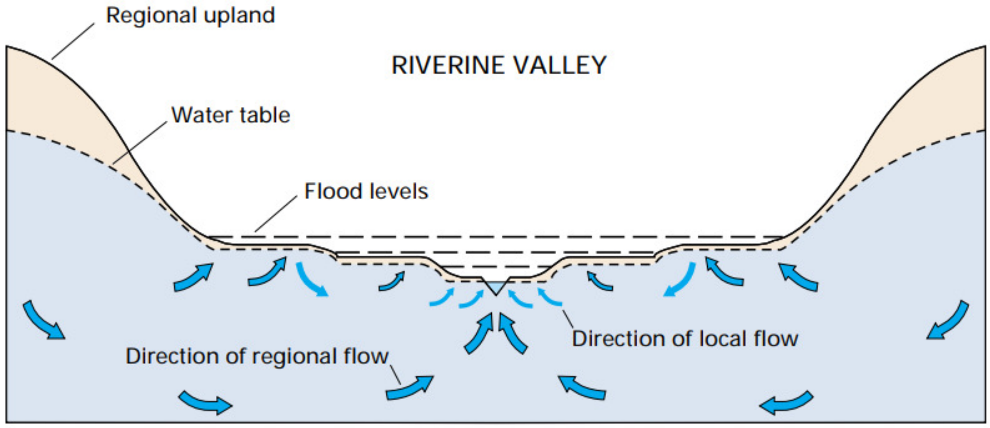

Figure 1: Illustrated the Various Places across the Flood Plain

Ground water from regional flow systems discharges to the river as well as at various places across the flood plain as mention in Figure 1. If terraces are present in the alluvial valley, local ground-water flow systems may be associated with each terrace, and lakes and wetlands may be formed because of this source of ground water. At some locations, such as at the valley wall and at the river, local and regional groundwater flow systems may discharge in close proximity. Furthermore, in large alluvial valleys, significant down-valley components of flow in the streambed and in the shallow alluvium also may be present.

Added to this distribution of ground-water discharge from different flow systems to different parts of the valley is the effect of flooding. At times of high river flows, water moves into the groundwater system as bank storage. The flow paths can be as lateral flow through the riverbank or, during flooding, as vertical seepage over the flood plain. As flood waters rise, they cause bank storage to move into higher and higher terraces. The water table generally is not far below the land surface in alluvial valleys. Therefore, vegetation on flood plains, as well as at the base of some terraces, commonly has root systems deep enough so that the plants can transpire water directly from ground water. Because of the relatively stable source of ground water, particularly in areas of ground-water discharge, the vegetation can transpire water near the maximum potential transpiration rate, resulting in the same effect as if the water were being pumped by a well. This large loss of water can result in drawdown of the water table such that the plants intercept some of the water that would otherwise flow to the river, wetland, or lake. Furthermore, in some settings it is not uncommon during the growing season for the pumping effect of transpiration to be significant enough that surface water moves into the subsurface to replenish the transpired ground water[3].

Riverine alluvial deposits range in size from clay to boulders, but in many alluvial valleys, sand and gravel are the predominant deposits. Chemical reactions involving dissolution or precipitation of minerals commonly do not have a significant effect on water chemistry in sand and gravel alluvial aquifers because the rate of water movement is relatively fast compared to weathering rates. Instead, sorption and desorption reactions and oxidation/reduction reactions related to the activity of microorganisms probably have a greater effect on water chemistry in these systems. As in small streams, biogeochemical processes in the hyporheic zone may have a significant effect on the chemistry of ground water and surface water in larger riverine systems. Movement of oxygen-rich surface water into the subsurface, where chemically reactive sediment coatings are abundant, causes increased chemical reactions related to activity of microorganisms. Sharp gradients in concentration of some chemical constituents in water, which delimit this zone of increased biogeochemical activity, are common near the boundary between ground water and surface water. In addition, chemical reactions in the hyporheic zone can cause precipitation of some reactive solutes and contaminants, thereby affecting water quality.

Field Studies of Riverine Terrain

Streams are present in virtually all landscapes, and in some landscapes, they are the principal surface-water features. The interaction of ground water with streams varies in complexity because they vary in size from small streams near headwaters areas to large rivers flowing in large alluvial valleys, and also because streams intersect ground-water flow systems of greatly different scales. Examples of the interaction of ground water and surface water for small and large riverine systems are presented below. The Straight River, which runs through a sand plain in central Minnesota, is typical of a small stream that does not have a flood plain and that derives most of its water from ground-water inflow. The water-table contours near the river bend sharply upstream, indicating that ground water moves directly into the river. It is estimated from base flow studies that, on an annual basis, ground water accounts for more than 90% of the water in the river[4].

In contrast, the results of a study of the lower Missouri River Valley indicate the complexity of ground-water flow and its interaction with streams in large alluvial valleys. Configuration of the water table in this area indicates that ground water flows into the river at right angles in some reaches, and it flows parallel to the river in others. This study also resulted in a map that showed patterns of water-table fluctuations with respect to proximity to the river. This example shows the wide variety of ground-water flow conditions that can be present in large alluvial valleys. Another study of part of a large alluvial valley provides an example of the presence of smaller scale flow conditions.

The Cache River is a stream within the alluvial valley of the Mississippi River Delta system in eastern Arkansas. In a study of the Black Swamp, which lies along a reach of the river, a number of wells and piezometers were installed to determine the interaction of ground water with the swamp and the river. By measuring hydraulic head at different depths in the alluvium, it was possible to construct a hydrologic section through the alluvium, showing that the river receives ground-water discharge from both local and regional ground-water flow systems. In addition, the section also shows the effect of the break in slope associated with the terrace at the edge of the swamp, which causes ground water from a local flow system to discharge into the edge of the swamp rather than to the river.

COASTAL TERRAIN

Coastal terrain, such as that along the east central and southern coasts of the United States, extends from inland scarps and terraces to the ocean. This terrain is characterized by:

- **a.** Low scarps and terraces that were formed when the ocean was higher than at present;
- **b.** Streams, estuaries, and lagoons that are affected by tides;
- **c.** Ponds that are commonly associated with coastal sand dunes;
- **d.** Barrier islands. Wetlands cover extensive areas in some coastal terrains.

The interaction of ground water and surface water in coastal terrain is affected by discharge of ground water from regional flow systems and from local flow systems associated with scarps and terraces as mention in Figure 2, evapotranspiration, and tidal flooding. The local flow systems associated with scarps and terraces are caused by the configuration of the water table near these features. Where the water table has a downward break in slope near the top of scarps and terraces, downward components of ground-water flow are present; where the water table has an upward break in slope near the base of these features, upward components of ground-water flow are present.

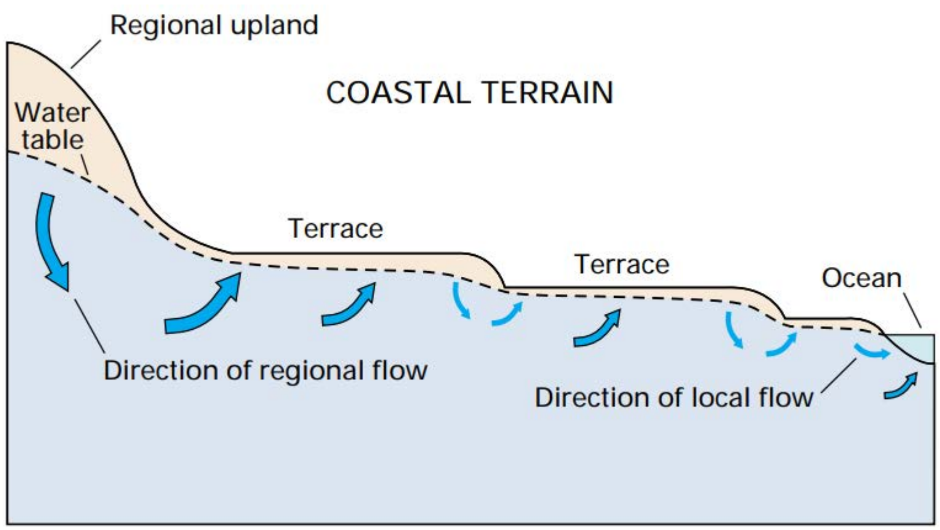

Figure 2: Represented the Flow Systems Associated with Scarps and Terraces

Evapotranspiration directly from ground water is widespread in coastal terrain. The land surface is flat and the water table generally is close to land surface; therefore, many plants have root systems deep enough to transpire ground water at nearly the maximum potential rate. The result is that evapotranspiration causes a significant water loss, which affects the configuration of ground water flow systems as well as how ground water interacts with surface water. In the parts of coastal landscapes that are affected by tidal flooding, the interaction of ground water and surface water is similar to that in alluvial valleys affected by flooding. The principal difference between the two is that tidal flooding is more predictable in both timing and magnitude than river flooding. The other significant difference is in water chemistry. The water that moves into bank storage from rivers is generally fresh, but the water that moves into bank storage from tides generally is brackish or saline[5].

Estuaries are a highly dynamic interface between the continents and the ocean, where discharge of freshwater from large rivers mixes with saline water from the ocean. In addition, ground water discharges to estuaries and the ocean, delivering nutrients and contaminants directly to coastal waters. However, few estimates of the location and magnitude of ground-water discharge to coasts have been made. In some estuaries, sulfate-rich regional ground water mixes with carbonate-rich local ground water and with chloride-rich seawater, creating sharp boundaries that separate plant and wildlife communities. Biological communities associated with these sharp boundaries are adapted to different hydro chemical conditions, and they undergo periodic stresses that result from inputs of water having different chemistry. The balance between river inflow and tides causes estuaries to retain much of the particulate and dissolved matter that is transported in surface and subsurface flows, including contaminants.

Field Studies of Coastal Terrain

Along the Atlantic, Gulf of Mexico, and Arctic Coasts of the United States, broad coastal plains are transected by streams, scarps, and terraces. In some parts of these regions, local ground-water flow systems are associated with scarps and terraces, and freshwater wetlands commonly are present. Other parts of coastal regions are affected by tides, resulting in very complex flow and biogeochemical processes. Underlying the broad coastal plain of the mid-Atlantic United States are sediments 600 or more feet thick. The sands and clays were deposited in stratigraphic layers that slope gently from west to east. Ground water moves regionally toward the east in the more permeable sand layers.

These aquifers are separated by discontinuous layers of clay that restrict vertical ground-water movement. Near land surface, local ground-water flow systems are associated with changes in land slope, such as at major scarps and at streams. Studies of the Dismal Swamp in Virginia and North Carolina provide examples of the interaction of ground water and wetlands near a coastal scarp. The Suffolk Scarp borders the west side of Great Dismal Swamp. Water-table wells and deeper piezometers placed across the scarp indicated a downward component of ground-water flow in the upland and an upward component of ground-water flow in the lowland at the edge of the swamp. However, at the edge of the swamp the direction of flow changed several times between May and October in 1982 because transpiration of ground water lowered the water table below the water level of the deep piezometer.

The gentle relief and sandy, well-drained soils of coastal terrain are ideal for agriculture. Movement of excess nutrients to estuaries are a particular problem in coastal areas because the slow rate of flushing of coastal bays and estuaries can cause them to retain nutrients. At high concentrations, nutrients can cause increased algal production, which results in overabundance of organic matter. This, in turn, can lead to reduction of dissolved oxygen in surface water to the extent that organisms are killed throughout large areas of estuaries and coastal bays[6].

Movement of nutrients from agricultural fields has been documented for the Rhode River watershed in Maryland. Application of fertilizer accounts for 69% of nitrogen and 93% of phosphorus input to this watershed. Almost all of the nitrogen that is not removed by harvested crops is transported in ground water and is taken up by trees in riparian forests and wetlands or is denitrified to nitrogen gas in ground water before it reaches streams. On the other hand, most of the phosphorus not removed by harvested crops is attached to soil particles and is transported only during heavy precipitation when sediment from fields is transported into streams and deposited in wetlands and sub tidal mudflats at the head of the Rhode River estuary.

Whether phosphorus is retained in sediments or is released to the water column depends in part on whether sediments are exposed to oxygen. Thus, the uptake of nutrients and their storage in riparian forests, wetlands, and sub tidal mudflats in the Rhode River watershed has helped maintain relatively good water quality in the Rhode River estuary. In other areas, however, agricultural runoff and input of nutrients have overwhelmed coastal systems, such as in the northern Gulf of Mexico near the mouth of the Mississippi River. The 1993 flood in the Mississippi River system delivered an enormous amount of nutrients to the Gulf of Mexico. Following the flood, oxygen-deficient sediments created areas of black sediment devoid of animal life in parts of the northern Gulf of Mexico.

Glacial and Dune Terrain

Glacial and dune terrain is characterized by a landscape of hills and depressions. Although stream networks drain parts of these landscapes, many areas of glacial and dune terrain do not contribute runoff to an integrated surface drainage network. Instead, surface runoff from precipitation falling on the landscape accumulates in the depressions, commonly resulting in the presence of lakes and wetlands. Because of the lack of stream outlets, the water balance of these “closed” types of lakes and wetlands is controlled largely by exchange of water with the atmosphere precipitation and evapotranspiration and with ground water[7].

Lakes and wetlands in glacial and dune terrain can have inflow from ground water, outflow to ground water, or both. The interaction between lakes and wetlands and ground water is determined to a large extent by their position with respect to local and regional ground-water flow systems. A common conception is that lakes and wetlands that are present in topographically high areas recharge ground water, and that lakes and wetlands that are present in low areas receive discharge from ground water. However, lakes and wetlands underlain by deposits having low permeability can receive discharge from local ground-water flow systems even if they are located in a regional ground-water recharge area. Conversely, they can lose water to local ground-water flow systems even if they are located in a regional ground-water discharge area as display in Figure 3.

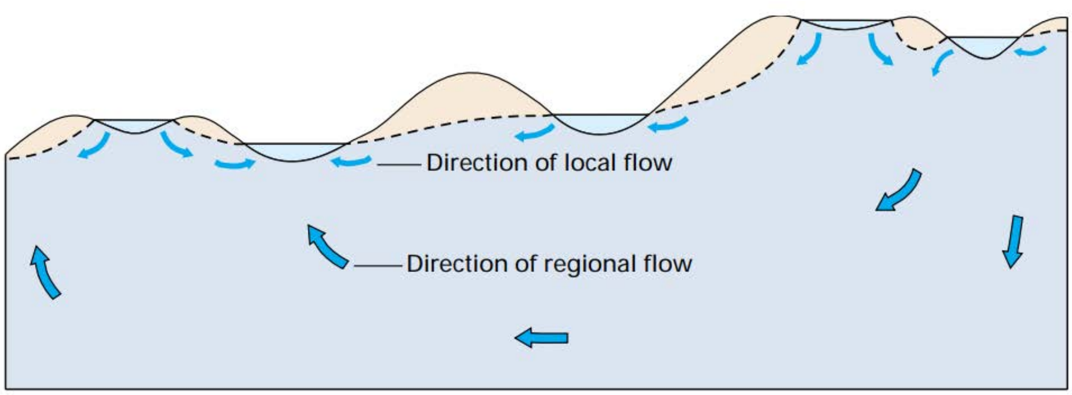

Figure 3: Illustrated the glacial and dune terrain, local, intermediate, and regional groundwater flow systems interact with lakes and wetlands.

Lakes and wetlands in glacial and dune terrain underlain by highly permeable deposits commonly have ground-water seepage into one side and seepage to ground water on the other side. This relation is relatively stable because the water table gradient between surface-water bodies in this type of setting is relatively constant. However, the boundary between inflow to the lake or wetland and outflow from it, termed the hinge line, can move up and down along the shoreline. Movement of the hinge line between inflow and outflow is a result of the changing slope of the water table in response to changes in ground-water recharge in the adjacent uplands.

Transpiration directly from ground water has a significant effect on the interaction of lakes and wetlands with ground water in glacial and dune terrain. Transpiration from ground water has perhaps a greater effect on lakes and wetlands underlain by low-permeability deposits than in any other landscape. The lateral movement of ground water in low-permeability deposits may not be fast enough to supply the quantity of water at the rate it is removed by transpiration, resulting in deep and steep-sided cones of depression. These cones of depression commonly are present around the perimeter of the lakes and wetlands. In the north-central United States, cycles in the balance between precipitation and evapotranspiration that range from 5 to 30 years can result in large changes in water levels, chemical concentrations, and major-ion water type of individual wetlands. In some settings, repeated cycling of water between the surface and subsurface in the same locale results in evaporative concentration of solutes and eventually in mineral precipitation in the subsurface. In addition, these dynamic hydrological and chemical conditions can cause significant changes in the types, number, and distribution of wetland plants and invertebrate animals within wetlands. These changing hydrological conditions that range from seasons to decades are an essential process for rejuvenating wetlands that provide ideal habitat and feeding conditions for migratory waterfowl[8].

Field Studies of Glacial and Dune Terrain

Glacial terrain and dune terrain are characterized by land-surface depressions, many of which contain lakes and wetlands. Although much of the glacial terrain covering the north-central United States has low topographic relief, neighboring lakes and wetlands are present at a sufficiently wide range of altitudes to result in many variations in how they interact with ground water, as evidenced by the following examples. The Cottonwood Lake area, near Jamestown, North Dakota, is within the prairie-pothole region of North America. The hydrologic functions of these small depression wetlands are highly variable in space and time. With respect to spatial variation, some wetlands recharge ground water, some receive ground-water inflow and have outflow to ground water, and some receive ground-water discharge. Wetland P1 provides an example of how their functions can vary in time. The wetland receives ground-water discharge most of the time; however, transpiration of ground water by plants around the perimeter of the wetland can cause water to seep from the wetland. Seepage from wetlands commonly is assumed to be ground-water recharge, but in cases like Wetland P1, the water is actually lost to transpiration. This process results in depressions in the water table around the perimeter of the wetland at certain times.

Transpiration-induced depressions in the water table commonly are filled in by recharge during the following spring, but then form again to some extent by late summer nearly every year. Nevins Lake, a closed lake in the Upper Peninsula of Michigan, illustrates yet another type of interaction of lakes with ground water in glacial terrain. Water-chemistry studies of Nevins Lake indicated that solutes such as calcium provide an indicator of ground-water inflow to the lake. Immediately following spring snowmelt, the mass of dissolved calcium in the lake increased rapidly because of increased ground-water inflow. Calcium then decreased steadily throughout the summer and early fall as the lake received less ground-water inflow. This pattern varied annually depending on the amount of ground-water recharge from snowmelt and spring rains. The chemistry of water in the pores of the lake sediments was used to determine the spatial variability in the direction of seepage on the side of the lake that had the most ground-water inflow. Seepage was always out of the lake at the sampling site farthest from shore and was always upward into the lake at the site nearest to shore. Flow reversals were documented at sites located at intermediate distances from shore[9].

Dune terrain also commonly contains lakes and wetlands. Much of the central part of western Nebraska, for example, is covered by sand dunes that have lakes and wetlands in most of the lowlands between the dunes. Studies of the interaction of lakes and wetlands with ground water at the Crescent Lake National Wildlife Refuge indicate that most of these lakes have seepage inflow from ground water and seepage outflow to ground water. The chemistry of inflowing ground water commonly has an effect on lake water chemistry. However, the chemistry of lake water can also affect ground water in areas of seepage from lakes. In the Crescent Lake area, for example, plumes of lake water were detected in ground water down gradient from the lakes, as indicated by the plume of dissolved organic carbon down gradient from Roundup Lake and Island Lake.

Karst Terrain

Karst may be broadly defined as all land forms that are produced primarily by the dissolution of rocks, mainly limestone and dolomite. Which is characterized by:

a. Closed surface depressions of various sizes and shapes known as sinkholes,
b. An underground drainage network that consists of solution openings that range in size from enlarged cracks in the rock to large caves,
c. Highly disrupted surface drainage systems, which relate directly to the unique character of the underground drainage system.

Dissolution of limestone and dolomite guides the initial development of fractures into solution holes that are diagnostic of karst terrain. Perhaps nowhere else is the complex interplay between hydrology and chemistry so important to changes in landform. Limestone and dolomite weather quickly, producing calcium and magnesium carbonate waters that are relatively high in ionic strength. The increasing size of solution holes allows higher ground-water flow rates across a greater surface area of exposed minerals, which stimulates the dissolution process further, eventually leading to development of caves.

Development of karst terrain also involves biological processes. Microbial production of carbon dioxide in the soil affects the carbonate equilibrium of water as it recharges ground water, which then affects how much mineral dissolution will take place before solute equilibrium is reached. Ground-water recharge is very efficient in karst terrain because precipitation readily infiltrates through the rock openings that intersect the land surface. Water moves at greatly different rates through karst aquifers; it moves slowly through fine fractures and pores and rapidly through solution enlarged fractures and conduits. As a result, the water discharging from many springs in karst terrain may be a combination of relatively slow moving water draining from pores and rapidly moving storm-derived water[10].

The slow-moving component tends to reflect the chemistry of the aquifer materials, and the more rapidly moving water associated with recent rainfall tends to reflect the chemical characteristics of precipitation and surface runoff. Water movement in karst terrain is especially unpredictable because of the many paths ground water takes through the maze of fractures and solution openings in the rock. Because of the large size of interconnected openings in well-developed karst systems, karst terrain can have true underground streams. These underground streams can have high rates of flow, in some places as great as rates of flow in surface streams. Furthermore, it is not unusual for medium-sized streams to disappear into the rock openings, thereby completely disrupting the surface drainage system, and to reappear at the surface at another place. Seeps and springs of all sizes are characteristic features of karst terrains.

Springs having sufficiently large ground-water recharge areas commonly are the source of small- to medium-sized streams and constitute a large part of tributary flow to larger streams. In addition, the location where the streams emerge can change, depending on the spatial distribution of ground-water recharge in relation to individual precipitation events. Large spring inflows to streams in karst terrain contrast sharply with the generally more diffuse ground-water inflow characteristic of streams flowing across sand and gravel aquifers. Because of the complex patterns of surfacewater and ground-water flow in karst terrain, many studies have shown that surface-water drainage divides and ground-water drainage divides do not coincide. An extreme example is a stream that disappears in one surface-water basin and reappears in another basin. This situation complicates the identification of source areas for water and associated dissolved constituents, including contaminants, in karst terrain. Water chemistry is widely used for studying the hydrology of karst aquifers. Extensive tracer studies and field mapping to locate points of recharge and discharge have been used to estimate the recharge areas of springs, rates of ground-water movement, and the water balance of aquifers. Variations in parameters such as temperature, hardness, calcium/magnesium ratios, and other chemical characteristics have been used to identify areas of ground-water recharge, differentiate rapid and slow moving ground-water flow paths, and compare spring flow characteristics in different regions.

Rapid transport of contaminants within karst aquifers and to springs has been documented in many locations. Because of the rapid movement of water in karst aquifers, water-quality problems that might be localized in other aquifer systems can become regional problems in karst systems. Some landscapes considered to be karst terrain do not have carbonate rocks at the land surface. For example, in some areas of the south eastern United States, surficial deposits overlie carbonate rocks, resulting in a “mantled” karst terrain. Lakes and wetlands in mantled karst terrain interact with shallow ground water in a manner similar to that in sandy glacial and dune terrains. The difference between how lakes and wetlands interact with ground water in sandy glacial and dune terrain and how they interact in the mantled karst is related to the buried carbonate rocks. If dissolution of the buried carbonate rocks causes slump age of an overlying confining bed, such that water can move freely through the confining bed, the lakes and wetlands also can be affected by changing hydraulic heads in the aquifers underlying the confining bed.

Field Studies of Karst Terrain

Karst terrain is characteristic of regions that are underlain by limestone and dolomite bedrock. In many karst areas, the carbonate bedrock is present at land surface, but in other areas it may be covered by other deposits and is referred to as "mantled" karst. The Edwards Aquifer in south-central Texas is an example of karst terrain where the limestones and dolomites are exposed at land surface. In this outcrop area, numerous solution cavities along vertical joints and sinkholes provide an efficient link between the land surface and the water table. Precipitation on the outcrop area tends to infiltrate rapidly into the ground, recharging ground water. In addition, a considerable amount of recharge to the aquifer is provided by losing streams that cross the outcrop area. Even the largest streams that originate to the north are dry in the outcrop area for most of the year. The unusual highway signs in this area go beyond local pride in a prolific water supply they reflect a clear understanding of how vulnerable this water supply is to contamination by human activities at the land surface. Just as solution cavities are major avenues for ground water recharge, they also are focal points for ground-water discharge from karst aquifers. For example, springs near the margin of the Edwards Aquifer provide a continuous source of water for streams to the south[11].

An example of mantled karst can be found in northcentral Florida, a region that has many sinkhole lakes. In this region, unconsolidated deposits overlie the highly soluble limestone of the Upper Floridan aquifer. Most land-surface depressions containing lakes in Florida are formed when unconsolidated surficial deposits slump into sinkholes that form in the underlying limestone. Thus, although the lakes are not situated directly in limestone, the sinkholes in the bedrock underlying lakes commonly have a significant effect on the hydrology of the lakes. Lake Barco is one of numerous lakes occupying depressions in northern Florida. Results of a study of the interaction of Lake Barco with ground water indicated that shallow ground water flows into the northern and northeastern parts of the lake, and lake water seeps out to shallow ground water in the western and southern parts. In addition, ground-water flow is downward beneath most of Lake Barco. The studies of lake and ground-water chemistry included the use of tritium, chlorofluorocarbons (CFCs), and isotopes of oxygen. The results indicated significant differences in the chemistry of:

- **a.** Shallow ground water flowing into Lake Barco,
- **b.** Lake Barco water,
- **c.** Shallow ground water down gradient from Lake Barco,
- **d.** Deeper ground water beneath Lake Barco.

Oxygen-rich lake water moving through the organic-rich lake sediments is reduced, resulting in discharge of oxygen-depleted water into the ground water beneath Lake Barco. This downward-moving ground water may have an undesired effect on the chemical quality of ground water in the underlying Upper Floridan aquifer, which is the principal source of water supply for the region. The patterns of ground-water movement determined from hydraulic-head data were corroborated by chemical tracers. For example, the dates that ground water in different parts of the flow system was recharged, as determined from CFC dating, show a fairly consistent increase in the length of time since recharge with depth.

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CHAPTER 14

EFFECTS OF HUMAN ACTIVITIES ON THE INTERACTION OF GROUND WATER AND SURFACE WATER

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Human activities commonly affect the distribution, quantity, and chemical quality of water resources. The range in human activities that affect the interaction of ground water and surface water is broad. The following discussion does not provide an exhaustive survey of all human effects but emphasizes those that are relatively widespread. To provide an indication of the extent to which humans affect the water resources of virtually all landscapes, some of the most relevant structures and features related to human activities are super imposed on various parts of the conceptual land scape as mention in Figure 1. The effects of human activities on the quantity and quality of water resources are felt over a wide range of space and time scales. In the following discussion, "short term" implies time scales from hours to a few weeks or months, and "long term" may range from years to decades. "Local scale" implies distances from a few feet to a few thousand feet and areas as large as a few square miles, and "sub regional and regional scales" range from tens to thousands of square miles[1].

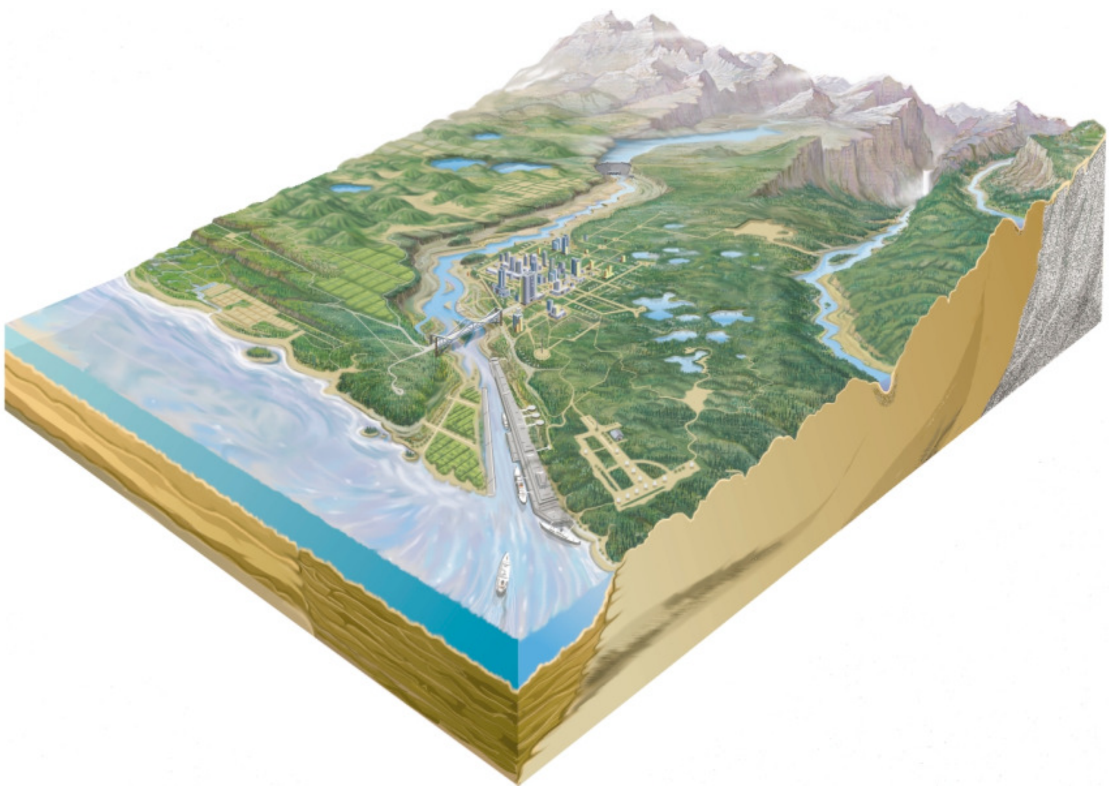

Figure 1: Illustrated the Human Activities and Structures, as Depicted by the Distribution of Various Examples in the Conceptual Landscape, affect the Interaction of Ground Water and Surface Water in all types of Landscape.

Agricultural Development

Agriculture has been the cause of significant modification of landscapes throughout the world. Tillage of land changes the infiltration and runoff characteristics of the land surface, which affects recharge to ground water, delivery of water and sediment to surface-water bodies, and evapotranspiration. All of these processes either directly or indirectly affect the interaction of ground water and surface water. Agriculturalists are aware of the substantial negative effects of agriculture on water resources and have developed methods to alleviate some of these effects. For example, tillage practices have been modified to maximize retention of water in soils and to minimize erosion of soil from the land into surface-water bodies. Two activities related to agriculture that are particularly relevant to the interaction of ground water and surface water are irrigation and application of chemicals to cropland.

Point and Nonpoint Sources of Contaminants

Contaminants may be present in water or in air as a result of natural processes or through mechanisms of displacement and dispersal related to human activities. Contaminants from point sources discharge either into ground water or surface water through an area that is small relative to the area or volume of the receiving water body. Examples of point sources include discharge from sewage-treatment plants, leakage from gasoline storage tanks, and seepage from landfills. Nonpoint sources of contaminants introduce contaminants to the environment across areas that are large compared to point sources, or nonpoint sources may consist of multiple, closely spaced point sources. A nonpoint source of contamination that can be present anywhere, and affect large areas, is deposition from the atmosphere, both by precipitation (wet deposition) or by dry fallout (dry deposition). Agricultural fields, in aggregate, represent large areas through which fertilizers and pesticides can be released to the environment[2].The differentiation between point and nonpoint sources of contamination is arbitrary to some extent and may depend in part on the scale at which a problem is considered. For example, emissions from a single smokestack is a point source, but these emissions may be meaningless in a regional analysis of air pollution. However, a fairly even distribution of tens or hundreds of smokestacks might be considered as a nonpoint source. As another example, houses in suburban areas that do not have a combined sewer system have individual septic tanks. At the local scale, each septic tank may be considered as point source of contamination to shallow ground water. At the regional scale, however, the combined contamination of ground water from all the septic tanks in a suburban area may be considered a nonpoint source of contamination to a surface-water body.

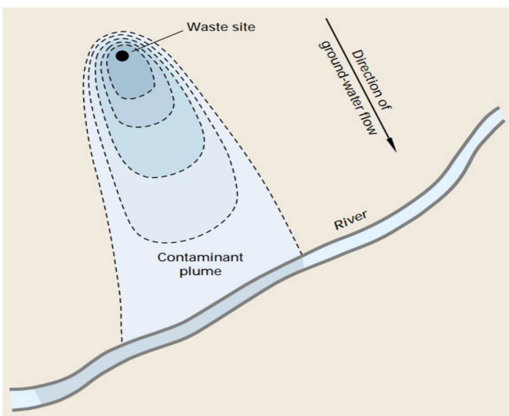

Figure 2: Illustrated the Direction of Ground Water Flow.

Irrigation Systems

Surface-water irrigation systems represent some of the largest integrated engineering works undertaken by humans. The number of these systems greatly increased in the western United States in the late 1840s. In addition to dams on streams, surface-water irrigation systems include:

- **a.** A complex network of canals of varying size and carrying capacity that transport water, in many cases for a considerable distance, from a surface water source to individual fields,
- **b.** A drainage system to carry away water not used by plants that may be as extensive and complex as the supply system.

The drainage system may include underground tile drains. Many irrigation systems that initially used only surface water now also use ground water. The pumped ground water commonly is used directly as irrigation water, but in some cases the water is distributed through the system of canals. Average quantities of applied water range from several inches to 20 or more inches of water per year, depending on local conditions, over the entire area of crops. In many irrigated areas, about 75% to 85% of the applied water is lost to evapotranspiration and retained in the crops. The remainder of the water either infiltrates through the soil zone to recharge ground water or it returns to a local surface-water body through the drainage system[3].

The quantity of irrigation water that recharges ground water usually is large relative to recharge from precipitation because large irrigation systems commonly are in regions of low precipitation and low natural recharge. As a result, this large volume of artificial recharge can cause the water table to rise, possibly reaching the land surface in some areas and waterlogging the fields. For this reason, drainage systems that maintain the level of the water table below the root zone of the crops, generally 4 to 5 feet below the land surface, are an essential component of some irrigation systems. The permanent rise in the water table that is maintained by continued recharge from irrigation return flow commonly results in an increased outflow of shallow ground water to surface-water bodies down gradient from the irrigated area.

Effects of Irrigation Development on the Interaction of Ground Water and Surface Water

Nebraska ranks second among the States with respect to the area of irrigated acreage and the quantity of water used for irrigation. The irrigation water is derived from extensive supply systems that use both surface water and ground water. Hydrologic conditions in different parts of Nebraska provide a number of examples of the broad-scale effects of irrigation development on the interactions of ground water and surface water. As would be expected, irrigation systems based on surface water are always located near streams. In general, these streams are perennial and (or) have significant flow for at least part of the year. In contrast, irrigation systems based on ground water can be located nearly anywhere that has an adequate ground-water resource. Areas of significant rise and decline in ground-water levels due to irrigation systems. Ground-water levels rise in some areas irrigated with surface water and decline in some areas irrigated with ground water. Rises in ground-water levels near streams result in increased ground-water inflow to gaining streams or decreased flow from the stream to ground water for losing streams. In some areas, it is possible that a stream that was losing water before development of irrigation could become a gaining stream following irrigation. This effect of surface-water irrigation probably caused the rises in ground-water levels in areas F and G in south-central Nebraska[4].

Average annual precipitation ranges from less than 15 inches in western Nebraska to more than 30 inches in eastern Nebraska. A large concentration of irrigation wells is present in area E. The ground-water withdrawals by these wells caused declines in ground-water levels that could not be offset by recharge from precipitation and the presence of nearby flowing streams. In this area, the withdrawals cause decreases in ground-water discharge to the streams and induce flow from the streams to shallow ground water. In contrast, the density of irrigation wells in areas A, B, and C is less than in area E, but water-level declines in these three western areas are similar to area E. The similar decline caused by fewer wells in the west compared to the east is related to less precipitation, less ground-water recharge, and less streamflow available for seepage to ground water. Although early irrigation systems made use of surface water, the development of large-scale sprinkler systems in recent decades has greatly increased the use of ground water for irrigation for several reasons:

a. A system of supply canals is not needed,

b. Ground water may be more readily available than surface water,

c. Many types of sprinkler systems can be used on irregular land surfaces; the fields do not have to be as flat as they do for gravity-flow, surface-water irrigation.

Whether ground water or surface water was used first to irrigate land, it was not long before water managers recognized that development of either water resource could affect the other. This is particularly true in many alluvial aquifers in arid regions where much of the irrigated land is in valleys. Significant changes in water quality accompany the movement of water through agricultural fields. The water lost to evapotranspiration is relatively pure; therefore, the chemicals that are left behind precipitate as salts and accumulate in the soil zone. These continue to increase as irrigation continues, resulting in the dissolved-solids concentration in the irrigation return flows being significantly higher in some areas than that in the original irrigation water. To prevent excessive buildup of salts in the soil, irrigation water in excess of the needs of the crops is required to dissolve and flush out the salts and transport them to the ground-water system. Where these dissolved solids reach high concentrations, the artificial recharge from irrigation return flow can result in degradation of the quality of ground water and, ultimately, the surface water into which the ground water discharges[5].

Use of Agricultural Chemicals

Applications of pesticides and fertilizers to cropland can result in significant additions of contaminants to water resources. Some pesticides are only slightly soluble in water and may attach to soil particles instead of remaining in solution; these compounds are less likely to cause contamination of ground water. Other pesticides, however, are detected in low, but significant, concentrations in both ground water and surface water. Ammonium, a major component of fertilizer and manure, is very soluble in water, and increased concentrations of nitrate that result from nitrification of ammonium commonly are present in both ground water and surface water associated with agricultural lands. In addition to these nonpoint sources of water contamination, point sources of contamination are common in agricultural areas where livestock are concentrated in small areas, such as feedlots. Whether the initial contamination is present in ground water or surface water is somewhat immaterial because the close interaction of the two sometimes results in both being contaminated.

Effects of Nitrogen Use on the Quality of Ground Water and Surface Water

Nitrate contamination of ground water and surface water in the United States is widespread because nitrate is very mobile in the environment. Nitrate concentrations are increasing in much of the Nation's water, but they are particularly high in ground water in the midcontinent region of the United States. Two principal chemical reactions are important to the fate of nitrogen in water:

a. Fertilizer ammonium can be nitrified to form nitrate, which is very mobile as a dissolved constituent in shallow ground water,

b. Nitrate can be denitrified to produce nitrogen gas in the presence of chemically reducing conditions if a source of dissolved organic carbon is available.

High concentrations of nitrate can contribute to excessive growth of aquatic plants, depletion of oxygen, fish kills, and general degradation of aquatic habitats. For example, a study of Waquoit Bay in Massachusetts linked the decline in eelgrass beds since 1950 to a progressive increase in nitrate input due to expansion of domestic septic-field developments in the drainage basin. Loss of eelgrass is a concern because this aquatic plant stabilizes sediment and provides ideal habitat for juvenile fish and other fauna in coastal bays and estuaries. Larger nitrate concentrations supported algal growth that caused turbidity and shading, which contributed to the decline of eelgrass.

Significant DE nitrification has been found to take place at locations where oxygen is absent or present at very low concentrations and where suitable electron-donor compounds, such as organic carbon, are available. Such locations include the interface of aquifers with silt and clay confining beds and along riparian zones adjacent to streams. For example, in a study on the eastern shore of Maryland, nitrogen isotopes and other environmental tracers were used to show that the degree of DE nitrification that took place depended on the extent of interaction between ground-water and the chemically reducing sediments near or below the bottom of the Aquia Formation. Two drainage basins were studied: Morgan Creek and Centerville Branch. Ground-water discharging beneath both streams had similar nitrate concentration when recharged. Significant denitrification took place in the Morgan Creek basin where a large fraction of local ground-water flow passed through the reducing sediments, which are present at shallow depths in this area. Evidence for the denitrification included decreases in nitrate concentrations along the flow path to Morgan Creek and enrichment of the ^{15}N isotope. Much less denitrification took place in the Chesterville Branch basin because the top of the reducing sediments are deeper in this area and a smaller fraction of ground water flow passed through those sediments[6].

Effects of Pesticide Application to Agricultural Lands on the Quality of Ground Water and Surface Water

Pesticide contamination of ground water and surface water has become a major environmental issue. Recent studies indicate that pesticides applied to cropland can contaminate the underlying ground water and then move along ground-water flow paths to surface water. In addition, as indicated by the following examples, movement of these pesticides between surface water and ground water can be dynamic in response to factors such as bank storage during periods of high runoff and ground-water withdrawals. A study of the sources of atrazine, a widely used herbicide detected in the Cedar River and its associated alluvial aquifer in Iowa, indicated that ground water was the major source of atrazine in the river during base-flow conditions. In addition, during periods of high streamflow, surface water containing high concentrations of atrazine moved into the bank sediments and alluvial aquifer, then slowly discharged back to the river as the river level declined. Reversals of flow related to bank storage were documented using data for three sampling periods. The first sampling which is mention in Figure 3, was before atrazine was applied to cropland, when concentrations in the river and aquifer were relatively low. The second sampling was after atrazine was applied to cropland upstream. High streamflow at this time caused the river stage to peak almost 6 feet above its base-flow level, which caused the herbicide to move with the river water into the aquifer. By the third sampling date (Figure P–1C), the hydraulic gradient between the river and the alluvial aquifer had reversed again, and atrazinecontaminated water discharged back into the river.

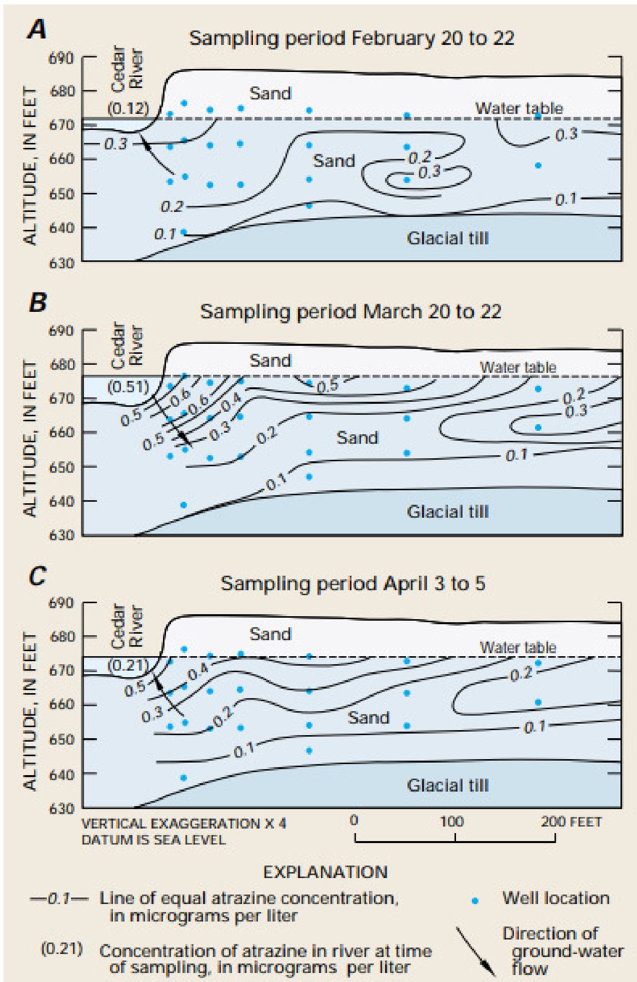

Figure 3: Represented the Concentrations of Atrazine Increased in the Cedar River in Iowa.

In a second study, atrazine was detected in ground water in the alluvial aquifer along the Platte River near Lincoln, Nebraska. Atrazine is not applied in the vicinity of the well field, so it was suspected that ground-water withdrawals at the well field caused contaminated river water to move into the aquifer. To define the source of the atrazine, water samples were collected from monitoring wells located at different distances from the river near the well field. The pattern of concentrations of atrazine in the ground water indicated that peak concentrations of the herbicide showed up sooner in wells close to the river compared to wells farther away. Peak concentrations of atrazine in ground water were much higher and more distinct during periods of large groundwater withdrawals than during periods of much smaller withdrawals[7].

Urban and Industrial Development

Point sources of contamination to surface water bodies are an expected side effect of urban development. Examples of point sources include direct discharges from sewage-treatment plants, industrial facilities, and storm water drains. These facilities and structures commonly add sufficient loads of a variety of contaminants to streams to strongly affect the quality of the stream for long distances downstream. Depending on relative flow magnitudes of the point source and of the stream, discharge from a point source such as a sewage treatment plant may represent a large percentage of the water in the stream directly downstream from the source. Contaminants in streams can easily affect ground-water quality, especially where streams normally seep to ground water, where ground-water withdrawals induce seepage from the stream, and where floods cause stream water to become bank storage. Point sources of contamination to ground water can include septic tanks, fluid storage tanks, landfills, and industrial lagoons.

If a contaminant is soluble in water and reaches the water table, the contaminant will be transported by the slowly moving ground water. If the source continues to supply the contaminant over a period of time, the distribution of the dissolved contaminant will take a characteristic "plume like" shape. These contaminant plumes commonly discharge into a nearby surface-water body. If the concentration of contaminant is low and the rate of discharge of plume water also is small relative to the volume of the receiving surface-water body, the discharging contaminant plume will have only a small, or perhaps unmeasurable, effect on the quality of the receiving surface-water body. Furthermore, biogeochemical processes may decrease the concentration of the contaminant as it is transported through the shallow ground water system and the hyporheic zone. On the other hand, if the discharge of the contaminant plume is large or has high concentrations of contaminant, it could significantly affect the quality of the receiving surface-water body.

Drainage of the Land Surface

In landscapes that are relatively flat, have water ponded on the land surface, or have a shallow water table, drainage of land is a common practice preceding agricultural and urban development. Drainage can be accomplished by constructing open ditches or by burying tile drains beneath the land surface. In some glacial terrain underlain by deposits having low permeability, drainage of lakes and wetlands can change the areal distribution of ground-water recharge and discharge, which in turn can result in significant changes in the biota that are present and in the chemical and biological processes that take place in wetlands. Furthermore, these changes can ultimately affect the base flow to streams, which in turn affects riverine ecosystems. Drainage also alters the water-holding capacity of topographic depressions as well as the surface runoff rates from land having very low slopes. More efficient runoff caused by drainage systems results in decreased recharge to ground water and greater contribution to flooding. Drainage of the land surface is common in regions having extensive wetlands, such as coastal, riverine, and some glacial-lake landscapes. Construction of artificial drainage systems is extensive in these regions because wetland conditions generally result in deep, rich, organic soils that are much prized for agriculture. In the most extensive artificially drained part of the Nation, the glacial terrain of the upper Midwest, it is estimated that more than 50% of the original wetland areas have been destroyed. In Iowa alone, the destruction exceeds 90%. Although some wetlands were destroyed by filling, most were destroyed by drainage[8].

Modifications to River Valleys

Construction of Levees are built along riverbanks to protect adjacent lands from flooding. These structures commonly are very effective in containing smaller magnitude floods that are likely to occur regularly from year to year. Large floods that occur much less frequently, however, sometimes overtop or breach the levees, resulting in widespread flooding. Flooding of low-lying land is, in a sense, the most visible and extreme example of the interaction of ground water and surface water. During flooding, recharge to ground water is continuous; given sufficient time, the water table may rise to the land surface and completely saturate the shallow aquifer. Under these conditions, an extended period of drainage from the shallow aquifer takes place after the floodwaters recede. The irony of levees as a flood protection mechanism is that if levees fail during a major flood, the area, depth, and duration of flooding in some areas may be greater than if levees were not present.

Construction of Reservoirs

The primary purpose of reservoirs is to store water for uses such as public water supply, irrigation, flood attenuation, and generation of electric power. Reservoirs also can provide opportunities for recreation and wildlife habitat. Water needs to be stored in reservoirs because streamflow is highly variable, and the times when streamflow is abundant do not necessarily coincide with the times when the water is needed. Streamflow can vary daily in response to individual storms and seasonally in response to variation in weather patterns. The effects of reservoirs on the interaction of ground water and surface water are greatest near the reservoir and directly downstream from it. Reservoirs can cause a permanent rise in the water table that may extend a considerable distance from the reservoir, because the base level of the stream, to which the ground-water gradients had adjusted, is raised to the higher reservoir levels.

Near the dam, reservoirs commonly lose water to shallow ground water, but this water commonly returns to the river as base flow directly downstream from the dam. In addition, reservoirs can cause temporary bank storage at times when reservoir levels are high. In some cases, this temporary storage of surface water in the ground-water system has been found to be a significant factor in reservoir management. Human-controlled reservoir releases and accumulation of water in storage may cause high flows and low flows to differ considerably in magnitude and timing compared to natural flows. As a result, the environmental conditions in river valleys downstream from a dam may be altered as organisms try to adjust to the modified flow conditions.

For example, the movement of water to and from bank storage under controlled conditions would probably be much more regular in timing and magnitude compared to the highly variable natural flow conditions, which probably would lead to less biodiversity in river systems downstream from reservoirs. The few studies that have been made of riverine ecosystems downstream from a reservoir indicate that they are different from the pre-reservoir conditions, but much more needs to be understood about the effects of reservoirs on stream channels and riverine ecosystems downstream from dams[9].

Removal of Natural Vegetation

To make land available for agriculture and urban growth, development sometimes involves cutting of forests and removal of riparian vegetation and wetlands. Forests have a significant role in the hydrologic regime of watersheds. Deforestation tends to decrease evapotranspiration, increase storm runoff and soil erosion, and decrease infiltration to ground water and base flow of streams. From the viewpoint of water-resource quality and management, the increase in storm runoff and soil erosion and the decrease in base flow of streams are generally viewed as undesirable. In the western United States, removal of riparian vegetation has long been thought to result in an increase in streamflow.

It commonly is believed that the phreatophytes in alluvial valleys transpire ground water that otherwise would flow to the river and be available for use. Some of the important functions of riparian vegetation and riparian wetlands include preservation of aquatic habitat, protection of the land from erosion, flood mitigation, and maintenance of water quality. Destruction of riparian vegetation and wetlands removes the benefits of erosion control and flood mitigation, while altering aquatic habitat and chemical processes that maintain water quality.

Effects of Surface-Water Reservoirs on the Interaction of Ground Water and Surface Water

The increase of water levels in reservoirs causes the surface water to move into bank storage. When water levels in reservoirs are decreased, this bank storage will return to the reservoir. Depending on the size of the reservoir and the magnitude of fluctuation of the water level of the reservoir, the amount of water involved in bank storage can be large. A study of bank storage associated with Hungry Horse Reservoir in Montana, which is part of the Columbia River system, indicated that the amount of water that would return to the reservoir from bank storage after water levels are lowered is large enough that it needs to be considered in the reservoir management plan for the Columbia River system. As a specific example, if the water level of the reservoir is raised 100 feet, held at that level for a year, then lowered 100 feet, the water that would drain back to the reservoir during a year would be equivalent to an additional 3 feet over the reservoir surface.

Effects of the Removal of Flood-Plain Vegetation on the Interaction of Ground Water and Surface Water

In low-lying areas where the water table is close to land surface, such as in flood plains, transpiration directly from ground water can reduce ground-water discharge to surface water and can even cause surface water to recharge ground water. This process has attracted particular attention in arid areas, where transpiration by phreatophytes on flood plains of western rivers can have a significant effect on stream flows. To assess this effect, a study was done on transpiration by phreatophytes along a reach of the Gila River upstream from San Carlos Reservoir in Arizona. During the first few years of the 10-year study, the natural hydrologic system was monitored using observation wells, streamflow gages, and meteorological instruments. Following this initial monitoring period, the phreatophytes were removed from the flood plain and the effects on streamflow were evaluated. The average effect of vegetation removal over the entire study reach was that the Gila River changed from a continually losing river for most years before clearing to a gaining stream during some months for most years following clearing. Specifically, average monthly values of gain or loss from the stream indicated that before clearing, the river lost water to ground water during all months for most years. After clearing, the river gained ground-water inflow during March through June and during September for most years[10].

Modifications to the Atmosphere

- **Atmospheric Deposition**

Atmospheric deposition of chemicals, such as sulfate and nitrate, can cause some surface-water bodies to become acidic. Concern about the effects of acidic precipitation on aquatic ecosystems has led to research on the interaction of ground water and surface water, especially in small headwaters catchments. It was clear when the problem was first recognized that surface water bodies in some environments were highly susceptible to acidic precipitation, whereas in other environments they were not. Research revealed that the interaction of ground water and surface water is important to determining the susceptibility of a surface-water body to acidic precipitation. For example, if a surface-water body received a significant inflow of ground water, chemical exchange while the water passed through the subsurface commonly neutralized the acidic water, which can reduce the acidity of the surface water to tolerable levels for aquatic organisms. Conversely, if runoff of acidic precipitation was rapid and involved very little flow through the ground-water system, the surface-water body was highly vulnerable and could become devoid of most aquatic life.

Global Warming

The concentration of gases, such as carbon dioxide (CO_2) and methane, in the atmosphere has a significant effect on the heat budget of the Earth's surface and the lower atmosphere. The increase in concentration of CO_2 in the atmosphere of about 25% since the late 1700s generally is thought to be caused by the increase in burning of fossil fuels. At present, the analysis and prediction of "global warming" and its possible effects on the hydrologic cycle can be described only with great uncertainty. Although the physical behavior of CO_2 and other greenhouse gases is well understood, climate systems are exceedingly complex, and long-term changes in climate are embedded in the natural variability of the present global climate regime. Surficial aquifers, which supply much of the streamflow nationwide and which contribute flow to lakes, wetlands, and estuaries, are the aquifers most sensitive to seasonal and longer term climatic variation. As a result, the interaction of ground water and surface water also will be sensitive to variability of climate or to changes in climate. However, little attention has been directed at determining the effects of climate change on shallow aquifers and their interaction with surface water, or on planning how this combined resource will be managed if climate changes significantly.

Effects of Atmospheric Deposition on the Quality of Ground Water and Surface Water

In areas where soils have little capacity to buffer acids in water, acidic precipitation can be a problem because the infiltrating acidic water can increase the solubility of metals, which results in the flushing of high concentrations of dissolved metals into surface water. Increased concentrations of naturally occurring metals such as aluminum may be toxic to aquatic organisms. Studies of watersheds have indicated that the length of subsurface flow paths has an effect on the degree to which acidic water is buffered by flow through the subsurface. For example, studies of watersheds in England have indicated that acidity was higher in streams during storms when more of the subsurface flow moved through the soil rather than through the deeper flow paths. Moreover, in a study of the effects of acid precipitation on lakes in the Adirondack Mountains of New York, the length of time that water was in contact with deep subsurface materials was the most important factor affecting acidity because contact time determined the amount of buffering that could take place.

Challenges and Opportunities

The interaction of ground water and surface water involves many physical, chemical, and biological processes that take place in a variety of physiographic and climatic settings. For many decades, studies of the interaction of ground water and surface water were directed primarily at large alluvial stream and aquifer systems. Interest in the relation of ground water to surface water has increased in recent years as a result of widespread concerns related to water supply; contamination of ground water, lakes, and streams by toxic substances; acidification of surface waters caused by atmospheric deposition of sulfate and nitrate; eutrophication of lakes; loss of wetlands due to development; and other changes in aquatic environments. As a result, studies of the interaction of ground water and surface water have expanded to include many other settings, including headwater streams, lakes, wetlands, and coastal areas. Issues related to water management and water policy were presented at the beginning of this report. The following sections address the need for greater understanding of the interaction of ground water and surface water with respect to the three issues of water supply, water quality, and characteristics of aquatic environments.

Water Supply

Water commonly is not present at the locations and times where and when it is most needed. As a result, engineering works of all sizes have been constructed to distribute water from places of abundance to places of need. Regardless of the scale of the water-supply system, development of either ground water or surface water can eventually affect the other. For example, whether the source of irrigation water is ground water or surface water, return flows from irrigated fields will eventually reach surface water either through ditches or through ground-water discharge. Building dams to store surface water or diverting water from a stream changes the hydraulic connection and the hydraulic gradient between that body of surface water and the adjacent ground water, which in turn results in gains or losses of ground water. In some landscapes, development of ground water at even a great distance from surface water can reduce the amount of ground-water inflow to surface water or cause surface water to recharge ground water. The hydrologic system is complex, from the climate system that drives it, to the earth materials that the water flows across and through, to the modifications of the system by human activities. Much research and engineering has been devoted to the development of water resources for water supply. However, most past work has concentrated on either surface water or ground water without much concern about their interrelations. The need to understand better how development of one water resource affects the other is universal and will surely increase as development intensifies[11].

Water Quality

For nearly every type of water use, whether municipal, industrial, or agricultural, water has increased concentrations of dissolved constituents or increased temperature following its use. Therefore, the water quality of the water bodies that receive the discharge or return flow are affected by that use. In addition, as the water moves downstream, additional water use can further degrade the water quality. If irrigation return flow, or discharge from a municipal or industrial plant, moves downstream and is drawn back into an aquifer because of ground-water withdrawals, the ground-water system also will be affected by the quality of that surface water.

Application of irrigation water to cropland can result in the return flow having poorer quality because evapotranspiration by plants removes some water but not the dissolved salts. As a result, the dissolved salts can precipitate as solids, increasing the salinity of the soils. Additional application of water dissolves these salts and moves them farther down gradient in the hydrologic system. In addition, application of fertilizers and pesticides to cropland can result in poor-quality return flows to both ground water and surface water. The transport and fate of contaminants caused by agricultural practices and municipal and industrial discharges are a widespread concern that can be addressed most effectively if ground water and surface water are managed as a single resource.

Water scientists and water managers need to design data-collection programs that examine the effects of biogeochemical processes on water quality at the interface between surface water and near-surface sediments. These processes can have a profound effect on the chemistry of ground water recharging surface water and on the chemistry of surface water recharging ground water. Repeated exchange of water between surface water and near surface sediments can further enhance the importance of these processes. Research on the interface between ground water and surface water has increased in recent years, but only a few stream environments have been studied, and the transfer value of the research results is limited and uncertain.

The tendency for chemical contaminants to move between ground water and surface water is a key consideration in managing water resources. With an increasing emphasis on watersheds as a focus for managing water quality, coordination between watershed-management and ground water-protection programs will be essential to protect the quality of drinking water. Furthermore, ground-water and surface-water interactions have a major role in affecting chemical and biological processes in lakes, wetlands, and streams, which in turn affect water quality throughout the hydrologic system. Improved scientific understanding of the interconnections between hydrological and biogeochemical processes will be needed to remediate contaminated sites, to evaluate applications for waste-discharge permits, and to protect or restore biological resources.

Characteristics of Aquatic Environments

The interface between ground water and surface water is a really restricted, but particularly sensitive and critical niche in the total environment. At this interface, ground water that has been affected by environmental conditions on the terrestrial landscape interacts with surface water that has been affected by environmental conditions upstream. Furthermore, the chemical reactions that take place where chemically distinct surface water meets chemically distinct ground water in the hyporheic zone may result in a biogeochemical environment that in some cases could be used as an indicator of changes in either terrestrial or aquatic ecosystems. The ability to understand this interface is challenging because it requires the focusing of many different scientific and technical disciplines at the same, really restricted locality. The benefit of this approach to studying the interface of ground water and surface water could be the identification of useful biological or chemical indicators of adverse or positive changes in larger terrestrial and aquatic ecosystems.

Wetlands are a type of aquatic environment present in most landscapes; yet, in many areas, their perceived value is controversial. The principal characteristics and functions of wetlands are determined by the water and chemical balances that maintain them. These factors in large part determine the value of a wetland for flood control, nutrient retention, and wildlife habitat. As a result, they are especially sensitive to changing hydrological conditions. When the hydrological and chemical balances of a wetland change, the wetland can take on a completely different function, or it may be destroyed. Generally, the most devastating impacts on wetlands result from changes in land use. Wetlands commonly are drained to make land available for agricultural use or filled to make land available for urban and industrial development. Without understanding how wetlands interact with ground water, many plans to use land formerly occupied by wetlands fail. For example, it is operationally straight forward to fill in or drain a wetland, but the ground water flow system that maintains many wetlands may continue to discharge at that location.

Many structures and roads built on former wetlands and many wetland restoration or construction programs fail for this reason. Saline soils in many parts of the central prairies also result from evaporation of ground water that continues to discharge to the land surface after the wetlands were drained. Riparian zones also are particularly sensitive to changes in the availability and quality of ground water and surface water because these ecosystems commonly are dependent on both sources of water. If either water source changes, riparian zones may be altered, changing their ability to provide aquatic habitat, mitigate floods and erosion, stabilize shorelines, and process chemicals, including contaminants. Effective management of water resources requires an understanding of the role of riparian zones and their dependence on the interaction of ground water and surface water.

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CHAPTER 15

AVAILABILITY OF WATER ON EARTH SURFACE

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Water on the surface of earth is available in the atmosphere, the oceans, on land and within the soil and fractured rock of the earth's crust. Water molecules from one location to another are driven due to the solar energy transmitted to the surface of the earth from Sun. Moisture circulates from the earth into the atmosphere through evaporation and then back into the earth as precipitation[1].

Hydrology

It is the study of physical geographic which deals with the origin, distribution and properties of water present in earth surface and hydrological cycle display in Figure 1:

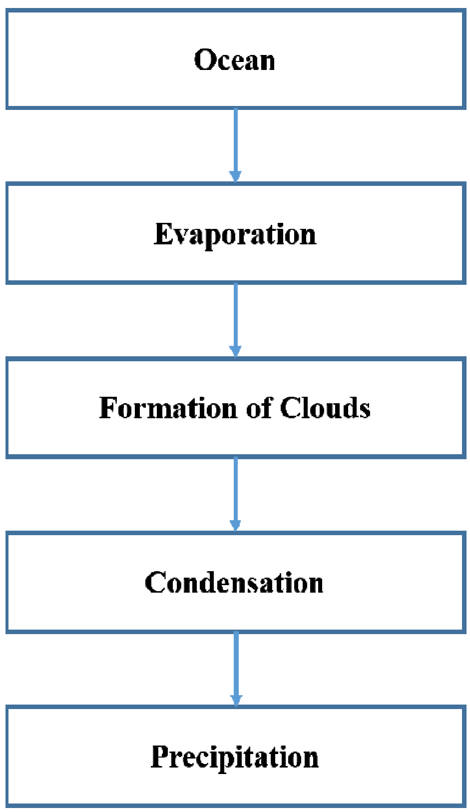

Figure 1: Represented the Hydrological Cycle.

World Water Balance

Total quantity of water in the world is estimated to be about 1386 million cubic kilometer (M Km^3). About 96.5% of this water is contained in the oceans as saline water. Some of the water on the land amounting to about 1% of the total water is also saline. Thus, only about 35.0 M Km^3 of fresh water is available. Out of this about 10.6 M Km^3 is both liquid and fresh and the remaining

24.4 M Km^3 is contained in frozen state as ice in the Polar Regions and on mountain tops and glaciers. The term "precipitation" denotes all forms of water that reach the earth from the atmosphere. The usual forms are rainfall, snowfall, hail, frost and dew. The magnitude of precipitation varies with time and space. For precipitation to form[2]:

- **i.** The atmosphere must have moisture,
- **ii.** There must be sufficient nuclei present to aid condensation, weather conditions must be good for condensation of water vapor to take place,
- **iii.** The products of condensation must reach the earth.

Forms of Precipitation

Some of the common forms of precipitation are rain, snow, drizzle, glaze, sleet and hail.

i. Rain

It is the principal form of precipitation in India. The term rainfall is used to describe precipitation in the form of water drops of sizes larger than 0.5mm. The maximum size of a raindrop is 6mm. Any drop larger in size than this tends to break up into drops of smaller sizes during its fall from the clouds. On the basis of its intensity rainfall is classified as follows:

Light rain: trace to 2.5 mm/hr

Moderate rain: 2.5mm/hr to 7.5mm/hr

Heavy rain: > 7.5mm/hr

ii. Snow

Snow is another important form of precipitation. Snow consists of ice crystals which usually combine to form flakes. When fresh, snow has an initial density varying from 0.06 to 0.15g/cm^3 and it is usual to assume an average density of 0.1 g /cm^3. In India, snow occurs only in the Himalayan regions.

iii. Drizzle

A fine sprinkle of numerous water droplets of size less than 0.5mm and intensity less than 1mm/hr is known as drizzle. In this, the drops are so small that they appear to float in the air.

iv. Glaze

When rain or drizzle comes in contact with cold ground at 0^0C, the water drops freeze to form an ice coating called glaze or freezing rain.

v. Sleet

It is frozen raindrops of transparent grains which form when rain falls through air at sub-freezing temperature. In Britain, sleet denotes precipitation of snow and rain simultaneously.

vi. Hail

It is a showery precipitation in the forms of irregular pellets of lump of ice of size more than 8mm. Hails occur in violent thunderstorms in which vertical currents are very strong.

Weather Systems for Precipitation

For the formation of clouds and subsequent precipitation, it is necessary that the moist air masses cool to form condensation. This is normally accomplished by adiabatic cooling of moist air through a process of being lifted to higher altitude. Some of the terms and processes connected with weather systems associated with precipitation are given below[3]:

a. **Front**

A front is the interface between two distinct air masses. Under certain favorable conditions when a warm air mass and cold air mass meet, the warmer air mass is lifted over the colder one with the formation of front. The ascending warmer air cools adiabatically with the consequent formation of clouds and precipitation.

b. **Cyclone**

A cyclone is a large low pressure region with circular wind motion. Two types of cyclones are recognized: tropical cyclones and extra tropical cyclones.

- **Tropical Cyclone**

A tropical cyclone, also called cyclone in India, hurricane in USA and typhoon in south East Asia, is a wind system with an intensely strong depression with MSL pressures sometimes below 915 m bars. The normal areal extend of cyclone is about 100-200 km in diameter. The isobars are closely spaced and the winds are anticlockwise in the northern hemisphere. The center of the storm called the eye, which may extend to about 10-50 km in diameter, will be relatively quiet. However, right outside the eye, very strong winds/reaching to as much as 200 km per hr exist. The wind speed gradually decreases towards the outer edge. The pressure also increases outwards. The rainfall will normally be heavy in the entire area occupied by the cyclone[4].

- **Extra Tropical Cyclone**

These are cyclones formed in locations outside the tropical zone. Associated with a frontal system, they possess a strong counter clockwise wind circulation in the northern hemisphere. The magnitude of precipitation and wind velocities are relatively lower than those of a tropical cyclone. However, the duration of precipitation is usually longer and the areal extend is also larger.

- **Anticyclones**

These are regions of high pressure, usually of large areal extent. The weather is usually calm act the center. Anticyclones cause clockwise wind circulations in the northern hemisphere. Winds are of moderate speed, and at the outer, cloudy and precipitation conditions exist.

- **Convective Precipitation**

In this type of precipitation, a packet of air which is warmer than the surrounding air due to localized heating rises because of its lesser density. Air from cooler surroundings flows to take up its place, thus setting up a convective cell. The warm air continues to rise, undergoes cooling and results in precipitation. Depending upon the moisture, thermal and other conditions, light showers to thunderstorms can be expected in convective precipitation. Usually, the aerial extent of such rains is small, being limited to a diameter of about 10km.

- **Orographic Precipitation**

The moist air masses may get lifted up to higher altitudes due to the presence of mountain barriers and consequently undergo cooling, condensation and precipitation. Such a precipitation is known as orographic precipitation. Thus, in mountain ranges, the windward slopes of heavy precipitation and the leeward slopes have light rainfall[5].

Annual Rainfall

Considerable areal variation exists for the annual rainfall of the magnitude of 200cm in Assam and north-eastern parts and Western-Ghats, and scanty rainfall in eastern Rajasthan and parts of Gujarat, Maharashtra and Karnataka. The average annual rainfall for the entire country is estimated as 118.3cm. It is well known that there is considerable variation of annual rainfall in time at a place. The coefficient of variation,

C_v= (100* standard deviation)/ Mean

Of the annual rainfall varies between 15 and 70, from place to place with an average value of about 30. Variability is least in regions of high rainfall and largest in regions of scanty rainfall. Gujarat, Haryana, Punjab and Rajasthan have large variability of rainfall. Some of the interesting statistics relating to the variability of the seasonal and annual rainfall of India are as follows:

- A few heavy spells of rain contribute nearly 90% of total rainfall.
- While the average annual rainfall of the country is 118 cm, average annual rainfall varies from 10 cm in the western desert to 1100 cm in the north-east region.
- More than 50% rain occurs within 15 days and less than 100 hours in a year.
- More than 805 of seasonal rainfall is produced in 10-20% rain events, each lasting 1-3 days.

Measurement of Precipitation

Rainfall

Precipitation is expressed in terms of the depth to which rainfall water would stand on an area if all the rain were collected on it. Thus, 1cm of rainfall over a catchment area of 1km^2 represents a volume of water equal to 104 m^3. In the case of snowfall, an equivalent depth of water is used as the depth of precipitation. The precipitation is collected and measured in a rain gauge. Terms such pluviometer barometer and hyetometer area also sometimes used to designate a rain gauge. A rain gauge essentially consists of a cylindrical vessel assembly kept in the open to collect rain. The rainfall catch of the rain gauge is affected by its exposure conditions.

To enable the catch of rain gauge to accurately represent the area in the surrounding the rain gauge standard settings are adopted. For setting up a rain gauge the following considerations are important: The ground must be level and in the open and the instrument must present a horizontal catch surface. The gauge must be set as near the ground as possible to reduce wind effects but it must be sufficiently high to prevent splashing flooding etc. The instrument must be surrounded by an open fenced area of at least 5.5 m * 5.5 m. No object should be nearer to the instrument than 30 m or twice the height of the obstruction. Rain gauges can be broadly classified into two categories as[6]:

a. Non recording gauges,

b. Recording gauges.

Non-recording Gauges

The non-recording gauge extensively used in India is the Symon's gauge. It essentially consists of a circular collection area of 12.7 cm (5.0 inch) diameter connected to a funnel. The rim of the collector is set in a horizontal plane at a height of 30.5 cm above the ground level. The funnel discharges the rainfall catch into a receiving vessel. The funnel and receiving vessel are housed in a metallic container.

Fig below shows the details of the installation. Water contained in the receiving vessel is measured by a suitably graduated measuring glass, with accuracy up to 0.1mm. Recently, the Indian Meteorological Department (IMD) has changed over to the use of fiber glass reinforced polyester rain-gauges, which is an improvement over the Symon's gauge. These come in different combinations of collector is in two sizes having areas of 200 and 100 cm^2 respectively. Indian standard gives details of these new rain-gauges.

For uniformity, the rainfall is measured every day at 8.30a.m. and is recorded as the rainfall of that day. The receiving bottle normally does not hold more than 10cm of rain and as such, in the case of heavy rainfall, the measurements must be done more frequently and entered. However, the last reading must be taken at 8.30 a.m. and the sum of the previous readings in the past 24 hours entered as the total of that day.

Proper care, maintenance and inspection of rain-gauges, especially during dry weather to keep the instrument free from dust and dirt, is very necessary. The details of installation of non-recording rain-gauges and measurement of rain are specified in Indian Standard[7].This rain-gauge can also be used to measure snowfall. When snow is expected, the funnel and receiving bottle are removed and the snow is allowed to collect in the outer metal container. The snow is then melted and the depth of resulting water measured. Antifreeze agents are sometimes used to facilitate melting of snow. In areas where considerable snowfall is expected, special snow-gauges with shields for minimizing the wind effect and storage pipes to collect snow over longer durations are used.

Recording Gauges

Recording gauges produce a continuous plot of rainfall against time and provide valuable data of intensity and duration of rainfall for hydrological analysis of storms. The following are some of the commonly used recording rain-gauges.

a. Tipping-Bucket Type

This is a 30.5 cm size rain-gauge adopted for use by the US Weather Bureau. The catch from the funnel falls onto one of a pair of small buckets. These buckets are so balanced that when 0.25 mm of rainfall collects in one bucket, it tips and brings the other one in position. The water from the tipped bucket is collected in a storage can. The tipping actuates an electrically driven pen to trace a record on the clockwork-driven chart. The water collected in the storage can is measured at regular intervals to provide the total rainfall and also serve as a check. It may be noted that the record from the tipping bucket gives data on the intensity of rainfall. Further, the instrument is ideally suited for digitalizing of the output signal[8], [9].

b. Weighing-Bucket Type

In this rain-gauge, the catch from the funnel empties into a bucket mounted on a weighing scale. The weight of the bucket and its contents are recorded on a clockwork-driven chart. The clockwork mechanism has the capacity to run for as long as one week. This instrument gives a plot of the accumulated rainfall against the elapsed time, i.e. the mass curve of rainfall. In some instruments of this type, the recording unit is so constructed that the pen reverses its direction at every preset value, say 7.5 cm (3inch) so that a continuous plot of storm is obtained.

c. Natural-Syphon Type

This type of recording rain-gauge is also known as float-type gauge. Here, the rainfall collected by a funnel-shaped collector is led into a float chamber causing a float to rise. As the float rises, a pen attached to the float through a lever system records the elevation of the float on a rotating drum driven by a clockwork mechanism. A siphon arrangement empties the float chamber when the float has reached a preset maximum level[10], [11]. This type of rain-gauge is adopted as the standard recording-type rain-gauge in India and in details is described in Indian Standard.

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CHAPTER 16

AN OVERVIEW OF STORAGE WORKS-RESERVOIRS

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Water storage reservoirs may be created by constructing a dam across a river, along with suitable appurtenant structures. However, in that lesson not much was discussed about fixing the size of reservoir based on the demand for which it is being constructed. Further, reservoirs are also meant to absorb a part of flood water and the excess is discharged through a spillway. It is also essential to study the relation between flood discharge, reservoirs capacity and spillway size in order to propose an economic solution to the whole project. These and topics on reservoir sedimentation have been discussed in this lesson which shall give an idea as to how a reservoir should be built and optimally operated. Fundamentally, a reservoir serves to store water and the size of the reservoir is governed by the volume of the water that must be stored, which in turn is affected by the variability of the inflow available for the reservoir. Reservoirs are of two main categories[1]:

- **a.** Impounding reservoirs into which a river flows naturally,
- **b.** Service or balancing reservoirs receiving supplies that are pumped or channeled into them artificially.

In general, service or balancing reservoirs are required to balance supply with demand. Reservoirs of the second type are relatively small in volume because the storage required by them is to balance flows for a few hours or a few days at the most. Impounding or storage reservoirs are intended to accumulate a part of the flood flow of the river for use during the non-flood months. In this lesson, our discussions would be centered on these types of reservoirs.

Reservoir storage zone and uses of reservoir

The storage capacity in a reservoir is nationally divided into three or four parts as mention in Figure 1, distinguished by corresponding levels.

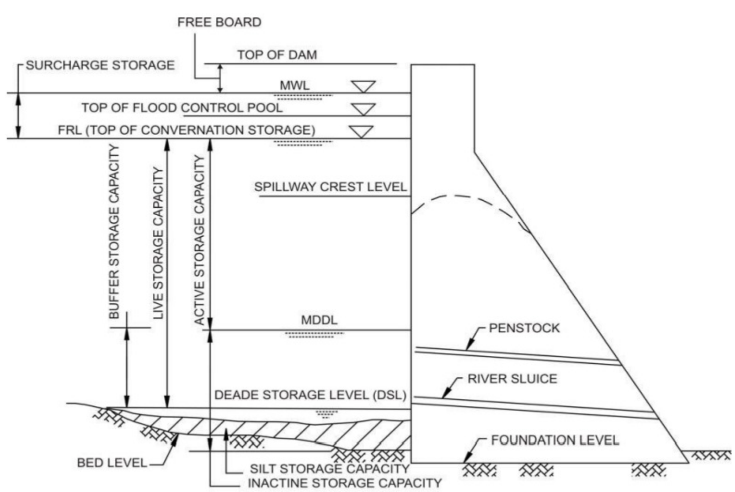

Figure 1: Represented the Storage Zones.

These specific levels and parts are generally defined as follows:

i. Full Reservoir Level (FRL)

It is the level corresponding to the storage which includes both inactive and active storages and also the flood storage, if provided for. In fact, this is the highest reservoir level that can be maintained without spillway discharge or without passing water downstream through sluiceways.

ii. Minimum Drawdown Level (MDDL)

It is the level below which the reservoir will not be drawn down so as to maintain a minimum head required in power projects.

iii. Dead Storage Level (DSL)

Below the level, there are no outlets to drain the water in the reservoir by gravity.

iv. Maximum Water Level (MWL)

This id the water level that is ever likely to be attained during the passage of the design flood. It depends upon the specified initial reservoir level and the spillway gate operation rule. This level is also called sometimes as the Highest Reservoir Level or the Highest Flood Level.

v. Live Storage

This is the storage available for the intended purpose between Full Supply Level and the Invert Level of the lowest discharge outlet. The Full Supply Level is normally that level above which over spill to waste would take place. The minimum operating level must be sufficiently above the lowest discharge outlet to avoid vortex formation and air entrainment. This may also be termed as the volume of water actually available at any time between the Dead Storage Level and the lower of the actual water level and Full Reservoir Level[2].

vi. Dead Storage

It is the total storage below the invert level of the lowest discharge outlet from the reservoir. It may be available to contain sedimentation, provided the sediment does not adversely affect the lowest discharge.

vii. Outlet Surcharge or Flood Storage

This is required as a reserve between Full Reservoir Level and the Maximum Water level to contain the peaks of floods that might occur when there is insufficient storage capacity for them below Full Reservoir Level.

Some other terms related to reservoirs are defined as follows:

i. Buffer Storage

This is the space located just above the Dead Storage Level up to Minimum Drawdown Level. As the name implies, this zone is a buffer between the active and dead storage zones and releases from this zone are made in dry situations to cater for essential requirements only. Dead Storage and Buffer Storage together is called Interactive Storage.

ii. Within-the-Year Storage

This term is used to denote the storage of a reservoir meant for meeting the demands of a specific hydrologic year used for planning the project.

iii. Carry-Over Storage

When the entire water stored in a reservoir is not used up in a year, the unused water is stored as carry-over storage for use in subsequent years.

iv. Silt / Sedimentation Zones

The space occupied by the sediment in the reservoir can be divided into separate zones. A schematic diagram showing these zones is illustrated in Figure 2[3].

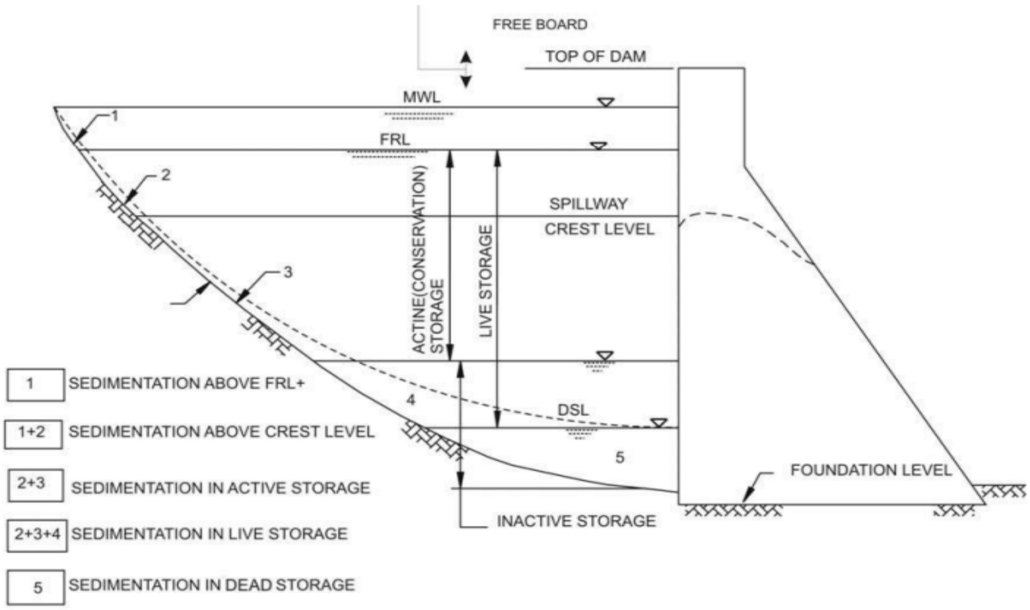

Figure 2: Illustrated the Zones of Reservoir Sedimentation

Freeboard

It is the margin kept for safety between the level at which the dam would be overtopped and the maximum still water level. This is required to allow for settlement of the dam, for wave run up above still water level and for unforeseen rises in water level, because of surges resulting from landslides into the reservoir from the peripheral hills, earthquakes or unforeseen floods or operational deficiencies. The functions of reservoirs are to provide water for one or more of the following purposes. Reservoirs that provide water for a combination of these purpose, are termed as Multi Purpose reservoirs.

- **a.** Human consumption and/or industrials
- **b.** **Irrigation:** usually to supplement insufficient rainfall.
- **c.** **Hydropower:** to generate power and energy whenever water is available or to provide reliable supplies of power and energy at all times when needed to meet demand[4].
- **d.** **Pumped storage hydropower schemes:** in which the water flows from an upper to a lower reservoir, generating power and energy at times of high demand through turbines, which may be reversible, and the water is pumped back to the upper.Reservoir when surplus energy is available. The cycle is usually daily or twice daily to meet peak

demands. Inflow to such a reservoir is not essential, provided it is required to replace water losses through leakage and evaporation or to generate additional electricity. In such facilities, the power stations, conduits and either or both of the reservoirs could be constructed underground if it was found to do so.

e. Flood control

Storage capacity is required to be maintained to absorb foreseeable flood inflows to the reservoirs, so far as they would cause excess of acceptable discharge spillway opening. Storage allows future use of the flood water retained.

f. Amenity use: this may include provision for boating, water sports, fishing, sightseeing.

Formally, the Bureau of Indian Standards code “Glossary of terms relating to river valley projects -Reservoirs" defines the following types of reservoirs:

i. **Auxiliary or Compensatory Reservoir:** A reservoir which supplements and absorbed the spill of a main reservoir.

ii. **Balancing Reservoirs:** A reservoir downstream of the main reservoir for holding water let down from the main reservoir in excess of that required for irrigation, power generation or other purposes.

iii. **Conservation Reservoir:** A reservoir impounding water for useful purposes, such as irrigation, power generation, recreation, domestic, industrial and municipal supply etc.

iv. **Detention Reservoir:** A reservoir where in water is stored for a relatively brief period of time, past of it being retained until the stream can safely carry the ordinary flow plus the released water. Such reservoirs usually have outlets without control gates and are used for flood regulation. These reservoirs are also called as the Flood Control Reservoir or Retarding Reservoir.

v. **Distribution Reservoir:** A reservoir connected with distribution system a water supply project, used primarily to care for fluctuations in demand which occur over short periods and as local storage in case of emergency such as a break in a main supply line failure of a pumping plant[5].

vi. **Impounding or Storage Reservoir:** A reservoir with gate-controlled outlets wherein surface water may be retained for a considerable period of time and released for use at a time when the normal flow of the stream is in sufficient to satisfy requirements.

vii. **Multipurpose Reservoir:** A reservoir constructed and equipped to provide storage and release of water for two or more purposes such as irrigation, flood control, power generation, navigation, pollution abatement, domestic and industrial water supply, fish culture, recreation, etc.

It may be observed that some of these objectives may be incompatible in combination. For example, water may has to be released for irrigation to suit crop growing seasons, while water releases for hydropower are required to suit the time of public and industrial demands. The latter will be affected not only by variations in economic conditions but also by variations over a day and night cycle.

Compatibility between irrigation demand and flood control strategy in operating a reservoir is even more difficult for a reservoir which intends to serve both, like the Hirakud Dam reservoir on the river Mahanadi. Flood wave moderation requires that the reservoir be emptied as much as possible so that it may absorb any incoming flood peak. However, this decision means reducing the water stored for irrigation.

Usually, such a reservoir would be gradually emptied just before the arrival of monsoon rains, anticipating a certain flood and hoping that the reservoir would be filled to the brim at the end of the flood season. However, this anticipation may not hold good for all years and the reservoir does not get filled up to the optimal height. On the other hand, if the reservoir is not depleted sufficiently well, and actually a flood of high magnitude arrives, then the situation may lead to the flood inundations on the downstream.

Planning of Reservoirs

The first step in planning the construction of a reservoir with the help of a dam is for the decision makers to be sure of the needs and purposes for which the reservoir is going to be built together with the known constraints (including financial), desired benefits. There may be social constraints, for examples people's activism may not allow a reservoir to be built up to the desired level or even the submergence of good agricultural level may be a constraint. Sometimes, the construction of a dam may be done that is labour intensive and using local materials, which helps the community for whom the dam is being built. This sort of work is quite common in the minor irrigation departments of various steps, especially in the drought prone areas. The Food-forWork schemes can be utilized in creating small reservoirs that helps to serve the community. In a larger scale, similar strategy was adopted for the construction of the Nagarjuna Sagar Dam on the River Krishna, which was built entirely of coursed rubble masonry and using manual labour in thousands[6].

The second step is the assembly of all relevant existing information, which includes the following:

- **a.** Reports of any previous investigations and studies, if any.
- **b.** Reports on projects similar to that proposed which have already been constructed in the region.
- **c.** A geographical information system (GIS) for the area of interest may be created 8 using a base survey map of the region.
- **d.** Topographical data in the form of maps and satellite pictures, which may be integrated within the GIS.
- **e.** Geological data in the form of maps and borehole logs, along with the values of relevant parameters.
- **f.** Seismic activity data of the region that includes recorded peak accelerations or ground motion record.
- **g.** Meteorological and hydrological data of available parameters like rainfall, atmospheric and water temperatures, evaporation, humidity, wind speed, hours of sunshine, river flows, river levels, sediment concentration in rivers, etc.

h. For water supply projects, data on population and future population growth based on some acceptable forecast method, industrial water requirement and probable future industrial development.

i. For irrigation projects, data on soils in the project area and on the crops already grown, including water requirement for the crops.

j. For hydropower projects, data on past demand and forecasts of future public and industrial demand for power and energy; data on existing transmission systems, including transmission voltage and capacity.

k. Data on flora and fauna in the project and on the fish in the rivers and lakes, including data on their migratory and breeding habits.

l. Data on tourism and recreational use of rivers and lakes and how this may be encouraged on completion of the proposed reservoir.

As may be noted, some of the data mentioned above would be needed to design and construct the dam and its appurtenant structures which would help to store water behind the reservoir. However, there are other data that decides the following:

a. How large the reservoir should be and, consequently, what should be the dam height?

b. What should be the size of the spillway and at what elevation the crest level of the spillway be located?

c. How many and at what levels sluices be provided and they should be of what sizes?

Two important aspects of reservoirs planning: Sedimentation Studies and Geological Explorations are described in detail in the following section.

Effect of sedimentation in planning of reservoirs

It is important to note that storage reservoirs built across rivers and streams lose their capacity on account of deposition of sediment. This deposition which takes place progressively in time reduces the active capacity of the reservoir to provide the outputs of water through passage of time. Accumulation of sediment at or near the dam may interfere with the future functioning of water intakes and hence affects decisions regarding location and height of various outlets. It may also result in greater inflow of into canals / water conveyance systems drawing water from the reservoir. Problems of rise in flood levels in the head reaches and unsightly deposition of sediment from recreation point of may also crop up in course of time. In this regard, the Bureau of Indian Standard code IS: 12182 - 1987 “Guidelines for determination of effects of sedimentation in planning and performance of reservoir” is an important document which discusses some of the aspects of sedimentation that have to be considered while planning reservoirs. Some of the important points from the code are as follows[7]:

While planning a reservoir, the degree of seriousness and the effect of sedimentation at the proposed location has to be judged from studies, which normally combination consists of:

a. Performance Assessment (Simulation) Studies with varying rate of sedimentation.

b. Likely effects of sedimentation at dam face.

In special cases, where the effects of sedimentation on backwater levels are likely to be significant, backwater studies would be useful to understand the size of river water levels. Similarly, special studies to bring out delta formation region changes may be of interest. The steps to be followed for performance assessment studies with varying rates of sedimentation are as follows:

a. Estimation of annual sediment yields into the reservoir or the average annual sediment yield and of trap efficiency expected.

b. Distribution of sediment within reservoir to obtain a sediment elevation and capacity curve at any appropriate time.

c. Simulation studies with varying rates of sedimentation.

d. Assessment of effect of sedimentation.

In general, the performance assessment of reservoir projects has to be done for varying hydrologic inputs to meet varying demands. Although analytical probability based methods are available to some extent, simulation of the reservoir system is the standard method. The method is also known as the working tables or sequential routing. In this method, the water balance of the reservoir s and of other specific locations of water use and constraints in the systems are considered. All inflows to and outflows from the reservoirs are worked out to decide the changed storage during the period. In simulation studies, the inflows to be used may be either historical inflow series, adjusted for future up stream water use changes or an adjusted synthetically generated series.

Procedure for planning a new reservoir

The standard procedure that needs to be carried out for planned storages requires an assessment of the importance of the problem to classify the reservoir sedimentation problem as insignificant, significant, or serious. Assessment of reservoir sedimentation problem, in a particular case may be made by comparing the expected average annual volume of sediment deposition with the gross capacity of the reservoir planned. If the 10 ratio is more than 0.5 percent per year, the problem is usually said to be serious and special care is required in estimating the sediment yields from the catchment. If it is less than 0.1 percent per year, the problem of siltation may be insignificant and changes in reservoir performance. For cases falling between these two limits, the sedimentation problem is considered significant and requires further studies[8].

The following studies are required if the problem is insignificant:

a. No simulation studies with sediment correlation isnecessary.

b. The feasible service time for the project may be decided. Sediment distribution studies to ensure that the new zero-elevation does not exceed the dead storage level may be made.

In the above, the following terms have been used, which are explained below:

a. **Feasible Service Time:** For a special purpose, the period or notional period for which a reservoir is expected to provide a part of the planned benefit in respect of storage in the reservoirs being impaired by sedimentation. Customarily, it is estimated as the time after which the new zero elevation of the reservoir would equal the sill of the outlet relevant for the purpose.

b. **New Zero Elevation:** The level up to which all the available capacity of the reservoir is expected to be lost due to progressive sedimentation of the reservoir up to the specified time. The specified time should be any length of time such as Full Service Time, Feasible Service time, etc.

c. **Full Service Time:** For a specified purpose, the period or notional period for which the reservoir provided is expected to provide, a part of the full planned benefit inspite of sedimentation.

The following studies are required if the problem of sedimentation in the reservoir is assessed to be significant, but not serious.

a. Both the full service time and feasible service time for the reservoir may be decided.

b. Simulation studies for conditions expected at the end of full service time may be made to ensure that firm outputs with required depend ability are obtained. The studies used also assess non-dependable secondary outputs, if relevant, available at the end of this period. Studies without sedimentation, with the same firm outputs should bring out the additional potential secondary outputs which may be used, if required in economic analysis, using a linear decrease of these additional benefits over the full service time.

c. No simulation studies beyond full service time, is required.

d. Sediment distribution studies required for feasible service time are essential.

The following studies are required if the problem of sedimentation is serious.

a. All studies described for the „Significant□ case have to be made.

b. The secondary benefits available in the initial years should be more in such cases. If they are being utilized, for a proper assessment of the change of these, a simulation at half of full service time should be required.

c. In these cases, the drop of benefits after the full service time may be sharper. To bring out these effects, a simulation of the project at the end of the feasible service time is required to be done.

Life of reservoir and design criteria

A reservoir exists for a long time and the period of its operation should normally check large technological and socio-economic changes. The planning assumptions about the exact socioeconomic outputs are, therefore, likely to be changed during operation, and similarly, the implication of socio-economic differences in the output due to sedimentation are difficult to access. The ever-increasing demands due to both increase of population and increases in per capita needs are of a larger magnitude than the reductions in outputs, if any, of existing reservoirs. Thus effects of sedimentation, obsolescence, structural deterioration, etc. of reservoirs may require adjustments in future developmental plans and not simply replacement projects to bring back the lost potential.

On a regional or national scale, it is the sufficiency of the total economic outputs, and not outputs of a particular project which is relevant. However, from local considerations, the reduction of outputs of reservoir like irrigation and flood control may cause a much greater degree of distress to the population which has got used to better socio-economic conditions because of the reservoir. “Life” strictly is a term which may be used for system having two functional states “ON” and “OFF”. Systems showing gradual degradation of performance and not showing any sudden nonfunctional stage have no specific life period. Reservoirs fall in the latter category. The term life of reservoir as loosely used denotes the period during which whole or a specified fraction of its total or active capacity is lost. In calculating this life, the progressive changes in trap efficiency towards the end of the period are commonly not considered. In some of the earlier projects, it has been assumed that all the sedimentation would occur only in the dead storage pocket and the number of years in which the pocket should be filled under this assumption was also sometimes termed as the life of reservoir. This concept was in fact used to decide the minimum size of the pocket. Under this concept, no effect of sedimentation should be felt within the live storage of the reservoir. It has subsequently been established that the silt occupies the space in the live storage of reservoir as well as the dead storage. If the operation of the reservoir becomes impossible due to any structural defects, foundation defects, accidental damages, etc., this situation should also signify the end of the feasible service time. Before the expiry of this feasible service time, it may be possible to make large changes in the reservoir (for example, new higher level outlets, structural strengthening, etc.) or other measures, if it is economically feasible to do so. If these studies are done, the feasible service time may be extended.

Geological explorations for reservoir sites

In geological exploration procedures for constructions of dams were discussed in detail. Though a dam is constructed to build a reservoir, a reservoir has a large area of spread and contained in a big chunk of the river valley upstream of the dam. Hence, while identifying a suitable site for a proposed dam, it is of paramount importance that the proposed reservoir site is also thoroughly investigated and explored. The basis of planning for such explorations is to have a rapid economical and dependable pre-investment evaluation of subsurface conditions. It is also necessary that a degree of uniformity be followed while carrying out subsurface explorations so that the frame of reference of the investigation covers all requisite aspects. In view of above, the Bureau of Indian Standards has brought out a code IS: 13216 - 1991 “Code of practice for geological exploration for reservoir sites”, that discusses the relevant aspects. According to the code since reservoir projects in river valleys are meant to hold water; therefore, the following aspects of the reservoirs have to be properly investigated:

a. Water tightness of the basins
b. Stability of the reservoir rim
c. Availability of construction material in the reservoir area
d. Silting
e. Direct and indirect submergence of economic mineral wealth
f. Seismo-techtonics

These aspects are determined through investigations carried out by surface and sub- surface exploration of proposed basin during the reconnaissance, preliminary investigation, detailed investigation, construction and post-construction stages of the project. The two basic stages of investigation: reconnaissance and preliminary investigations are explained below[9]:

a. Reconnaissance

In the reconnaissance stage, the objective of investigation is to bring out the overall geological features of the reservoir and the adjacent area to enable the designers, construction engineers and geologists to pinpoint the geotechnical and ecological problems which have to be tackled. The scale of geological mapping for this stage of work need not be very large and the available geological maps on 1:50,000 or 1: 250,000 scales may be made use of. It is advantageous to carry out photo geological interpretation of aerial photographs of the area, if available. If a geological map of the area is not available, a traverse geological map should be prepared at this stage preferably using the aerial photos as base maps on which the engineering evaluation of the various geotechnical features exposed in the area should be depicted.

A topographical index map on 1: 50 000 scales should be used at this stage to delineate the areas which would require detailed study, subsequently. To prevent an undesirable amount of leakage from the reservoir, the likely zones of such leakage, such as major dislocations and pervious or cavernous formations running across the divide of the reservoir should be identified at this stage of investigation for further detailed investigations.

Major unstable zones, particularly in the vicinity of the dam in tight gorges, should be identified at this stage for carrying out detailed investigations for the stability of the reservoir rim. The locations for suitable construction material available in the reservoir area should be pin pointed at this stage so that after detailed surveys such materials can be exploited for proper utilization during the construction stage prior to impounding of reservoir. The rate of silting of the reservoir is vital for planning the height of the dam and working out the economic life of the project. Since the rate of silting, in addition to other factors, is dependent on the type of terrain in the catchment area of the reservoir, the major geological formations and the ecological set up should be recognized at this stage to enable a more accurate estimation of the rate of silting of the reservoir. For example, it should be possible to estimate at this stage that forty percent of the catchment of a storage dam project is covered by Quaternary sediment and that this is a condition which is likely to a yield a high silt rate or that ninety percent of the catchment of another storage dam project is composed of igneous and metamorphic rocks and is likely to yield a relatively low sediment rate.

This information will also be useful in examining whether or not tributaries flowing for long distances through soft or unconsolidated formations, prior to forming the proposed reservoir, can be avoided and if not, what remedial measures can be taken to control the silt load brought by these tributaries. The impounding of a reservoir may submerge economic/strategic mineral deposits occurring within the reservoir area or the resultant rise in the water table around the reservoir may cause flooding, increased seepage in quarries and mines located in the area and water logging in other areas. It is, therefore, necessary that the economic mineral deposits, which are likely to be adversely affected by the reservoir area, are identified at this stage of the investigation. For example, if an underground working is located close to a proposed storage reservoir area, it should be identified for regular systematic geo-hydrological studies subsequently.

These studies would establish whether the impoundment of the water in the reservoir had adversely affected the underground working or not. References should also be made to various agencies dealing with the economic minerals likely to be affected by the impoundment in the reservoir for proper evaluation of the problem and suitable necessary action. A dam and its reservoir are affected by the environment in which they are located and in turn they also change the environment. Impoundment of a reservoir sometimes results in an increase of seismic activity at, or near the reservoir. The seismic activity may lead to micro tremors and in some cases lead to earthquakes of high magnitude. It is, therefore, necessary to undertake the regional seismotechtonic study of the project area. The faults having active seismic status should be delineated at this stage. Simultaneous action to plan and install a network of seismological observatories encompassing the reservoir area should also be taken[10].

Preliminary Investigation

The object of preliminary investigation of the reservoir area is to collect further details of the surface and subsurface geological conditions, with reference to the likely problems identified during the reconnaissance stage of investigation by means of surface mapping supplemented by photo geological interpretation of aerial photographs, hydro geological investigations, geophysical investigations, preliminary subsurface exploration and by conducting geoseismological studies of the area.

On the basis of studies carried out during the reconnaissance stage it should be possible to estimate the extent of exploration that may be required during the preliminary stage of investigation including the total number of holes required to be drilled and the total number and depth of pits, trenches and drifts as also the extent of geophysical surveys which may be necessary. For exploration by pits, trenches, drifts and shafts guidelines laid down in IS 4453: 1980 Name of IS code should be followed.

The potential zones of leakage from the reservoir and the lateral extent of various features, such as extent of aeolian sand deposits, glacial till, landslides, major dislocations or pervious and cavernous formations running across the divide, should be delineated on a scale of 1: 50000. The geo-hydrological conditions of the reservoir rim should be established by surface and subsurface investigation as well as inventory, as a free ground water divide rising above the proposed level of the reservoir is a favorable condition against leakage from the reservoir. The level of water in a bore hole should be determined as given in IS 6935: 1973.

The extension of various features at depth, wherever necessary, is investigated by geophysical exploration and by means of pits, trenches, drifts and drill holes. For example, the resistivity survey should be able to identify water saturated zones. The nature of the material is investigated by means of laboratory and in situ tests, to determine permeability and assess the quantum of leakage which may take place through these zones on impoundment of the reservoir. Moreover, permeability of rocks/overburden in the reservoir area is determined from water table fluctuations and pumping tests in wells. For determining in situ permeability in overburden and rock, reference should be made to IS 5529 (Part I): 1985 and IS: 5529 (Part II): 1985 respectively. The information about permeability would enable the designers to estimate the treatment cost for controlling leakage/seepage from the reservoir and to decide whether it would be desirable to change the location of height of the dam to avoid these zones.

Major unstable zones along the reservoir identified during the reconnaissance stage and which are of consequence to the storage scheme should be investigated in detail at this stage by means of surface and sub-surface exploration. The areas should be geologically mapped in detail on a scale of 1: 2000. The suspect planes/zones of failure should be identified and explored by means of of drifts, trenches and pits. Disturbed and undisturbed samples of the plastic material should be tested for cohesion (c) and angle of internal friction (ϕ) as well as for other relevant properties. The stability of slopes should also be evaluated considering the reservoirs operational conditions. These studies should provide the designers with an idea of the magnitude of the problems that may be encountered, so that they may be able to take remedial measures to stabilize zones or to abandon the site altogether, if the situation demands.

The areas having potential economic mineral wealth and which are likely to be adversely affected by the impoundment of the reservoir should be explored by means of surface and subsurface investigation to establish their importance both in terms of their value as well as strategic importance. This information would be necessary for arriving at a decision regarding the submergence, or otherwise, of the mineral deposit. The nature and amount of the existing seepage, if any, in the existing mines and quarries in the adjacent areas of the reservoir should be recorded and monitored regularly.

This data is necessary, to ascertain whether or not there has been any change in the quantum of seepage in the mines and quarries due to the impoundment of water in the reservoir, directly or indirectly. Large scale geological mapping and terrace matching across the faults with seismically active status, delineated during the reconnaissance stage, should be carried out on a scale of 1 : 2000 and the trend, and behavior of the fault plane should be investigated in detail by means of surface studies and sub-surface exploration by pits, trenches and drifts etc.

A network of geodetic survey points should be established on either side of the suspected faults to study micro movements along these suspected faults, if any, both prior to and after impoundment of the reservoir.

Micro earthquake studies should be carried out using portable 3-station or 4-station networks in areas with proven seismically active fault features. On the basis of the studies carried out during the preliminary stage it should be possible to estimate the quantum of exploration which may be required during the detailed stage of investigation including the total number of holes required to be drilled and the total number and depth of pits, trenches and drifts as also the extent of geophysical survey which may be necessary. Detailed surface and sub-surface investigation of all features connected with the reservoir should be carried out to provide information on leakage of water through the periphery and/or basin of the reservoir area. Based on these investigations and analysis of data it should be possible to decide as to whether the reservoir area in question would hold water without undue leakage. If, not, the dam site may have to be abandoned in favor of suitable alternative site.

The zones, which on preliminary investigation are found to be potential zones of leakage/seepage from the reservoir, and which due to other considerations cannot be avoided are geologically mapped on a scale of 1 : 2 000 and investigated in detail at this stage by means of a close spaced sub-surface exploration programme The unstable zones around the reservoir rim, especially those close to the dam sites in tight gorges, should be explored in detail by means of drifts, pits and trenches so that the likely planes of failures are located with precision. The physical properties including angle of internal friction and cohesion of representative samples of the material along which movement is anticipated should be determined. The above information would enable the designers to work out details for preventive measures, for example, it may be possible to unload the top of the slide area or to load the toe of the slide with well drained material, within economic limits.

Sub-surface explorations by drill holes, drifts, pits and trenches should be carried out at possible locations of check dams and at the locations of other preventive structures proposed to restrict the flow of silt into the reservoir. These studies would enable the designers to assess the feasibility of such proposals. Detailed plans, regarding the economic mineral deposits within the zones of influence of the reservoir should be finalized during this stage by the concerned agencies. The seepage investigations in the quarries and mines within the zone of influence of the reservoir should be continued. The purpose of this stage of investigation is to provide the designers sufficient data to enable them to plan the programme of remedial treatment. The subsurface explorations are carried out by means of pits and trenches, if the depth to be explored is shallow, say up to 5 meters, and by drill holes and drifts, if the depth to be explored is greater than 5 meters.

Precipitation, Run-Off and Silt Record

The network of precipitation and discharge measuring stations in the catchment upstream and near the project needs to be considered to assess the capacity of the same to adequately sample both spatially and temporally the precipitation and the stream flows. The measurement procedures and gap filling procedures in respect of missing data as also any rating tables or curves need to be critically examined so that they are according to guidelines of World Meteorological Organization (WMO). Long-term data has to be checked for internal consistency between rainfall and discharges, as also between data sets by double mass analysis to highlight any changes in the test data for detection of any long term trends as also for stationary.

It is only after such testing that the data should be used for generating the long term inflows of water into the reservoir. Sufficiently long term precipitation and run-off records are required for preparing the water inflow series. For working out the catchment average sediment yield, long-term data of silt measurement records from existing reservoirs are essential. These are pre-requisites for fixing the storage capacity of reservoirs. If long term run-off records are not available, concurrent rainfall and run-off data may be used to convert long term rainfall data which is generally available in many cases into long-term runoff series adopting appropriate statistical/conceptual models. In some cases regression analysis may also be resorted to for data extension.

Estimation of average Sediment Yield from the catchment area above the reservoir

It is usually attempted using river sediment observation data or more commonly from the experience of sedimentation of existing reservoirs with similar characteristics. Where observations of stage/flow data is available for only short periods, these have to be suitably extended with the help of longer data on rainfall to estimate as far as possible sampling errors due to scanty records. Sediment discharge rating curve may also be prepared from hydraulic considerations using any of the standard sediment load formulae, such as, Modified Einstein□s procedure, Young□s stream power, etc. It is also necessary to account for the bed load which may not have been measured. Bed load measurement is preferable and when it is not possible, it is often estimated as a percentage generally ranging from 5 to 20 percent of the suspended sediment load. However, actual measurement of bed load needs to be undertaken particularly in cases where high bed loads are anticipated. To assess the volume of sediment that would deposit in the reservoir, it is further necessary to make estimates of average trap efficiency of the reservoir and the likely unit weight of sediment deposits, along with time average over the period selected. The trap efficiency would depend on the capacity inflow ratio but would also vary with the locations of controlling outlets and reservoir operating procedures.

Elevation Area Capacity Curves

Topographic survey of the reservoir area should form the basis for obtaining these curves, which are respectively the plots of elevation of the reservoir versus surface area and elevation of the reservoir versus volume. For preliminary studies, in case suitable topographic map with contours, say at intervals less than 2.5 m is not available, stream profile and valley cross sections taken at suitable intervals may form the basis for computing the volume. Aerial survey may also be adopted when facilities are available.

Losses in Reservoir

Water losses mainly of evaporation and seepage occur under pre-project conditions and are reflected in the stream flow records used for estimating water yield. The construction of new reservoirs and canals is often accompanied by additional evaporation and infiltration. Estimation of these losses may be based on measurements at existing reservoirs and canals. The measured inflows and outflows and the rate of change of storage are balanced by computed total loss rate. The depth of water evaporated per year from the reservoir surface may vary from about 400 mm in cool and humid climate to more than 2500 mm in hot and arid regions. Therefore, evaporation is an important consideration in many projects and deserves careful attention. Various methods like water budget method, energy budget method, etc may be applied for estimating the evaporation from reservoir. However, to be more accurate, evaporation from reservoir is estimated by using data from pan-evaporimeters or pans exposed to atmosphere with or without meshing in or near the reservoir site and suitably adjusted. Seepage losses from reservoirs and irrigation canals may be significant if these facilities are located in an area underlain by permeable strata. Avoidance in full or in part of seepage losses may be very expensive and technical difficulties involved may render a project unfeasible. These are generally covered under the conveyance losses in canals projected on the demand side of simulation studies.

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CHAPTER 17

RESERVOIR LOSSES AND THEIR MINIMIZATION

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Loss of reservoir water would mainly take place due to evaporation and a number of methods have been suggest for controlling such loss. The Bureau of Indian Standard code IS: 14654 - 1999 “Minimizing evaporation losses from reservoirs- guidelines” describes the cause of evaporation reduction methods in detail, some important aspects of which are described in the subsequent paragraphs. As such, percolation or seepage loss is small for most of the reservoirs and progressively gets lowered with the passage of time since the sediment getting deposited at the reservoir bottom helps to reduce percolation losses.

Of course, in some hills and valleys forming the reservoir, there may be continuous seams of porous rock strata or limestone caverns which cause huge amount of water to get drained out of the reservoirs. The reservoir of the Kopili Hydroelectric Project in Assam-Meghalaya border had faced similar problems due to the presence of large caverns which had to be sealed later at quite large cost at a later stage[1]. A number of factors affect the evaporation from open water surface, of which, the major factors are water spread area and frequent change of speed and direction of wind over the water body. Other meteorological factors like.

- **a.** Vapor pressure difference between water surface and the layer of air above;
- **b.** Temperature of water and air;
- **c.** Atmospheric pressure;
- **d.** Radiation;
- **e.** Heat storage in water body;
- **f.** Quality of water,

Since the meteorological factors affecting evaporation cannot be controlled under normal conditions, efforts are made for inhibition of evaporation by control of flow of wind over water surface or by protection of the water surface area by physical or chemical methods. The methods generally used are as follows:

- **a.** Wind breakers,
- **b.** Covering the water surface,
- **c.** Reduction of exposed water surface,
- **d.** Integrated operation of reservoirs,
- **e.** Treatment with chemical water evaporetardants (WERs).

Wind Breakers

Wind is one of the most important factors which affect rate of evaporation loss from water surface. The greater the movement of air over the water surface, greater is the evaporation loss. Planting of trees normal to windward direction is found to be an effective measure for checking of evaporation loss.

Plants like trees, shrubs or grass should be grown around the rim of tanks in a row or rows to act as wind breaker. These wind breakers are found to influence the temperature, atmospheric humidity, soil moisture, evaporation and transpiration of the area protected. Plants to act as wind breakers are usually arranged in rows, [2] with tallest plants in the middle and the smallest along the end rows, so that more or less conical formation is formed.

Covering the Water Surface

Covering the surface of water bodies with fixed or floating covers considerably retards evaporation loss. These covers reflect energy inputs from atmosphere, as a result of which evaporation loss is reduced. The covers literally trap the air and prevent transfer of water vapor to outer atmosphere. Fixed covers are suitable only for relatively small storages. For large storages, floating covers or mat or spheres may be useful and effective. However, for large water surfaces the cost of covering the surface with floats is prohibitive, further in case of reservoirs with flood outlets, there is also the danger of floats being lost over spillway or through outlets. The floating covers are thus of limited utility to larger water bodies.

Reduction of Exposed

Water Surface In this method shallow portions of the reservoirs are isolated or curtailed by construction of dykes or bunds at suitable locations. Water accumulated during the monsoon season in such shallow portions IS diverted or pumped to appropriate deeper pockets in summer months, so that the shallow water surface area exposed to evaporation is effectively reduced[3].

Control of Sedimentation in Reservoirs

Sedimentation of a reservoir is a natural phenomenon and is a matter of vital concern for storage projects in meeting various demands, like irrigation, hydroelectric power, flood control, etc. Since it affects the useful capacity of the reservoir based on which projects are expected to be productive for a design period. Further, the deposited sediment adds to the forces on structures in dams, spillways, etc.

The rate of sedimentation will depend largely on the annual sediment load carried by the stream and the extent to which the same will be retained in the reservoir. This, in turn, depends upon a number of factors such as the area and nature of the catchment, level use pattern (cultivation practices, grazing, logging, construction activities and conservation practices), rainfall pattern, storage capacity, period of storage in relation to the sediment load of the stream, particle size distribution in the suspended sediment, channel hydraulics, location and size of sluices, outlet works, configuration of the reservoir, and the method and purpose of releases through the dam. Therefore, attention is required to each one of these factors for the efficient control of sedimentation of reservoirs with a view to enhancing their useful life and some of these methods are discussed in the Bureau of Indian Standard code IS: 6518-1992 “Code of practice for control of sediment in reservoirs”. In this section, these factors are briefly discussed[4].

There are different techniques of controlling sedimentation in reservoirs which may broadly be classified as follows:

- Adequate design of reservoir
- Control of sediment inflow
- Control of sediment deposition
- Removal of deposited sediment.

Each of these methods is briefly described as follows:

Design of Reservoirs

The capacity of reservoirs is governed by a number of factors which are covered in IS: 5477. From the point of view of sediment deposition, the following points may be given due consideration:

a. The sediment yield which depends on the topographical, geological and geomorphological set up, meteorological factors, land use/land cover, intercepting tanks, etc.;

b. Sediment delivery characteristics of the channel system;

c. The efficiency of the reservoir as sediment trap;

d. The ratio of capacity of reservoir to the inflow; e) Configuration of reservoir;

e. Method of operation of reservoir;

f. Provisions for silt exclusion.

The rate of sediment delivery increases with the volume of discharge. The percentage of sediment trapped by a reservoir with a given drainage area increases with the capacity. In some cases an increased capacity will however, result in greater loss of water due to evaporation. However, with the progress of sedimentation, there is decrease of storage capacity which in turn lowers the trap efficiency of the reservoir.

The capacity of the reservoir and the size and characteristics of the reservoir and its drainage area are the most important factors governing the annual rate of accumulation of sediment. Periodical reservoir sedimentation surveys provide guidance on the rate of sedimentation. In the absence of observed data for the reservoir concerned, data from other reservoirs of similar capacity and catchment characteristics may be adopted. Silting takes place not only in the dead storage but also in the live storage space in the reservoir. The practice for design of reservoir is to use the observed suspended sediment data available from key hydroIogical networks and also the data available from hydrographic surveys of other reservoirs in the same region[5].

Check Dams

Check dams are helpful for the following reasons:

a. They help arrest degradation of stream bed thereby arresting the slope failure;

b. They reduce the velocity of stream flow, thereby causing the deposition of the sediment load.

Check dams become necessary, where the channel gradients are steep and there is a heavy inflow of sediment from the watershed. They are constructed of local material like earth, rock, timber, etc. These are suitable for small catchment varying in size from 40 to 400 hectares. It is necessary to provide small check dams on the subsidiary streams flowing into the main streams besides the check dams in the main stream. Proper consideration should be given to the number and location of check dams required. It is preferable to minimize the height of the check dams. If the stream ha, a very-steep slope, it is desirable to start with a smaller height for the check dams than may ultimately be necessary.

Check dams may generally cost more per unit of storage than the reservoirs they protect. Therefore, it may not always be possible to adopt them as a primary method of sediment control in new reservoirs. However, feasibility of providing check dams at a later date should not be overlooked while planning the protection of-a new reservoir.

Contour Bonding and Trenching

These are important methods of controlling soil erosion on the hills and sloping lands, where gradients of cultivated fields or terraces are flatter, say up to 10 percent. By these methods the hill side is split up into small compartments on which the rain is retained and surface run-off is modified with prevention of soil erosion. In addition to contour bunding, side trenching is also provided sometimes.

Gully Plugging

This is done by small rock fill dams. These dams will be effective in filling up the gullies with sediment coming from the upstream of the catchment and also prevent further widening of the gully.

Control of Sediment Deposition

The deposition of sediment in a reservoir may be controlled to a certain extent by designing and operating gates or other outlets in the dam in such a manner as to permit selective withdrawals of water having a higher-than-average sediment content. The suspended sediment content of the water in reservoirs is higher during and just after flood flow. Thus, more the water wasted at such times, the smaller will be the percentage of the total sediment load to settle into permanent deposits. There are generally two methods[6]:

a. Density currents,

b. Waste-water release, for controlling the deposition and both will necessarily result in loss of water.

Density Current

Water at various levels of a reservoir often contains radically different concentrations of suspended sediment particularly during and after flood flows and if all waste-water could be withdrawn at those levels where the concentration is highest, a significant amount of sediment might be removed from the reservoir. Because a submerged outlet draws water towards it from all directions, the vertical dimension of the opening should be small with respect to the thickness of the layer and the rate of withdrawal also should be low. With a view to passing the density current by sluices that might be existed, it is necessary to trace the movement of density currents and observation stations consisting of permanently anchored rafts from which measurements could be made of temperature and conductivity gradient from the surface of the lake to the bottom, besides collecting water samples at various depths at least one just above the dam and two or more additional stations in the upstream one in the inlet and one in the middle should be located.

Waste-Water Release

Controlling the sedimentation by controlling waste-water release is obviously possible only when water can be or should be wasted. This method is applicable only when a reservoir is of such size that a small part of large flood flows will fill it. In the design of the dam, sediment may be passed through or over it as an effective method of silt control by placing a series of outlets at various elevations. The percentage of total sediment load that might be ejected from the reservoir through proper gate control will differ greatly with different locations. It is probable that as much as 20 percent of the sediment inflow could be passed through many reservoirs by venting through outlets designed and con-trolled.

Scouring Sluicing

This method is somewhat similar to both the control of waste-water release and the draining and flushing methods. The distinction amongst them care the following:

a. The waste-water release method ejects sediment laden flood flows through deep spillway gates or large under sluices at the rate of discharge that prevents sedimentation.

b. Drainage and flushing method involves the slow release of stored water from the reservoir through small gates or valves making use of normal or low flow to entrain and carry the sediment,

c. Scouring sluicing depends for its efficiency on either the scouring action exerted by the sudden rush of impounded water under a high head through under sluices or on the scouring action of high flood discharge coming into the reservoir.

Scouring sluicing method can be used in the following:

a. Small power dams that depend to a great extent on pondage but not on storage;

b. Small irrigation reservoirs, where only a small fraction of the total annual flow can be stored;

c. Any reservoir in narrow channels, gorges, etc, where water wastage can be afforded;

d. When the particular reservoir under treatment is a unit in an interconnected system so that the other reservoirs can supply the water needed.

Removal of Deposited Sediment

The most practical means of maintaining the storage capacity are those designed to prevent accumulation of permanent deposits as the removal operations are extremely expensive, unless the material removed is usable. Therefore, the redemption of lost storage by removal should be adopted as a last resort. The removal of sediment deposit implies in general, that the deposits are sufficiently compacted or consolidated to act as a solid and, therefore, are unable to flow along with the water. The removal of sediment deposits may be accomplished by a variety of mechanical and hydraulic or methods, such as excavation, dredging, siphoning, draining, flushing, flood sluicing, and sluicing aided by such measures as hydraulic or mechanical agitation or blasting of the sediment. The excavated sediments may be suitably disposed of so that, these do not find the way again in the reservoir[7].

Excavation

The method involves draining most of or all the water in the basin and removing the sediment by hand or power operated shovel, dragline scraper or other mechanical means. The excavation of silt and clay which constitute most of the material in larger reservoirs is more difficult than the excavation of sand and gravel. Fine-textured sediment cannot be excavated easily from larger reservoirs unless it is relatively fluid or relatively compact.

Dredging

This involves the removal of deposits from the bottom of a reservoir and their conveyance to some other point by mechanical or hydraulic means, while water storage is being maintained. Dredging practices are grouped as:

- **a.** Mechanical dredging by bucket, ladder, etc;
- **b.** Suction dredging with floating pipeline and a pump usually mounted on barrage;
- **c.** Siphon dredging with a floating pipe extending over the dam or connected to an opening in the dam and usually with a pump on a barrage.

Draining and Flushing

The method involves relatively slow release of all stored water in a reservoir through gates or valves located near bottom of the dam and the maintenance thereafter of open outlets for a shorter or longer period during which normal stream flow cuts into or directed against the sediment deposits. Therefore, this method may be adopted in flood control reservoirs.

Sluicing with Controlled Water

This method differs from the flood sluicing in that the controlled water supply permits choosing the time of sluicing more advantageously and that the water may be directed more effectively against the sediment deposits. While the flood sluicing depends either on the occurrence of flood or on being able to release rapidly all of a full or nearly full supply of water in the main reservoir is empty. The advantage of this method is that generally more sediment can be removed per unit of water used than in flood scouring or draining and flushing.

Sluicing with Hydraulics and Mechanical Agitation

Methods that stir up, break up or move deposits of a sediment into a stream current moving through a drained reservoir basin or into a full reservoir will tend to make the removal of sediment from the reservoir more complete. Wherever draining, flushing or sluicing appear to be warranted, the additional use of hydraulic means for stirring up the sediment deposits, or sloughing them off, into a stream flowing through the reservoir basin should be considered. It has, however, limited application[8].

Reservoir operation

The flow in the river changes seasonally and from year to year, due to temporal and spatial variation in precipitation. Thus, the water available abundantly during monsoon season becomes scarce during the non-monsoon season, when it is most needed. The traditional method followed commonly for meeting the needs of water during the scarce period is construction of storage reservoir on the river course. The excess water during the monsoon season is stored in such reservoirs for eventual use in lean period. Construction of storages will also help in control of flood, as well as generation of electricity power. To meet the objective set forth in planning a reservoir or a group of reservoirs and to achieve maximum benefits out of the storage created, it is imperative to evolve guidelines for operation of reservoirs. Without proper regulation schedules, the reservoir may not meet the full objective for which it was planned and may also pose danger to the structure itself.

Control of flood is better achieved if the reservoir level is kept low in the early stages of the monsoon season. However, at a later stage, if the anticipated inflows do not result the reservoir may not get filled up to FRL in the early stages of monsoon, to avoid the risk of reservoir remaining unfilled at later stage, there may be problem of accommodating high floods occurring at later stage. In some cases while planning reservoirs, social and other considerations occasionally result in adoption of a plan that may not be economically the best.

Operation of Single Purpose Reservoirs

The common principles of single purpose reservoir operation are given below:

a. Flood Control

Operation of flood control reservoirs is primarily governed by the available flood storage capacity of damage centers to be protected, flood characteristics, ability and accuracy of flood/ storm forecast and size of the uncontrolled drainage area. A regulation plan to cover all the complicated situations may be difficult to evolve, but generally it should be possible according to one of the following principles:

- **Effective use of available flood control storage**

Operation under this principle aims at reducing flood damages of the locations to be protected to the maximum extent possible, by effective use of flood event. Since the release under this plan would obviously be lower than those required for controlling the reservoir design flood, there is distinct possibility of having a portion of the flood control space occupied during the occurrence of a subsequent heavy flood. In order to reduce this element of risk, maintenance of an adequate network of flood forecasting stations both in the upstream and downstream areas would be absolutely necessary.

- **Control of reservoir design flood**

According to this principle, releases from flood control reservoirs operated on this concept are made on the same hypothesis as adopted for controlling the reservoir design flood that is the full storage capacity would be utilized only when the flood develops into the reservoir design flood. However, as the design flood is usually an extreme event, regulation of minor and major floods, which occur more often, is less satisfactory when this method is applied[9].

- **Combination of principle (1) and (2)**

In this method, a combination of the principles (1) and (2) is followed. The principle (1) is followed for the lower portion of the flood reserve to achieve the maximum benefits by controlling the earlier part of the flood. Thereafter releases are made as scheduled for the reservoir design flood as in principle (2). In most cases this plan will result in the best overall regulation, as it combines the good points of both the methods.

- **Flood control in emergencies**

It is advisable to prepare an emergency release schedule that uses information on reservoir data immediately available to the operator. Such schedule should be available with the operator to enable him to comply with necessary precautions under extreme flood conditions.

b. Conservation

Reservoirs meant for augmentation of supplies during lean period should usually be operated to fill as early as possible during filling period, while meeting the requirements. All water in excess of the requirements of the filling period shall be impounded. No spilling of water over the spillway will normally be permitted until the FRL is reached. Should any flood occur when the reservoir is at or near the FRL, release of flood waters should be affected, so as not to exceed the discharge that would have occurred had there been no reservoir. In case the year happens to be dry, the draft for filling period should be curtailed by applying suitable factors. The depletion period should begin thereafter. However, in case the reservoir is planned with carry- over capacity, it is necessary to ensure that the regulation will provide the required carry-over capacity at the end of the depletion period[10].

Operation of multipurpose reservoirs: The general principles of operation of reservoirs with these multiple storage spaces are described below:

1. **Separate allocation of capacities**

When separate allocations of capacity have been made for each of the conservational uses, in addition to that required for flood control, operation for each of the function shall follow the principles of respective functions. The storage available for flood control could, however be utilized for generation of secondary power to the extent possible. Allocation of specific storage space to several purposes with the conservation zone may sometimes be impossible or very costly to provide water for the various purposes in the quantities needed and at the time they are needed.

2. **Joint use of storage space**

In multi-purpose reservoir where joint use of some of the storage space or storage water has been envisaged, operation becomes complicated due to competing and conflicting demands. While flood control requires low reservoir level, conservation interests require as high a level as is attainable. Thus, the objectives of these functions are not compatible and a compromise will have to be effected in flood control operations by sacrificing the requirements of these functions. In some cases parts of the conservational storage space is utilized for flood moderation, during the earlier stages of the monsoon. This space has to be filled up for conservation purpose towards the end of monsoon progressively, as it might not be possible to fill up this space during the post-monsoon periods, when the flows are insufficient even to meet the current requirements. This will naturally involve some sacrifice of the flood control interests towards the end of the monsoon[11].

Operation of system of reservoirs

It is not very uncommon to find a group or „system of reservoirs either in a single river or in a river and its tributaries. An example of the former are the dams proposed on the river Narmada and an example of the latter are the dams of the Damodar Valley project.

In case of system of reservoirs, it is necessary to adopt a strategy for integrated operated of reservoirs to achieve optimum utilization of the water resources available and to benefit the best out of the reservoir system. In the preparation of regulation plans for an integrated operation of system of reservoirs, principles applicable to separate units are first applied to the individual reservoirs.

Modifications of schedule so developed should then be considered by working out several alternative plans. In these studies optimization and simulation techniques may be extensively used with the application of computers in water resources development.

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CHAPTER 18

EARTH DAMS AND SPILLWAYS

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The previous lessons dealt with storage reservoirs built by impounding a river with a dam and the common types of dams constructed by engineers. However, in rare cases only it is economical or practical for the reservoir to store the entire volume of the design flood within the reservoir without overtopping of dam. Hence, a dam may be constructed to that height which is permissible within the given topography of the location or limited by the expenditure that may be possible for investment. The excess flood water, therefore, has to be removed from the reservoir before it overtops the dam. Passages constructed either within a dam or in the periphery of the reservoir to safely pass this excess of the river during flood flows are called Spillways[1].

Ordinarily, the excess water is drawn from the top of the reservoir created by the dam and conveyed through an artificially created waterway back to the river. In some cases, the water may be diverted to an adjacent river valley. In addition to providing sufficient capacity, the spillway must be hydraulically adequate and structurally safe and must be located in such a way that the out-falling discharges back into the river do not erode or undermine the downstream toe of the dam.

The surface of the spillway should also be such that it is able to withstand erosion or scouring due to the very high velocities generated during the passage of a flood through the spillway. The flood water discharging through the spillway has to flow down from a higher elevation at the reservoir surface level to a lower elevation at the natural river level on the downstream through a passage, which is also considered a part of the spillway.

At the bottom of the channel, where the water rushes out to meet the natural river, is usually provided with an energy dissipation device that kills most of the energy of the flowing water. These devices, commonly called as Energy Dissipaters, are required to prevent the river surface from getting dangerously scoured by the impact of the out falling water. In some cases, the water from the spillway may be allowed to drop over a free overfill, as in Kariba Dam on Zambezi River in Africa, where the free fall is over 100m. In some projects, like the Indira Sagar Dam on River Narmada, two sets of spillways are provided Main and Auxillary. The main spillway, also known as the service spillway is the one which is generally put into operation in passing most of the design flood.

The crest levels of the auxillary spillways are usually higher and thus the discharge capacities are also small and are put into operation when the discharge in the river is higher than the capacity of the main spillway. Sometimes, an Emergency or Fuse Plug types of spillway is provided in the periphery of the reservoir which operates only when there is very high flood in the river higher than the design discharge or during the malfunctioning of normal spillways due to which there is a danger of the dam getting overtopped[2].

Usually, spillways are provided with gates, which provides a better control on the discharges passing through. However, in remote areas, where access to the gates by personnel may not be possible during all times as during the rainy season or in the night unrated spillways may have to be provided. The capacity of a spillway is usually worked out on the basis of a flood routing study, explained in lesson 4.5. As such, the capacity of a spillway is seen to depend upon the following major factors:

- **a.** The inflow flood
- **b.** The volume of storage provided by the reservoir
- **c.** Crest height of the spillway
- **d.** Gated or unrated

According to the Bureau of Indian Standards guideline IS: 11223-1985 "Guidelines for fixing spillway capacity", the following values of inflow design floods (IDF) should be taken for the design of spillway:

- **a.** For large dams (defined as those with gross storage capacity greater than 60 million m^3 or hydraulic head greater than 60 million m^3 or hydraulic head between (2m and 30m), IDF should be based on the Standard Project Flood(SPF).
- **b.** For intermediate dams those with gross storage between 10 and 60 million m3 or hydraulic head between (2m and 30m), IDF should be based on the Standard Project Flood (SPF).
- **c.** For small dams (gross storage between 0.5 to 10 million m3 or hydraulic head between 7.5m to 12m), IDF may be taken as the 100 year return period flood.

The volume of the reservoir corresponding to various elevation levels as well as the elevation of the crest also affects the spillway capacity, as may be obvious from the flood routing procedure. If the spillway is gated, then the discharging water (Q) is controlled by the gate opening and hence the relation of Q to reservoir water level would be different from that of an ungated spillway. Whereas, in most practical cases, spillways are provided with gates and the gate operation is guided by a certain predetermined sequence which depends upon the inflow discharge. Hence, for an actual spillway capacity design, one has to consider not only the inflow hydrograph, but also the gate operation sequence[3].

Apart from spillways, which safely discharge the excess flood flows, outlets are provided in the body of the dam to provide water for various demands, like irrigation, power generation, etc. Hence, ordinarily river flows are usually stored in the reservoir or released through the outlets, and the spillway is not required to function. Spillway flows will result during floods or periods of sustained high runoff when the capacities of other facilities are exceeded. Where large reservoir storage is provided, or where large outlet or diversion capacity is available, the spillway will be utilized infrequently. This feature may be contrasted with that of a diversion structure-like a barrage-where the storage is almost nil, and hence, the spillway there is in almost continuous operation. Spillways are ordinarily classified according to their most prominent feature, either as it pertains to the control, to the discharge channel, or to some other component. The common types of spillway in use are the following:

- Free Overfall (Straight Drop) Spillway

- Overflow (Ogee) Spillway
- Chute (Open Channel/Trough) Spillway
- Side Channel Spillway
- Shaft (Drop Inlet/Morning Glory) Spillway
- Tunnel (Conduit) Spillway
- Siphon Spillway

These spillways are individually treated in the subsequent sections. The water flowing down from the spillways possess a large amount of kinetic energy that is generated by virtue of its losing the potential head from the reservoir level to the level of the river on the downstream of the spillway. If this energy is not reduced, there are danger of scour to the riverbed which may threaten the stability of the dam or the neighboring river valley slopes. The various arrangements for suppressing or killing of the high energy water at the downstream toe of the spillways are called Energy Dissipaters. These are discussed at the end of this lesson.

Free Overfill Spillway

In this type of spillway, the water freely drops down from the crest, as for an arch dam (Figure 1). It can also be provided for a decked over flow dam with a vertical or adverse inclined downstream face as mention in Figure 1. Flows may be free discharging, as will be the case with a sharp crested weir or they may be supported along a narrow section of the crest. Occasionally, the crest is extended in the form of an overhanging lip as mention in Figure 2 to direct small discharges away from the face of the overfill section. In free falling water is ventilated sufficiently to prevent a pulsating, fluctuating jet[4].

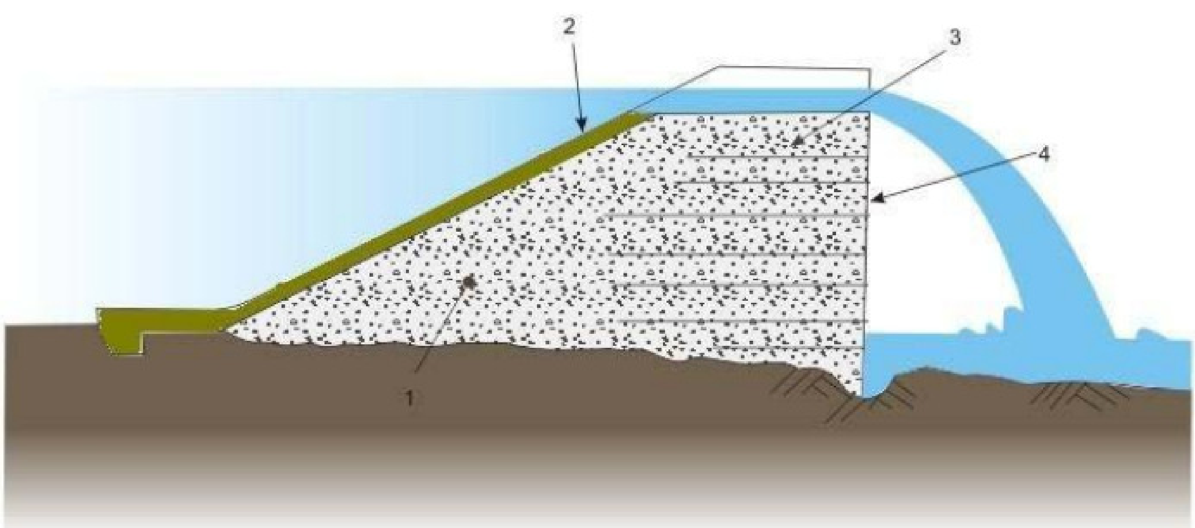

Figure 1: Illustrated the Free over fall Spillway.

Where artificial protection is provided at the loose, as in Figure 2, the bottom may not scour but scour may occur for unprotected streambeds which will form deep plunge pool as mention in Figure 3. The volume and the depth of the scour hole are related to the range of discharges, the height of the drop, and the depth of tail water. Where erosion cannot be tolerated an artificial pool can be created by constructing an auxiliary dam downstream of the main structure, or by excavating a basin which is then provided with a concrete apron or bucket.

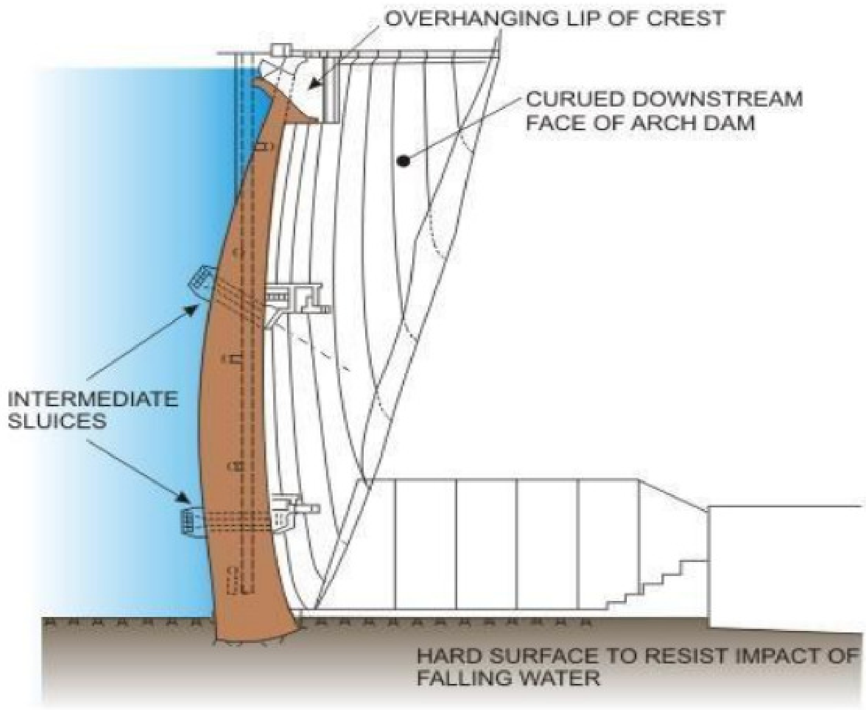

Figure 2: Illustrated the Short Lip Provided for Overfall Spilling.

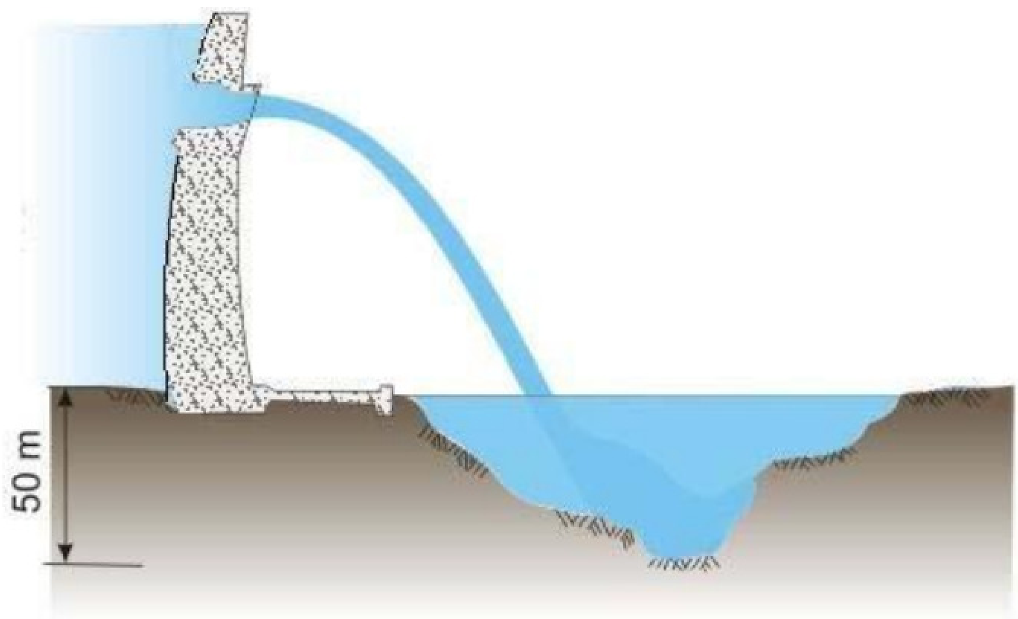

Figure 3: Illustrated the Deep Plunge Pool.

Overflow Spillway

The overflow type spillway has a crest shaped in the form of an ogee or S-shape. The upper curve of the ogee is made to conform closely to the profile of the lower napped of a ventilated sheet of water falling from a sharp crested weir as mention in Figure 4.

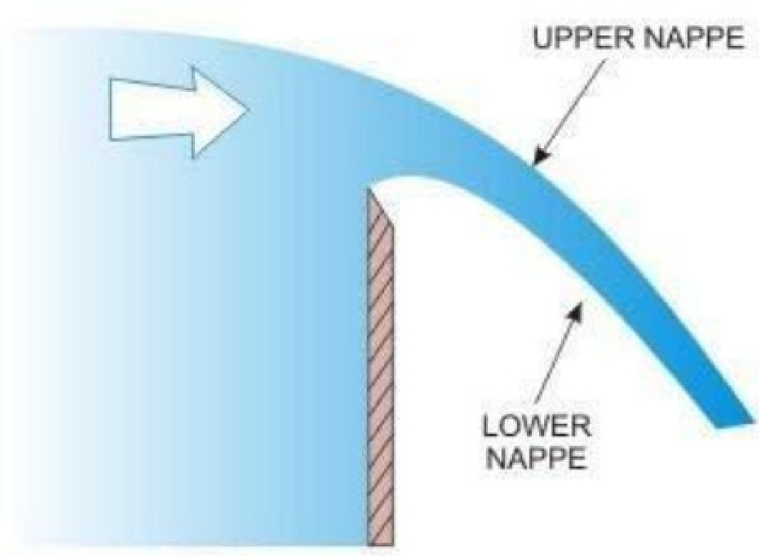

Figure 4: Illustrated the Outflow from Freefalling Weir.

Flow over the crest of an overflow spillway is made to adhere to the face of the profile by preventing access of air to the underside of the sheet of flowing water. Naturally, the shape of the overflow spillway is designed according to the shape of the lower nappe of a free flowing weir conveying the discharge flood. Hence, any discharge higher than the design flood passing through the overflow spillway would try to shoot forward and get detached from the spillway surface, which reduces the efficiency of the spillway due to the presence of negative pressure between the sheet of water and spillway surface. For discharges at designed head, the spillway attains near-maximum efficiency. The profile of the spillway surface is continued in a tangent along a slope to support the sheet of flow on the face of the overflow. A reverse curve at the bottom of the slope turns the flow in to the apron of a sliding basis or in to the spillway discharge channel[5].

Chute Spillway

A chute spillway, variously called as open channel or trough spillway, is one whose discharge is conveyed from the reservoir to the downstream river level through an open channel, placed either along a dam abutment or through a saddle as mention in Figure 5. The control structure for the chute spillway need not necessarily be an overflow crest, and may be of the side-channel type as display in Figure 6. However, the name is most often applied when the spillway control is placed normal or nearly normal to the axis of the open channel, and where the streamlines of flow both above and below the control crest follow in the direction of the axis. Generally, the chute spillway has been mostly used in conjunction with embankment dams, like the Tehri dam, for example. Chute spillways are simple to design and construct and have been constructed successfully on all types of foundation materials, ranging from solid rock to soft clay[6].

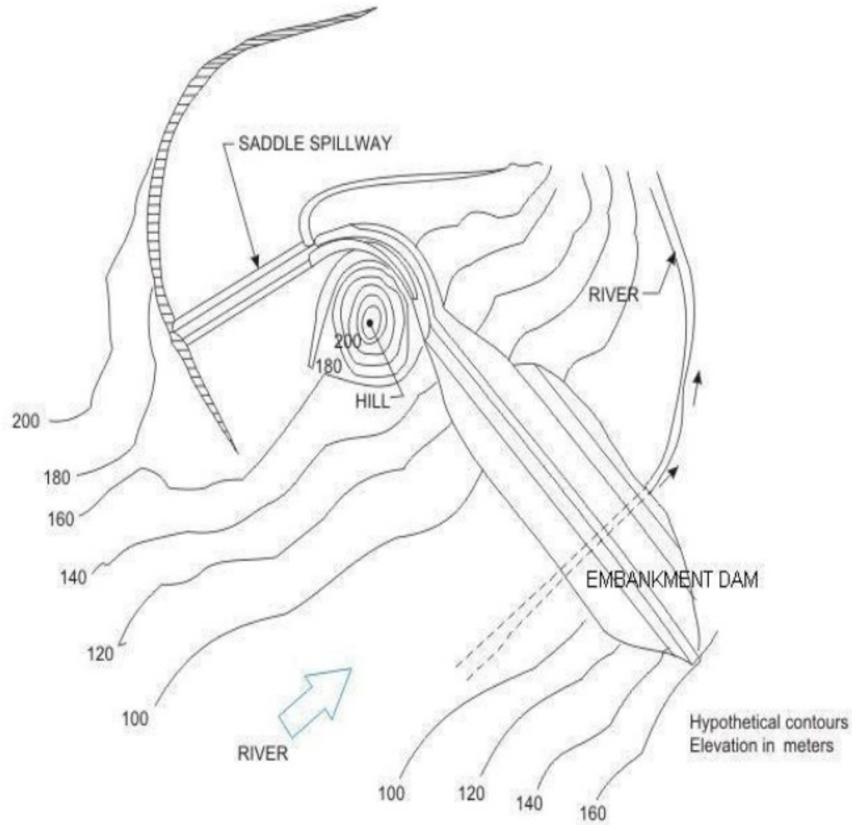

Figure 5: Illustrated the Saddle Spillway.

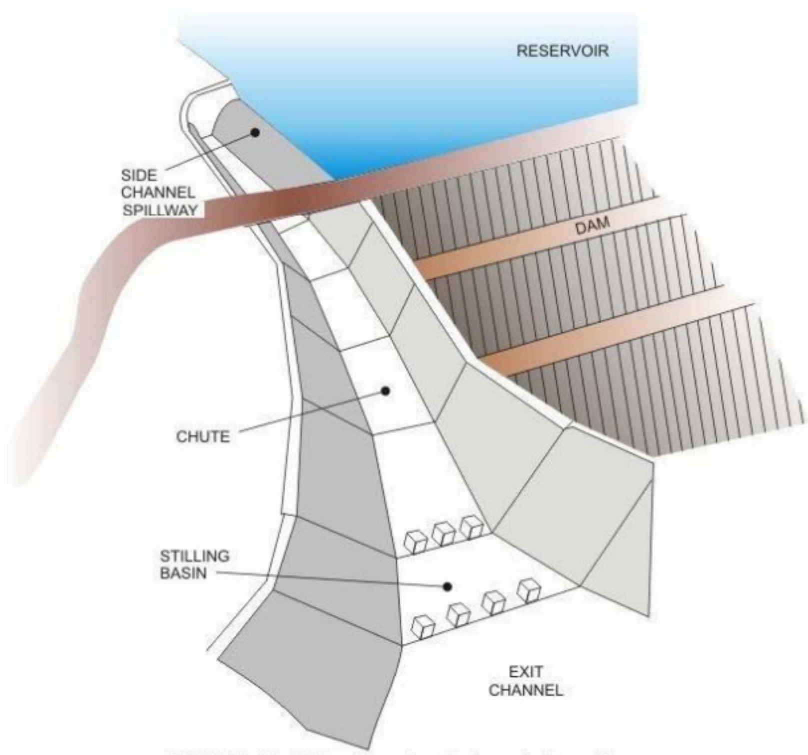

Figure 6: Illustrated the Side Entry Channel in Chute Spillway.

Side channel Spillway A side channel spillway is one in which the control weir is placed approximately parallel to the upper portion of the discharge channel, as may be seen from Figure 10. When seen in plan with reference to the dam, the reservoir and the discharge channel, the side channel spillway would look typically as in Figure 7.

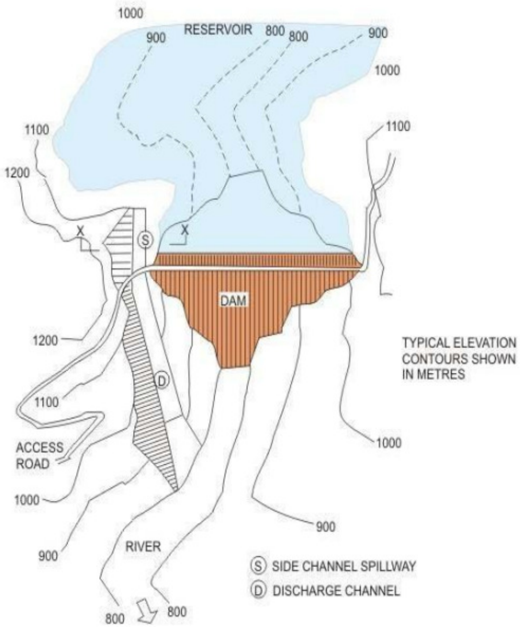

Figure 7: Illustrated the Side Channel Spillway.

The flow over the crest falls into a narrow trough opposite to the weir, turns an approximate right angle, and then continues into the main discharge channel. The side channel design is concerned only with the hydraulic action in the upstream reach of the discharge channel and is more or less independent of the details selected for the other spillway components. Flow from the side channel can be directed into an open discharge channel, as in Figure 8 showing a chute channel, or in to a closed conduit which may run under pressure or inclined tunnel. Flow into the side channel might enter on only one side of the trough in the case of a steep hill side location or on both sides and over the end of the trough if it is located on a knoll or gently sloping abutment[7].

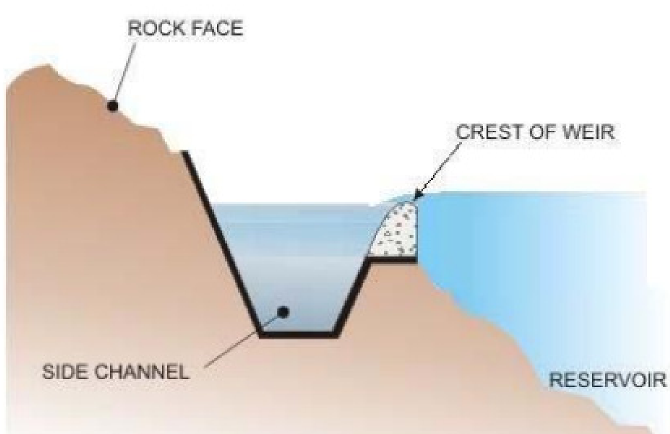

Figure 8: Illustrated the Magnified Sectional View X-X.

Discharge characteristics of a side channel spillway are similar to those of an ordinary overflow spillway and are dependent on the selected profile of the weir crest. Although the side channel is not hydraulically efficient, nor inexpensive, it has advantages which make it adoptable to spillways where a long overflow crest is required in order to limit the afflux and the abutments are steep and precipitous.

Shaft Spillway

A Shaft Spillway is one where water enters over a horizontally positioned lip, drops through a vertical or sloping shaft, and then flows to the downstream river channel through a horizontal or nearly horizontal conduit or tunnel. The structure may be considered as being made up of three elements, namely, an overflow control weir, a vertical transition, and a closed discharge channel. When the inlet is funnel shaped, the structure is called a Morning Glory Spillway. The name is derived from the flower by the same name, which it closely resembles especially when fitted with anti- vortex piers. These piers or guide vanes are often necessary to minimize vortex action in the reservoir, if air is admitted to the shaft or bend it may cause troubles of explosive violence in the discharge tunnel-unless it is amply designed for free flow. Discharge characteristics of the drop inlet spillway may vary with the range of head. As the head increases, the flow pattern would change from the initial weir flow over crest to tube flow and then finally to pipe flow in the tunnel. This type of spillway attains maximum discharging capacity at relatively low heads. However, there is little increase in capacity beyond the designed head, should a flood larger than the selected inflow design flood occur. A drop inlet spillway can be used advantageously at dam sites that are located in narrow gorges where the abutments rise steeply. It may also be installed at projects where a diversion tunnel or conduit is available for use[8].

Tunnel Spillway

Where a closed channel is used to convey the discharge around a dam through the adjoining hill sides, the spillway is often called a tunnel or conduit spillway. The closed channel may take the form of a vertical or inclined shaft, a horizontal tunnel through earth or rock, or a conduit constructed in open cut and backfilled with earth materials. Most forms of control structures, including overflow crests, vertical or inclined orifice entrances, drop inlet entrances, and side channel crests, can be used with tunnel spillways. When the closed channel is carried under a dam, it is known as a conduit spillway. With the exception of those with orifice or shaft type entrances, tunnel spillways are designed to flow partly full throughout their length. With morning glory or orifice type control, the tunnel size is selected so that it flows full for only a short section at the control and thence partly full for its remaining length. Ample aeration must be provided in a tunnel spillway in order to prevent a fluctuating siphon action which would result if some part of exhaustion of air caused by surging of the water jet, or wave action or backwater. Tunnel spillways are advantageous for dam sites in narrow gorges with steep abutments or at sites where there is danger to open channels from rock slides from the hills adjoining the reservoir. Conduit spillways are generally most suited to dams in wide valleys as in such cases the use of this types of spillway would enable the spillway to be located under the dam very close to the stream bed[9].

Siphon Spillway

A siphon spillway is a closed conduit system formed in the shape of an inverted U, positioned so that the inside of the bend of the upper passageway is at normal reservoir storage level. This type of siphon is also called a Saddle siphon spillway. The initial discharges of the spillway, as the reservoir level rises above normal, are similar to flow over a weir. Siphonic action takes place after the air in the bend over the crest has been exhausted. Continuous flow is maintained by the suction effect due to the gravity pull of the water in the lower leg of the siphon. Siphon spillways comprise usually of five components, which include an inlet, an upper leg, a throat or control section, a lower leg and an outlet. A siphon breaker air vent is also provided to control the siphonic action of the spillway so that it will cease operation when the reservoir water surface is drawn down to normal level. Otherwise the siphon would continue to operate until air entered the inlet. The inlet is generally placed well below the Full Reservoir Level to prevent entrance of drifting materials and to avoid the formation of vortices and drawdowns which might break siphonic action. Another type of siphon spillway designed by Ganesh Iyer has been named after him. It consists of a vertical pipe or shaft which opens out in the form of a funnel at the top and at the bottom it is connected by a right angle bend to a horizontal outlet conduit. The top or lip of the funnel is kept at the Full Reservoir Level. On the surface of the funnel are attached curved vanes or projections called the volutes[10]–[12].

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CHAPTER 19

SHAPE AND HYDRAULICS OF OGEE-CREST

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Crest Shape

The ogee shaped crest is commonly used as a control weir for many types of spillways Overflow, Chute, Side Channel etc. The ogee shape which approximates the profile of the lower nappe of a sheet of water flowing over a sharp-crested weir provides the ideal form for obtaining optimum discharges. The shape of such a profile depends upon the head, the inclination of the upstream face of the flow section, and the height of the overflow section above the floor of the entrance channel which influences the velocity of approach to the crest. The ogee profile to be acceptable should provide maximum possible hydraulic efficiency, structural stability and economy and also avoid the formation of sub atmospheric pressures at the surface which may induce cavitation's[1]. Ogee crested control structures are also sensitive to the upstream shape and hence, three types of ogee crests are commonly used. These are as follows:

- Ogee crests having vertical upstream face.
- Ogee crests having inclined upstreamface.
- Ogee crests having over hang on upstream face.

The effect of the above-mentioned factors on the variation of discharge and calculation for effective length are mentioned in the following paragraphs.

a. Effect of depth of approach

For a high sharp-crested ogee shaped weir, as that of an overall spillway of a large dam, the velocity of approach is small and the lower nappe flowing over the weir attains maximum vertical contraction. As the approach depth is decreased, the velocity of approach increases and the vertical contraction diminishes. For sharp-crested weirs whose heights are not less than about one-fifth of the head producing the flow, the coefficient of discharge remains fairly constant with a value of about 1.82 although the contraction diminishes. For weir heights less than about one-fifth the head, the contraction of the flow becomes increasingly suppressed and the crest coefficient decreases. This is the case of an ogee crested chute spillway control section. When the weir height becomes zero, the contraction is entirely suppressed and the weir turns into a broad crested one, for which the theoretical coefficient of discharge is 1.70. The relationship of the ogee crest coefficient of discharge Cd for various values of P/Hd where P is the height of the weir above base and Hd is the design head. The coefficients are valid only when ogee is formed to the ideal nappe shape[2].

b. Effect of the crest shape differing from the ideal nappe shape

When the ogee crest is formed to a shape differing from the ideal nappe shape or when the crest has been shaped for a head larger or smaller than the one under consideration, the coefficient of discharge will differ from that given in the previous section. A wider crest shape will reduce the coefficient of discharge while a narrower Crest Shape will reduce the coefficient. The application of this concept is required to deduce the discharge flowing over a spillway when the flow is less or more than the design discharge.

The variation of the coefficient of discharge in relation to H/Hd, where H is the actual head and Hd is the design head.

c. Effect of upstream face slope

For small ratio of P/Hd where P is the height of the weir and Hd the design head, as for the approach to a chute spillway, increase of the slope of upstream face tends to increase the coefficient of discharge. This figure shows the ratio of the coefficient for ogee crest with a sloping face to that with vertical face. For large ratios of P/Hd, the effect is a decrease of the coefficient. The coefficient of discharge is reduced for large ratios P/Hd only for relatively flat upstream slopes.

d. Effect of downstream apron interference and downstream submergence

This condition is possible for dams of relatively small heights compared to the natural depth of the river, when the water level downstream of the weir crest is high enough to affect the discharge, the condition being termed as submerged. The conditions that after the coefficient of discharge in this case are the vertical distance from the crest of the over flow to the downstream apron and the depth of flow in the downstream channel, measured above the apron.

Five distinct characteristic flow conditions can occur below an overflow crest, depending on the relative positions of the apron and the downstream water surface[3]:

- The flow will continue at supercritical stage
- A partial or incomplete hydraulic jump will occur immediately downstream from the crest
- A true hydraulic jump will occur
- A drowned jump will occur in which the high-velocity jet will follow the face of the overflow and then continue in an erratic and fluctuating path for a considerable distance under and through the slower water,
- No jump will occur - the jet will break away from the face of the overflow and ride along the surface for a short distance and then erratically intermingle with the slow moving water underneath.

Selection of Spillways

Guidelines for selection of spillways and energy dissipaters provide guidelines in choosing the appropriate type of spillway for the specific purpose of the project. The general considerations that provide the basic guidelines are as follows:

a. Safety Considerations Consistent with Economy

Spillway structures add substantially to the cost of a dam. In selecting a type of spillway for a dam, economy in cost should not be the only criterion. The cost of spillway must be weighed in the light of safety required below the dam.

Hydrological and Site Conditions

The type of spillway to be chosen shall depend on:

- Inflow flood;
- Availability of tail channel, its capacity and flow hydraulics;
- Power house, tail race and other structures downstream;
- Topography

Type of Dam

This is one of the main factors in deciding the type of spillway. For earth and rock fill dams, chute and ogee spillways are commonly provided, whereas for an arch dam a free fall or morning glory or chute or tunnel spillway is more appropriate. Gravity dams are mostly provided with ogee spillways.

Purpose of Dam and Operating Conditions

The purpose of the dam mainly determines whether the dam is to be provided with a gated spillway or a non-gated one. A diversion dam can have a fixed level crest, that is, non-gated crest.

Conditions Downstream of a Dam

The rise in the downstream level in heavy floods and its consequences need careful consideration. Certain spillways alter greatly the shape of the hydrograph downstream of a dam. The discharges from a siphon spillway may have surges and break-ups as priming and depriving occurs. This gives rise to the wave travelling downstream in the river, which may be detrimental to navigation and fishing and may also cause damage to population and developed areas downstream[4].

Nature and Amount of Solid Materials Brought by the River

Trees, floating debris, sediment in suspension, etc, affect the type of spillway to be provided. A siphon spillway cannot be successful if the inflow brings too much of floating materials. Where big trees come as floating materials, the chute or ogee spillway remains the common choice. Apart from the above, each spillway can be shown as having certain specific advantages under particular site conditions. These are listed below which might be helpful to decide which spillway to choose for a particular project.

Ogee Spillway

It is most commonly used with gravity dams. However, it is also used with earth and rockfill dams with a separate gravity structure; the ogee crest can be used as control in almost all types of spillways; and it has got the advantage over other spillways for its high discharging efficiency.

Chute Spillway

- It can be provided on any type of foundation,
- It is commonly used with the earth and rock fill dams,

- It becomes economical if earth received from spillway excavation is used in dam construction.

The following factors limit its adaption:

- It should normally be avoided on embankments;
- Availability of space is essential for keeping the spillway basins away from the dam paving;
- If it is necessary to provide too many bends in the chute because of the topography, its hydraulic performance can be adversely affected.

Side Channel Spillways

This type of spillway is preferred where a long overflow crest is desired in order to limit the intensity of discharge, it is useful where the abutments are steep, and it is useful where the control is desired by the narrow side channel. The factor limiting its adoption is that this type of spillway is hydraulically less efficient.

Shaft Spillways (Morning Glory Spillway)

- This can be adopted very advantageously in dam sites in narrow canyons,
- Minimum discharging capacity is attained at relatively low heads. This characteristic makes the spillway ideal where the maximum spillway outflow is to be limited. This characteristic becomes undesirable where a discharge more than the design capacity is to be passed. So, it can be used as a service spillway in conjunction with an emergency spillway.

The factor limiting its adoption is the difficulty of air-entrainment in a shaft, which may escape in bursts causing an undesirable surging[5].

Siphon Spillway

Siphon spillways can be used to discharge full capacity discharges, at relatively low heads, and great advantage of this type of spillway is its positive and automatic operation without mechanical devices and moving parts.

The following factors limit the adoption of a siphon spillway: It is difficult to handle flows materially greater than designed capacity, even if the reservoir head exceeds the design level; Siphon spillways cannot pass debris, ice, etc; There is possibility of clogging of the siphon passage way and breaking of siphon vents with logs and debris; In cold climates, there can be freezing inside the inlet and air vents of the siphon; When sudden surges occur and outflow stops; The structure is subject to heavy vibrations during its operation needing strong foundations; and Siphons cannot be normally used for vacuum heads higher than 8 m and there is danger of cavitation damage.

Overfall or Free Fall Spillway

This is suitable for arch dams or dams with downstream vertical faces; and this is suitable for small drops and for passing any occasional flood.

Tunnel or Conduit Spillway

This type is generally suitable for dams in narrow valleys, where overflow spillways cannot be located without risk and good sites are not available for a saddle spillway. In such cases, diversion tunnels used for construction can be modified to work as tunnel spillways. In case of embankment dams, diversion tunnels used during construction may usefully be adopted. Where there is danger to open channels from snow or rock slides, tunnel spillways are useful.

Energy Dissipaters

Different types of energy dissipators may be used along with a spillway, alone or in combination of more than one, depending upon the energy to be dissipated and erosion control required downstream of a dam. Broadly, the energy dissipators are classified under two categories Stilling basins or Bucket Type[6].

Bucket type Energy Dissipators

This type of energy dissipators includes the following:

- Solid roller bucket
- Slotted roller bucket
- Ski jump (Flip/Trajectory) bucket

Usually the hydraulic jump type stilling basins and the three types of bucket-type energy dissipators are commonly used in conjunction with spillways of major projects. The detailed designs of these are dealt in subsequent sections. Since energy dissipators are an integral part of a dam□s spillway section, they have to be viewed in conjuction with the latter. Two typical examples have been shown in Figures 45 and 46, though it must be remembered that any type of energy dissipator may go with any type of spillway, depending on the specific site conditions.

Design of Hydraulic Jump Stilling Basin type Energy Dissipators

A hydraulic jump is the sudden turbulent transition of supercritical flow to subcritical. This phenomena, which involves a loss of energy, is utilized at the bottom of a spillway as an energy dissipator by providing a floor for the hydraulic jump to take place. The amount of energy dissipated in a jump increases with the rise in Froude number of the supercritical flow.

Design of Bucket-type Energy Dissipators

Hydraulic behavior of bucket type energy dissipator depends on dissipation of energy through:

a. Interaction of two rollers formed, one in the bucket, rolling anti-clockwise if the flow is from the left to the right and the other downstream of the bucket, rolling clockwise;

b. Interaction of the jet of water, shooting out from the bucket lip, with the surrounding air and its impact on the channel bed downstream[7].

Bucket type energy dissipators can be either:

a. Roller bucket type energy dissipator;

b. Trajectory bucket type energy dissipator.

The following two types of roller buckets are adopted on the basis of tailwater conditions and importance of the structure:

a. Solid roller bucket,

b. Slotted roller bucket.

Hydraulic Design of Solid Roller Bucket

An upturn solid bucket is used when the tail water depth is much in excess of sequent depth and in which dissipation of considerable portion of energy occurs as a result of formation of two complementary elliptical rollers, one in bucket proper, called the surface roller, which is anticlockwise and the other downstream of the bucket, called the ground roller, which is clockwise. In the case of solid roller bucket the ground roller is more pronounced and picks up material from downstream bend and carried it towards the bucket where it is partly deposited and partly carried away downstream by the residual jet from the lip. The deposition in roller bucket is more likely when the spillway spans are not operated equally, setting up horizontal eddies downstream of the bucket. The picked-up material which is drawn into the bucket can cause abrasive damage to the bucket by churning action. For effective energy dissipation in a solid roller bucket, both the surface or dissipating roller and the ground or stabilizing roller, should be well formed. Otherwise, hydraulic phenomenon of sweep out or heavy submergence occurs depending upon which of the rollers is inhibited.

Hydraulic Design of Slotted Roller Bucket

An upturned bucket with teeth in it used when the tailwater depth is much in excess of sequent depth and in which the dissipation of energy occurs by lateral spreading of jet passing through bucket slots in addition to the formation of two complementary rollers as in the solid bucket. In the slotted roller bucket, a part of the flow passes through the slots, spreads laterally and is lifted away from the channel bottom by a short apron at the downstream end of the bucket. Thus the flow is dispersed and distributed over a greater area providing less violent flow concentrations compared to those in a solid roller bucket. The velocity distribution just downstream of the bucket is more akin to that in a natural stream, that is, higher velocities at the surface and lower velocities at the bottom. While designing a slotted roller bucket, for high head spillway exceeding the total head of 50 m or so, specific care should be taken especially for design of the teeth, to ensure that the teeth will perform cavitation free. Specific model tests should therefore be conducted to verify pressures on the teeth and the bucket invert should accordingly be fixed at such an elevation as to restrict the sub atmospheric pressures to the permissible magnitude[7].

The principal features of hydraulic design of the slotted roller bucket consists of determining in sequence:

a. Bucket radius;

b. Bucket invert elevation;

c. Bucket lip angle;

d. Bucket and tooth dimensions, teeth spacing and dimensions and profile of short apron.

Hydraulic Design of Trajectory Bucket Type Energy Dissipator

An upturn solid bucket used when the tailwater depth is insufficient for the formation of the hydraulic jump, the bed of the river channel downstream comprises sound rock and is capable of withstanding, without excessive scour, the impact of the high velocity jet. The flow coming down the spillway is thrown away from toe of the dam to a considerable distance downstream as a free discharging upturned jet which falls into the channel directly, thereby avoiding excessive scour immediately downstream of the spillway. There is hardly any energy dissipation within the bucket itself. The device is used mainly to increase the distance from the structure to the place where high velocity etc. hits the channel bed, thus avoiding the danger of excessive scour immediately downstream of the spillway. Due to the throw of the jet in the shape of a trajectory, energy dissipation takes place by:

a. Internal friction within the jet,

b. The interaction between the jet and surrounding air,

c. The diffusion of the jet in the tail water,

d. The impact on the channel bed.

When the tailwater depth is insufficient for the formation of the hydraulic jump and the bed of the channel downstream comprises sound rock which is capable of withstanding the impact of the high velocity jet, the provision of a trajectory bucket is considered more suitable as provision of conventional hydraulic jump type apron or a roller bucket involves considerable excavation in hard strata forming the bed. It is also necessary to have sufficient straight reach in the downstream of a skijump bucket. The flow coming down the spillway is thrown away in air from the toe of the structure to a considerable distance as a free discharging upturned jet which falls on the channel bed d/s. The hard bed can tolerate the spray from the jet and erosion by the plunging jet would not be a significant problem for the safety of the structure. Thus, although there is very little energy dissipation within the bucket itself, possible channel bed erosion close to the downstream toe of the dam is minimized. In the trajectory bucket, only part of the energy is dissipated through interaction of the jet with the surrounding air. The remaining energy is imparted to the channel bed below. The channel bed should consist of sound, hard strata and should be free from laminations, joints and weak pockets to withstand the impact of jet. The design of the trajectory bucket presupposes the formation of large craters or scour holes at the zone of impact of the jet during the initial years of operation and, therefore, the design shall be restricted to sites where generally sound rock is available in the river bed. Special care shall be taken to concrete weak pockets in the bed located in a length[8].

Protection of Downstream of Spillways from Scour

It may be noted that inspite of the provision of the best suited energy dissipator for a specific spillway under the prevailing site conditions, there may be still some energy is expected to be maximum for the trajectory type spillway, followed by the solid and slotted roller buckets and finally the hydraulic jump type stilling basins. In order to protect the downstream riverbed from these undesirable scour, the following types of protection works have been recommended by the Bureau of Indian Standards “Preliminary design, operation and maintenance of protection works downstream of spillways-guidelines”.

a. **Training Walls at the Flanks of the Spillways**- Training walls extended beyond the end-sill of the stilling basins or buckets generally serve to guide the flow into the river channel, protect the wrap-rounds of the adjacent earth dams, river banks or power house bays and tail race channels. To this extent, the training walls are - considered to be downstream protection works.

b. **Protective Aprons Downstream of Bucket Lips or End-sills of Stilling Basins-** Protective aprons of concrete laid on fresh rock or acceptable strata immediately downstream of bucket lips or end-sill of stilling basin, protect the energy dissipator against undermining due to excessive scour during or after construction of the spillways. A suitable concrete key is normally provided, at the downstream end of the apron. Where the normal river bed level is higher than the end-sill and a recovery slope is, provided, it sometimes becomes necessary to lay a concrete apron on such a recovery slope also for protection[9].

c. **Concrete Blocks or Concrete Filling on River Bed Downstream of Energy Dissipator**-Concrete blocks or concrete fillings are sometimes provided on the river bed downstream of energy dissipators to safeguard against excessive scour and prevent further scour.

d. Protective Pitchings on Natural or Artificial Banks Downstream of Spillways- Protective pitchings of stone rip rap, masonry or concrete blocks are provided on natural river banks or artificially constructed embankments of diversion channels, power house tail race channels or guide banks, for protecting them against high velocity flows or waves.

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CHAPTER 20

CONJUNCTIVE WATER MANAGEMENT

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Water on our planet is present in different forms: atmospheric water (rain, snow, hail and white frost); seawater; ice and snow cover; surface water (overland flow and water in streams, lakes, reservoirs and ponds); subsurface water (soil water and groundwater); and water temporarily in the human water use chain (after use returned to the natural water system). It needs to be emphasized that these different forms of water do not constitute different sources of water isolated from each other, but rather they are closely linked in what is called the water cycle. Water tends to pass from one component to another, at different rates: water vapor in the atmosphere condensates and forms precipitation; precipitation on the land surface is converted to soil water, surface water and groundwater; widespread exchange of water occurs between streams, soils and aquifers; water abstracted and used by humans is returned to the terrestrial water systems discharge to the sea and by evapotranspiration directly to the atmosphere, while evaporation from the oceans forms the largest return of water to the atmosphere.

The different water cycle components are directly linked by their hydraulic connectivity in the natural water cycle, and indirectly by the human water use chain. In the latter there are often alternative water source options for meeting a certain water demand and for discharging used water; the choices made by people have repercussions for the state of each of the corresponding water cycle components. From a water management perspective, the terrestrial waters are sometimes subdivided into so-called 'green water' water in the shallow, unsaturated soil zone, 'blue water' surface water and groundwater, 'grey water' wastewater without faecal contamination and 'black water' sewage. Water resources development and management are primarily focusing on 'blue water', but in spite of the linkages described above– the daily practice in most countries is characterized by a tradition of dealing with groundwater and surface water separately, without significant coordination[1].

Definition of Conjunctive Water Management

Any approach to water resources management that takes the linkages within the water cycle systematically into account may be called 'Conjunctive Water Management'. The linkages can be direct hydraulic connectivity in the natural water cycle or indirect (human water use chain) Box 1 presents a tentative definition. Worldwide, the stress on water resources is steadily increasing, because of population growth, urbanization, intensification of industries, agriculture and tourism, and rising economic welfare levels; and this stress is aggravated in recent years by the threats and impacts of climate change. Intelligent management of the water resources is required in order to cope with these growing challenges, and to achieve more resilience of the water systems and a higher level of water security at local and regional levels.

The complexity of the water resources and their local context call for a comprehensive approach to water resources management, nowadays called Integrated Water Resources Management. Among water professionals there are differences of opinion about how to interpret the designation 'integrated'. If this would imply a complete coordination at the operational level of all aspects that are in principle interrelated (both inside the water systems and beyond), then one might be sceptical about the feasibility of implementing IWRM. Interpretation at normative and strategic levels, however, leads to a much more optimistic judgment. As emphasized by GWP (2000), certain basic principles underlying IWRM may be generally applicable, independently of the local context and the stage of economic or social development, but there is no universal blueprint as to how such principles can be put into practice[2].

Putting the Conjunctive Water Management paradigm into practice

Conjunctive Water Management and its benefits will become reality only as a result of effective dedicated action. Table 1 lists typical activities and techniques to be considered for this purpose. These activities and techniques come under two main categories: those that have to play a role during area-wide water resources planning and those related to implementation at field level. At a lower level they are grouped under some tentatively defined 'immediate objectives' to clarify how they may contribute to water resources management benefits; but this classification is not rigorous, since certain activities may contribute to more than one of these immediate objectives. For example, wastewater management in the first place produces environmental benefits by the removal of pollutants, but the treated water may by recycling so to contribute to augmenting the available water resources (usually for non-potable uses). Each of these types of conjunctive management activities or techniques is briefly described in Table 1 below[3]:

Table 1: Illustrated the Putting Conjunctive Water Management into practice: activities and techniques

At area-wide planning level	**Activities and techniques at the level of implementation in the field**		
Incorporating all water components	**Optimal selection of source of supply**	**Resource augmentation**	**Environmental control**
• Exploring and analyzing hydraulic connectivity and exchanges of water • Preventing 'double counting' • Identifying promising opportunities • Identifying hazards of harmful interaction	• Conjunctive use of surface water and groundwater	• Managed aquifer recharge (MAR) • Watershed management • Desalination of brackish and saline water • Recycling treated wastewater	• Water level control in polder / low-low-lying and reclaimed areas • Groundwater level control in surface water irrigated zones • Restricting groundwater pumping to control surface water environmental flows • Managing wastewater

Activities at Area Wide Planning Level

Exploring and analyzing hydraulic connectivity and exchanges of water

Exploring and analyzing the hydraulic connectivity between surface water, groundwater and other components of the terrestrial water cycle form an indispensable first step towards Conjunctive Water Management. For each area concerned, the connectivity should be identified and the rates of water exchange between the components assessed. The underlying processes should be studied in order to enable predictions on water exchanges under modified boundary conditions. This activity requires sufficient field data of good quality to be available, in particular monitoring data. Furthermore, it will benefit from modern tools for processing and analysis, such as Geographic Information Systems and numerical simulation models.

Avoiding 'double counting'

If surface water resources and groundwater resources in an area are assessed separately, then the sum of the outcomes overestimates the total blue water resources of the area. This is due to the exchange of water between streams and aquifers, which causes an overlap in the surface water and groundwater budgets usually between 50 and 100% of the latter[4]. In practice, this overlap is often overlooked, thus leading to 'double counting', which may cause a mismatch between water development planning and available water resources. Exploring and analyzing the hydraulic connectivity and water exchanges properly see the previous section may help avoiding the erroneous practice of 'double counting'.

Identifying promising opportunities

Knowledge on the water regime within an area, including the hydraulic properties, the water quality and the time-dependent hydrologic behavior of all water systems involved in the water cycle, will allow to identify promising opportunities for beneficial conjunctive water resources development and management.

Important types of interventions are described below. Identifying hazards of harmful interaction Area-related knowledge may also reveal hazards of harmful interaction between different linked water systems in an area. Exploiting water from one system may have negative repercussions for another. Once the hazard has been identified, measures can be designed and implemented for mitigation or adaptation.

Specific activities and techniques for implementation at field level

A. Conjunctive use of surface water and groundwater

The fundamental idea behind conjunctive use is making optimal use of the available 'blue water' resources, by tapping at any moment the less costly or otherwise most attractive source or combination of sources (surface water, groundwater). This may lead to achieving benefits such as:

- Higher total quantities of 'blue water' supplied and used;
- Enhanced reliability of water supplies, since groundwater may act as a buffer during droughts, or as an emergency supply during and after disasters;
- Lowest cost for a given water supply pattern[5].

B. Managed aquifer recharge (MAR)

Managed aquifer recharge is a strategy or group of techniques based on diverting and storing water into an aquifer, usually for its use at a later moment of time like as a buffer resource during dry seasons or as a source of water for emergency situations like during severe long-term droughts or after accidental pollution of drinking water sources. Harvested rainwater, storm water runoff, surface water, treated wastewater and desalinized saline or brackish water are the main sources of water for managed aquifer recharge. Potential benefits of MAR include:

- Increase in the total available 'blue water' resources;
- More flexibility in the timing of using the blue water resources;
- Excess surface water is prevented from being lost or from causing flooding damage;
- Counteracting the encroachment of saline or brackish water into fresh groundwater bodies in coastal aquifers;
- Improvement of the quality of used waters going to be recycled like by removal of suspended sediment from surface water;
- Conservation of in-situ groundwater functions like maintaining ecosystems and stability of the land surface.

Important factors that are decisive for the successful application of managed aquifer recharge are:

a. The country's institutional and legal framework,

b. Access to relevant technologies and technical capacity recharge techniques, waste water treatment technologies, professional human resources,

c. The presence of suitable sites characterized by a source of recharge water and an aquifer with sufficient storage capacity.

C. Watershed Management

Watershed management aims at improving the living conditions of local communities by optimal and coherent use, protection and conservation of the land and water resources within the boundaries of hierologically defined geographical units (watersheds). It is most often implemented in relatively small upland watersheds and may use a large variety of technical measures, usually with strong involvement of local stakeholders. Several of its technical components have in common with managed aquifer recharge that they pursue an increase in the locally usable water resources and in their availability during a larger part of the year. Watershed management, however, tends to focus less on groundwater recharge and more on soil moisture conservation by rainfall and runoff harvesting, on pollution control and on the reduction of soil erosion. Typical technical interventions include contour trenches, contour bunds, gully plugs, check dams, ponds and reservoirs, most of which intercept rain and surface water flows and convert them into soil water, groundwater and surface water storage[6].

D. Supplementing fresh-water supplies with desalinated brackish and saline water

This activity also contributes to increased water availability for supplies, and it may be particularly an option in coastal zones with limited fresh water resources. The quantities of desalinized water have to be monitored and carefully controlled because this water has to be included in the assessment of usable water resources in the context of Conjunctive Water Management. At greater distance to the sea, desalinized seawater becomes less attractive than desalinized local brackish groundwater, because of the considerable energy required for long-distance conveyance.

E. Recycling treated used water

In many areas use is made of opportunities to augment the available water resources by treating used water and recycling it for re-use, instead of dumping it to either surface water or subsurface water bodies. Usually there will be some restrictions in the purposes for which the recycled water can be used, depending on the type of treatment applied.

F. Water level control in polder areas

Polder areas are characterized by their flat topography, shallow water-tables and technical provisions to control these water-tables. Their overall purpose is to create and maintain optimal conditions for the current or envisaged types of land use (residential area, agriculture land, nature conservation area, industrial zone, etc.) The technical approach consists of keeping phreatic water levels at an optimum depth by manipulating water levels in the connected surface water system ditches, canals, lakes, ponds. The simplest version is only designed for draining excess groundwater during wet periods and discharging it into connected surface water bodies). The more advanced versions implemented for centuries already have the additional aim to replenish groundwater and soil moisture during dry periods, by inducing inflow of water from the connected surface water bodies. In other words: they seek to maintain optimal groundwater and surface water regimes[7].

G. Groundwater level control in surface water irrigated zones

The primary purpose of surface water irrigation is to support crop growth by replenishing soil moisture, but as a side-effect it also creates or intensifies a physical link between surface water and groundwater systems. The downward percolating irrigation water losses form an additional source of groundwater recharge, which will affect the local groundwater level regime. Control of the groundwater levels requires surface water use to be planned in conjunction with groundwater management; this often leads to groundwater again being discharged into a surface water body.

H. Restricting groundwater pumping to maintain environmental flows

Base flows of streams, water fluxes feeding wet ecosystems and other environmental flows may be negatively affected by groundwater abstraction. To maintain the environmental flows and functions properly, it sometimes may be necessary to restrict groundwater pumping. A Conjunctive Water Management approach is then required to define critical pumping levels[8], [9].

I. Managing used waters and wastewater

A significant part of the volumes of water used by human's returns to the natural local water systems. It is important to ensure that these used waters and wastewater do not affect the usable fresh-water resources negatively, in terms of both water quantity and quality. In the case of irrigation, part of the applied irrigation water is bypassing the soil moisture zone and percolates downward, which under shallow-water-table conditions may lead to water-logging and eventually to soil salinity problems. As mentioned before, such problems can be controlled by draining the irrigated agricultural lands, thus triggering groundwater outflow into surface water bodies. Most categories of water use produce wastewater, i.e. water that is more or less severely polluted.

Treating this wastewater and allocating it optimally among the local water systems will reduce negative impacts such as polluting soils and water in streams or aquifers to a minimum. When feasible, treated wastewater may be recycled for re-use, which contributes to resource conservation and sustainability. Generally, pre-treated municipal and domestic wastewater, recharged into an aquifer, is considered a suitable source of water for irrigation and other non-potable purposes. Industrial wastewaters are often polluted by toxic components; consequently, they usually require relatively costly and technologically advanced treatment before they can be reused or safely discharged to water courses or aquifers[10]–[12].

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CHAPTER 21

POTENTIAL BENEFITS OF CONJUNCTIVE WATER MANAGEMENT

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It requires no explanation that desalination of brackish and saline water and recycling of treated wastewater contribute to increased quantities of water available for human uses. These techniques convert water unfit for most uses into usable water that satisfies certain water quality criteria. Managed aquifer recharge looks at first glance like merely rerouting water from surface water to the groundwater domains[1]. Nevertheless, it also augments the usable quantities of water by safeguarding volumes of water that otherwise would be lost by evaporation or outflow into the sea and it keeps water in storage for use during critical dry periods. Similar benefits are produced by watershed management. Rainfall- and runoff-harvesting, either for direct use or for augmenting soil moisture, and also small storage reservoirs, may reduce water availability downstream, but they enable the use of significant quantities of water that otherwise would be lost.

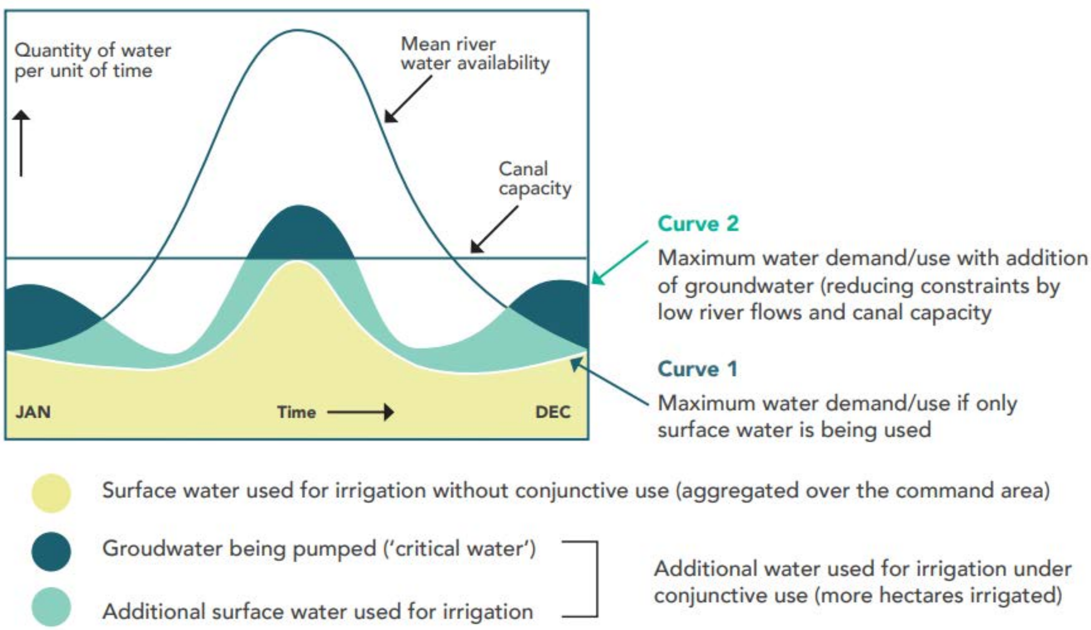

Figure 1: Represented the Graph how conjunctive use of surface water and groundwater in an irrigation.

Conjunctive use of surface water and groundwater does not transfer water between these two different components of the natural water cycle, but it rather focuses at optimizing the mix of both in water use. Conjunctive use, often emerging spontaneously, pursues making maximum benefit from the strengths of each component: the usually comparatively large quantities and low development cost of surface water during wet periods and the availability and reliability of groundwater during dry spells. Experience shows that these properties lead in practice to more water being used as display in Figure 1, more flexibility for the user and higher profits from water use. The latter in particular because the reliability of the groundwater component eliminates or reduces significantly the risk of unpredictable water shortages[2]. Combining groundwater and surface water in a single supply system like urban water supply has the additional advantage that the system does not break down in case of pollution of surface water due to accidental release of pollutants or due to natural hazards. In such cases, additional groundwater readily can be made available as an emergency supply.

Water Resources Sustainability

Most of the forms of Conjunctive Water Management intend to increase the quantities of water available for human uses, either by improving water quality (by treating saline, brackish or polluted water), or by preventing that fresh terrestrial water is lost unused. Regarding the benefits of increased usable water resources there is a trade-off between their contribution to human water use and to the sustainability of water resources and related ecosystems. Water managers have to decide on the balance between these counteractive contributions. They should also be keen on the allocation to different users, e.g. when enhanced upstream water availability would reduce availability for downstream users. Figure 2 shows schematically how Conjunctive Water Management may contribute to establishing sustainable development of intensively exploited aquifers[3].

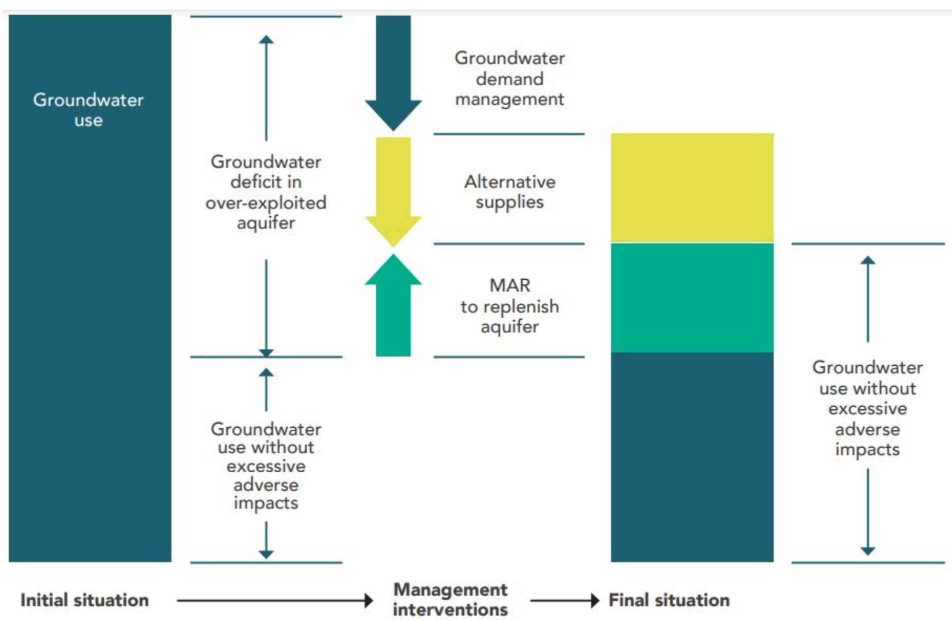

Figure 2: Represented the Conjunctive Water Management as an approach to re-establish hydrological equilibrium in an overexploited aquifer

Environmental Benefits

- **Reduction of water pollution hazards and impacts**

Uncontrolled discharge of wastewater and other used waters leads to environmental damage. Adequate wastewater management eliminates or reduces this damage, by removing pollutants carried by these waters (upgrading water quality by treatment) and by discharging the treated water to those blue water systems where it will do minimal harm, or even by recycling it into the water use chain[4].

- **Salinity Control**

Several of the conjunctive management approaches mentioned in the previous chapter have a potential impact on the encroachment of saline or brackish water into aquifers or lower reaches of rivers. An example is managed aquifer recharge in zones where fresh-water lenses are overlaying saline or brackish groundwater, such as practiced since the 1940s in the dune area of The Netherlands. In this particular case, treated river water is used for enhancing recharge through infiltration basins and injection wells.

- **Ecosystem Conservation**

Many natural water systems offer important ecosystems services. These are linked to hydrological features like shallow groundwater levels, springs, base flow of streams and mineralization levels of terrestrial and coastal waters. These features are essential for maintaining riparian and aquatic ecosystems, wetlands and oases. Diversion and abstraction of surface water, groundwater abstraction and other human interferences in the water cycle often modify the hydrological conditions to the extent that these ecosystems degrade or even disappear. Protection and conservation of valuable ecosystems require a good understanding of the interlink ages between the different components of the water cycle, often hidden for the layman's eye but revealed by field studies. Conjunctive Water Management approaches help taking these interlink ages properly into account[5].

Economic and social benefits

The fact that spontaneous implementation of conjunctive use of surface water and groundwater by individuals is rather common suggests that it creates substantial economic or social benefits; otherwise, the practice would not prevail. Not only conjunctive use, but also the other Conjunctive

Water Management techniques usually produce significant economic and social benefits, provided that they are properly tuned to the local conditions. In some cases, the efforts and benefits occur at the individual level such that harvesting rain water from roof catchments to enhance domestic water security, in other cases they are shared by all inhabitants of a certain river basin or area. Implementing such measures for collective benefit is usually preceded by project or basin management plans that include a cost-benefit analysis; while raising funds for the implementation is another important preparatory activity. Evidently, resources augmentation measures tend to produce particularly high benefits in water-scarce areas[6].

Elimination or reduction of planning flaws and errors

Adopting a Conjunctive Water Management approach reduces the risk that attractive water resources management opportunities are overlooked, thus that water resources management plans are sub-optimal. It also reduces the incidence of planning errors resulting from not overseeing the entire local water situation[7], [8].

A still rather common error in this category is so-called 'double-counting' of the available surface water and groundwater resources in an area, especially if both water cycle components are developed and managed separately. This error results from ignoring the usually very substantial overlap between the groundwater and surface water budgets, since the lion's share of groundwater discharge around the globe is in the form of outflow into surface water bodies, while in certain settings a large share of groundwater recharge comes from surface water. It goes without saying that eliminating or reducing planning flaws and errors produces benefits, either in terms of resources sustainability or environmental quality, or of economic or social benefits[9], [10].

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