M.A. GEOGRAPHY

SEMESTER II (CBCS)

GEOGRAPHY PAPER - 201

OCEANOGRAPHY AND HYDROLOGY

SUBJECT CODE:92123

Programme Co-ordinator : **Dr. Santosh Rathod**
Associate Professor, Dept. of English,
IDOL, University of Mumbai, Mumbai

Course Co-ordinator : **Mr. Ajit Gopichand Patil**
Assistant Professor,
IDOL, University of Mumbai, Mumbai

Course Writer : **DR.Sumant Autade**
Assistant Professor,
Swami Vivekanand Night College, Dombivili

: **Ms.Rupanjai Dasgupta**
Assistant Professor,
TISS, Mumbai

: **Dr.H.M.Pednekar**
Former Principal
Ondhe College, Vikramgad, Dist Palghar

: **Astha Smarth**
Dept. of Geography, University of Mumbai
Mumbai

April 2022, Print - 1

Published by : Director,
Institute of Distance and Open Learning ,
University of Mumbai,
Vidyanagari, Mumbai - 400 098.

DTP Composed & Printed by : Mumbai University Press,
Vidyanagari, Santacruz (E), Mumbai

CONTENTS

❖❖❖❖

MA GEOGRAPHY

Paper no. 201, Semester II
Oceanography and Hydrology

No. of Credits: 4

1. Fundamental Concepts in Oceanography

1.1 Definition, nature and scope of oceanography

1.2 Age and origin of oceans, and ocean morphology.

1.3 Distribution of temperature, salinity and density of oceans.

2. Ocean Currents and Resources

2.1 Ocean currents: Atlantic, Pacific and Indian Oceans.

2.2 waves and tsunamis, tides.

2.3 Marine sediments and deposits

2.4 Food and mineral resources of the sea.

3. Introduction to Hydrology

3.1 Hydrological cycle, Factors affecting movement of water, Patterns of movement

3.2 Water Budget, World water Resources,

3.3 World Water Balance, Global Freshwater Resources,

3.4 History of Hydrology

4. Watershed, Its Characteristics and Evaporation Process

4.1 Topographic and Effective Watershed

4.2 Physiographic characteristics of a Watershed- Geometric & Drainage Network

4.3 Agro-Pedo Geological Characteristics – Soil Cover, Soil type, Geology

4.4 Metrological Factors influencing Evaporation- Physical Factors involved inEvaporation Process.

References:

1. Agarwal A. and Narain, S. (1997), “Dying Wisdom: Rise, Fall and Potential ofIndia’s Traditional Water Harvesting System”, CSE, New Delhi.
2. Andre Musy (2011) Hydrology a Science of Nature, Science Publishers, NewHampshire.

2. Centre for Science and Environment (2002), “Citizens Report”, New Delhi.
3. Charlu, T.G.K. and Dutt, D. K. (1982), “Ground Water Development in India”Rural Electrification Corporation, New Delhi.
4. Chorley, R. J. (1967), “Water, Earth and Man”, Methuen, London.
5. Chorley, R. J. (1969), “Introduction to Physical Hydrology”, Methuen, London.
6. Elizabeth M. Shaw (1994) Hydrology in Practice, Taylor & Francis e-LibraryPublication New Hampshire.
7. Jones, J. A. (1997), “Global Hydrology : Processes, Resources and WaterManagement”, Longman, London.
8. Lvovich, M.I., (2010), Climatology, Hydrology, Glaciology, John Wiley and Sons, London
9. Mather, J. R. (1984), “Water Resources : Distribution, Use and Management”,John Wiley, Maryland.
10. Singh, R. A. and Singh, S. R. (1972), “Water Management: Principles andPractices”, Tara Publication, Varanasi.
11. Subramanya K (2014) Engineering Hydrology, Mc Graw Hill Publication,New Delhi.
12. Todd, D. K. ((1959), “Ground Water Hydrology”, John Wiley, New York.
13. Stewart, R. H. (2008). *Introduction to Physical Oceanography*.
14. Garrison, T. (2012). *Essentials of Oceanography* (Sixth Edit). Brooks/Cole, CengageLearning.
15. Singh, S. (2014). *Oceanography*. Allahabad: Pravalika Publications.
16. Rao, K. L. (1979), “India’s Water Wealth”, Orient Longman, New Delhi.

❖❖❖❖

1

FUNDAMENTAL CONCEPTS IN OCEANOGRAPHY

After going through this chapter, you will be able to understand the following

Unit Structure

1.1. OBJECTIVES

By the end of this unit, you will be able to -

- Describedifferent definitions, nature, and scope of oceanography.
- Know about the history of oceanography.
- Understand the age and how oceans originated.
- Explain ocean morphology andthe ocean's temperature, density, and salinity.

1.2. INTRODUCTION

The chapter will focus on oceanography as a branch or subdiscipline of physical geography. It will further discussthe historical events related to the development of ocean science to understand oceanography's growth as a multidisciplinary branch, along with an overview of how oceans originated. We shall learn the morphological pattern of the sea. Lastly, the chapter will discuss the Ocean's Temperature, density, and salinity variations.

1.3. SUBJECT DISCUSSION

Two-thirds of the earth's surface is covered by water. Nearly 97 percent of that water is saltwater swirling in the ocean. Oceanography is a broad field where many subjects are focused on the common goal of understanding the oceans.Oceanography as a branch started slowly and informally. During the mid-1800s, it began to develop as modern science and has grown dramatically, rather explosively, in the last few decades. Oceanography is the sum of several branches.

Oceanography is vital to understanding the effect of pollutants on ocean waters and preserving the quality of the ocean waters in the face of increasing human demands.More excellent knowledge of the world's oceans enables scientists to predict long-term weather and climatic changes more accurately, leading to more efficient exploitation of the earth's resources. When the sea is threatened by climate change, coastlines are eroding, and the entire marine species are at risk of extinction; the role of oceanographers is more critical now than it has ever been.The study of the oceans is also essential for marineresources, trade and commerce, and national security.

1.4. DEFINITION, NATURE,AND SCOPE OF OCEANOGRAPHY

Oceanography is the study of the ocean's chemical, physical and biological features, including its geologic framework and the life forms that inhabit the marine environment. Oceanography is a broad field in which many sciences like geography, geology, geophysics, chemistry, botany, etc., focus on the common goal of understanding the oceans. The first part of the term oceanography has been coined from the Greek word '*Okeanos*' or Oceanus, the name of the Titan sons of the god Gaea and Uranus. The second part also comes from the Greek word '*graphia*,' which describes the act of recording and representing. H.A. Marmer defines "Oceanography the science of the sea includes primarily the study of the form and nature of the oceans basins, the characteristics of the water in these basins and the movement to which these water are subject." According to J. Proudman: "Oceanography studies the fundamental principles of dynamics and thermodynamics in relation to the physical and biological properties of the seawater."

Nature and scope of oceanography - Oceanography is usually broken down into severalsubdisciplines though separate but related branches.

- Physical oceanography is "the study of the relationships between the seafloor, the coastline, and the atmosphere." It usually deals with the properties of seawater (temperature, density, pressure, and so on), causes and characteristics of its movement (waves, currents, and tides)

- Chemical oceanography is "the study of the chemical composition of seawater and how it is affected by weather, human activities, and other factors." Broadly it studies the composition of seawater and the chemical interaction of seawater with the atmosphere and seafloor

- Marine geologydescribes the ocean basins' structure, features, and evolution.

- Marine meteorology is "the study ofheat transfer, water cycles, and air-sea interactions. It is often included in the discipline of physical oceanography.

- Geological oceanography includes "the study of the earthat the sea's edge and below its surface and the historyof the processes that form the ocean basins."In other words, it focuses on the formation of the seafloor and how it changes over time.Geological oceanographers useunique GPS technology to map the seafloor and other underwater features.This can provide critical information, such as seismic activity, which could lead to more accurate earthquake and tsunami prediction.

- Biological oceanography/marine ecology is one of the most critical branches of oceanography. It is "the study of the ocean's plants and animals and their interactions with the marine environment."
- Ocean engineering is "the discipline thatdesigns and plans equipment and installations for use at sea."

Oceans are of great importance to humankind. Studying oceanography gives us a piece of basic information about how oceans are essential, both directly and indirectly.

- The harvest of fish and other living organisms from the ocean is a principal source of protein for billions of people worldwide.

- Ocean and sea waters contain several valuable minerals. The most utilized and exploited minerals are – oil, gas, and sulphur.

- Oceans are harbourers of fuels such as petroleum. Tides, waves, and temperature differences in the ocean generate power.

- Oceans and the sea are the major highways for domestic and international transportation of heavy or bulky materials.

- The oceans are crucial for defence (naval services) activities.

- They serve as a marine recreation like sailing, swimming, surfing, etc.

The oceans do not operate alone. According to Harald Sverdrup, an eminent Norwegian oceanographer, meteorologist, and arctic explorer - "our knowledge of the oceans is still incomplete and inadequate. There are large regions in the Pacific and Indian Oceans from which no information is available. From most areas, only general conditions in certain seasons of the year are known."

1.5. HISTORY OF OCEANOGRAPHY

Oceanographer Sir William Abbott Herdman rightly remarked, "Oceanography is a subject of modern development, though of ancient origin." Oceanography, as mentioned, is a multidisciplinary science. Understanding its growth demands gathering ideas about the historical events related to the development of Oceanography. History, which is concerned with humans' attempt to explore oceans scientifically and geographically, is divided into groups from early to modern times.

The Early History

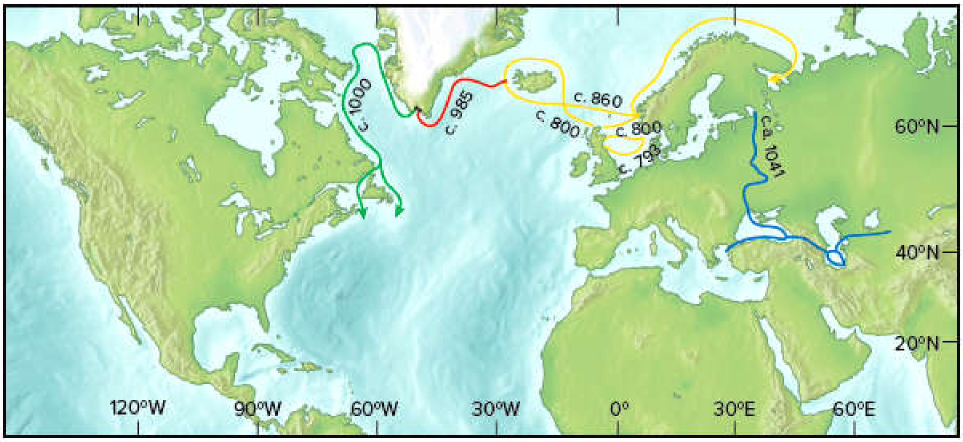
The search for trade routes led to the beginning of explorations of the oceans. Explorers and traders collected the early information and passed it on by word of mouth. Some documents record the first voyage by Pharaoh Snefru about 3200 B.C. While other records show that sea voyages were standard in the Indian Ocean during 3000 BC, as Indian traders had good knowledge about monsoon currents. The Phoenicians, people of a West Syrian country and present-day Lebanon,were excellent sailors. Theyoften traveled to Gibraltar's straits up to the Persian Gulf during 1500 BC for trading.

Archeological evidence suggests that the first people are known as Austronesians who navigated and populated the Pacific and Indian Ocean Basins were migrants from Asia to the island of Taiwan and then towards an island of north Philippines, Java, and Sumatraaround 4500–2500 B.C. Middle Eastern people started exploring the Indian Ocean by 1500 B.C. In the 7th century A.D., traders from the Middle East controlled the Indian and Chinese trade routes. Aristotle, in the 4th century B.C., described several marine organisms.Eratosthenes first calculated the accurate circumference of the earth. He also invented the study of geography and the latitude and longitude system and was the first person to calculate the tilt of the earth's axis. Posidonius, around 100 B.C.,measured the ocean's depthat about 6000 ft. near the island of Sardinia. Greek geographer, Strabo, weighted the sea's sound to a depth of 2000m. Pliny related phases of the Moon to the tides and reported on the currents moving through the Strait of Gibraltar.Ptolemy produced the world's first atlas.

The Middle Age

Shipbuilding, knowledge of navigation, and chart-making improved during this period.The Vikingswere engaged in the exploration, trade, and colonization for nearly three centuries,from about 793 to 1066,across the North Atlantic Ocean (map 1).

Map 1 - Major routes of the Vikings - to the British Isles, Asia, and across the Atlantic to Iceland, Greenland, and North America.



Source:Sverdrup, K. A., &Kudela, R. M., (2017). Investigating Oceanography. New York: McGraw-Hill Education.

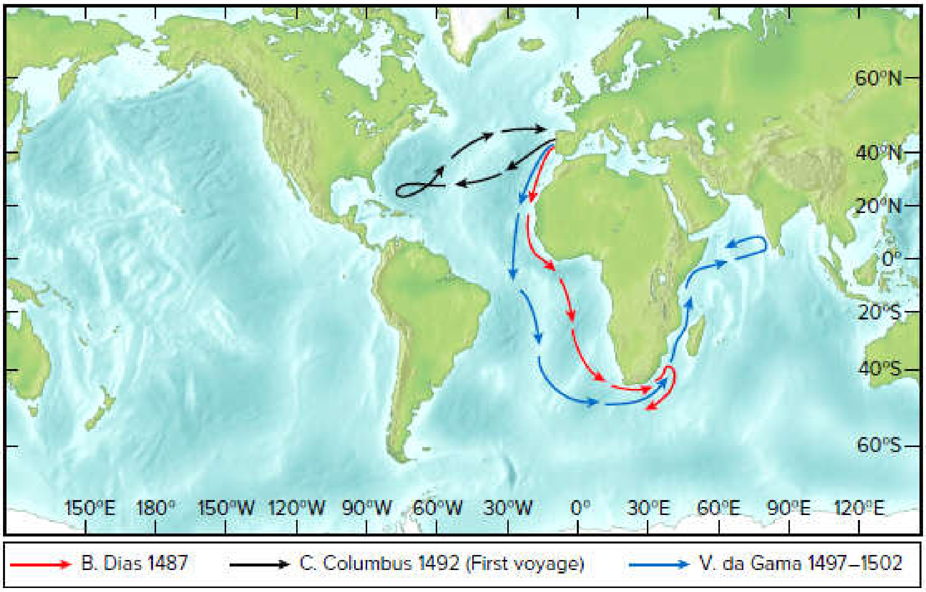
El-Mas'údé, the Arabic writer, described the "reversal of the currents due to the seasonal monsoon winds."The Arabs established regular trade routes across the Indian Ocean. The magnetic compass got introduced in the 13th century. Around the 1300s, Europeans had established successful trade routes, including some partial ocean crossings.

The Age of Discoveries

Zheng He, the admiral, conducted seven epic voyages in the western Pacific Ocean and across the Indian Ocean to Africa, from 1405 to 1433. Prince Henry of Portugal, in 1416 AD, was keenly interested in sailing and commerce and also studied navigation and mapmaking.He established a naval observatory for the teaching of navigation, astronomy, and cartography; and thus is considered most responsible for the "Great age of European discovery." After Prince Henry's death, Bartholomeu Dias (map 2) sailed around the Cape of Good Hope in 1487. In 1497, Vasco da Gama followed Dias's route to the Cape of Good Hope (fig 2), then continuedbeyond and found a new trade route to India through the Indian Ocean. Christopher Columbus, in 1492, undertook voyages (fig 2) across the Atlantic Ocean by relying on inaccurate estimates of the earth's size and believed that he had reached the eastern shore of Asia when he landed in the New World- the Americas.From 1499 to 1504, Italian navigator Amerigo Vespucci made several voyages to the Americasto reach the South American coastline and accepted it as a new continent. In 1513, Vasco Núñez de Balboa crossed the Isthmus of Panama and found the Pacific Ocean. In the same year, Juan Ponce de León discovered Florida and the Florida Current.

Map 2 - The routes of Christopher Columbus's first voyage, Bartholomeu Dias and

Vasco da Gama



Source:Sverdrup, K. A., &Kudela, R. M., (2017). Investigating Oceanography. New York: McGraw-Hill Education.

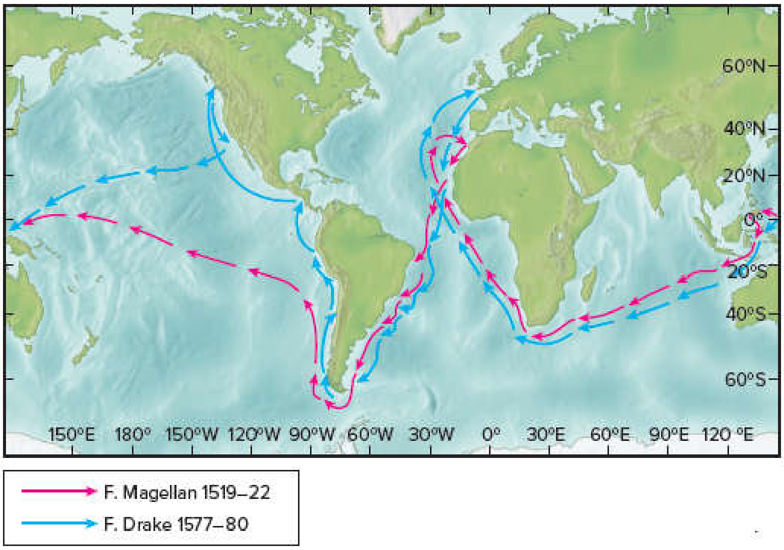
The discovery by voyages period witnessed the first historic circumnavigation of the earth by Ferdinand Magellan. Magellan expedition (map 3) discovered the present-day Strait of Magellan (natural passage between the Atlantic Oceanand the Pacific Ocean) while rounding the tip of South America in 1520. Two ships under the command of Juan Sebastián Del Cano sailed on after the murder of Magellan by natives of an island. One of the ships, the *Victoria,* continued sailing west and successfully crossed the Indian Ocean by rounding Africa's Cape of Good Hope and then arrived back in Spain on September 1522. Magellan's skill as a navigator makes this voyage the most outstanding single contribution to the early charting of the oceans.

Map 3 - First circumnavigation of the globe by Portuguese navigator Ferdinand Magellan

Source: Britannica

The latter half of the 16th century saw many Portuguese, Chinese, and Spanish explorers expeditions, mostly exploring the Atlantic Coast of North America, Central America, and South America. In 1577, Sir Francis Drake landed off the coast of present California and sailed north along the coast to the current United States–Canadian border (map 4). Then, he turned southwest and crossed the Pacific Ocean. In 1582, the present-day "Drake Passage," which is between South America and Antarctica, was discovered by him.

Map 4 - Circumnavigation voyages by Magellan and Drake

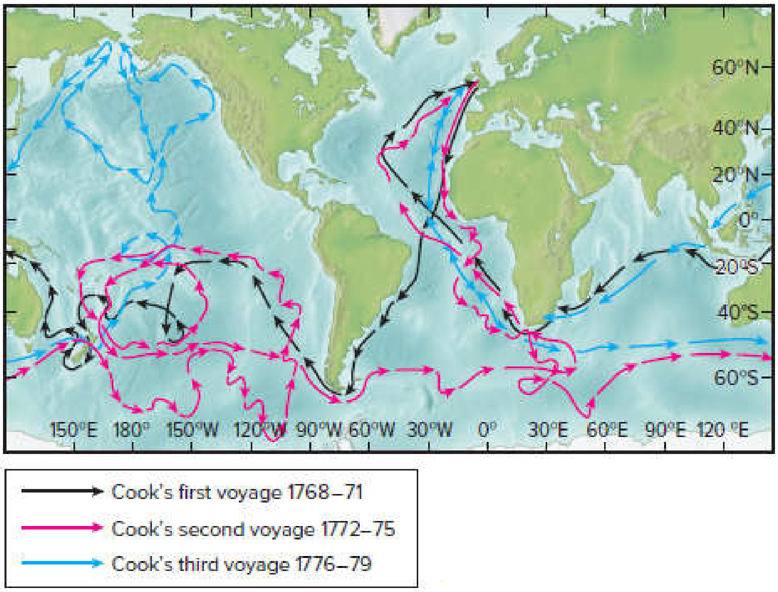


Source: Sverdrup, K. A., &Kudela, R. M., (2017). Investigating Oceanography. New York: McGraw-Hill Education.

The Importance of Charts and Navigational Information

The establishment of colonies played an essential role in developing accurate charts and navigational techniques. In 1530, Flemish astronomer Gemma Frisius proposed the relationship between time and longitude. Yorkshire-based clockmaker, John Harrison, built his first chronometer in 1735. From 1798 to 1779, Captain James Cook made three great voyages (map 5) to chart the Pacific Ocean. He also charted many islands to explore the Antarctic Ocean further. During the last phase of the expedition, Cook discovered the Hawaiian Islands. These voyages made Cook one of history's greatest navigators, scientists, and seamen. His valuable information made him one of the founders of oceanography.

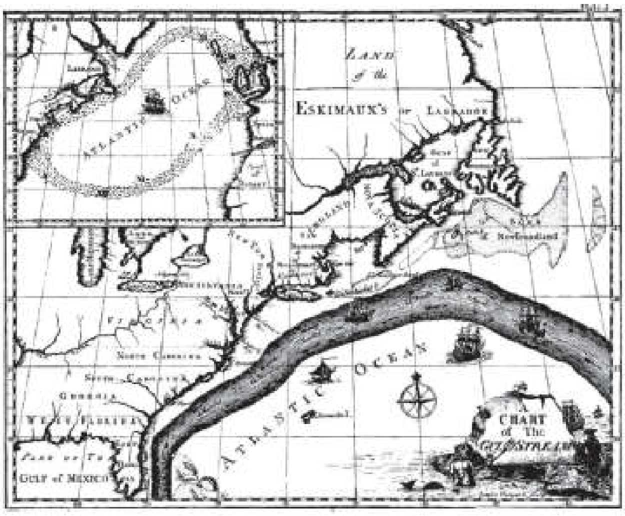
Map 5 - The voyages of Captain James Cook



Source:Sverdrup, K. A., &Kudela, R. M., (2017). Investigating Oceanography. New York: McGraw-Hill Education.

At the beginning of the 17th and 18th centuries, researchers felt the need for systematic scientific studies of the oceans and seas to improve speed and safety along trade routes. These requirements made Benjamin Franklin, the Post Master General of the colonies, concerned about the time required for cargoes to travel between America and England. With the help of Captain Timothy Folger, Franklin constructed the 1769 *Franklin-Folger* chart (map 6) of the Gulf Stream current. When published, the chart encouraged navigators to select the fastest route in the Atlantic Ocean. Nathaniel Bowditch, in 1802, published the techniques of celestial navigation for sailorsand set the stage for the U.S. supremacy of the seas.

Map 6 - The Franklin-Folger map of the Gulf Stream



Source:Sverdrup, K. A., &Kudela, R. M., (2017). Investigating Oceanography. New York: McGraw-Hill Education.

Following years witnessed the establishment of many institutions studying maritime studies in the U.S. Few are -

- 1807 - The Survey of the Coast under the Treasury Department, later named the Coast and Geodetic Survey and presently the National Ocean Survey, was formed under President Thomas Jefferson.
- 1830 - The U.S. Naval Hydrographic Office was set up,now the U.S. Naval Oceanographic Office.
- 1842 - Naval Depotof Charts was founded.

Slowly, the oceans captured the interest of biologists and naturalists. Baron Alexander von Humboldt was fascinated with the number of animals inhabiting the South American current that flows northward along the west coast of South America. The current bears his name and is known as Humboldt Current or Peru Current. Charles Darwin collected,described, and classified organisms from the land and sea. Edward Forbes, an English naturalist, began a systematic survey of marine life around the British Isles and the Mediterranean and AegeanSeas. His orderly predictions about the oceans made him another founder of oceanography. In 1818, Sir John Ross collected samples of worms and starfish from a depth of over 6000ft in the Baffin Bay, thus proving that life exists at such great depths. Even deeper samples were collected by Clark Rossfrom Antarctic waters and noted their similarity to the Arctic species. Mathew Fontaine Maury, an American naval official, contributed significantly to finding safe and efficient trade routes in the oceans. He published charts and instructions for sailings and gave patterns of winds, currents, and sea states. Maury was called the "*Pathfinder of the Seas*" for this outstanding contribution. In 1855, Maury published his book on oceanography, titled "*The Physical Geography of the Sea*."

In the last part of the 19th-century, governments started financing expeditions and studies about oceans. The introduction of transatlantic telegraph cables better understood the deep sea, where engineers needed to know about seafloor conditions, including bottom topography, currents, and organisms. The British slowly began a series of deep-sea studies. When brought to the surface, the transatlantic telegraph cable was covered with many never seen organisms.An expedition was funded to study the "erratic fish catches in European waters." The Fishery Board of Scotland undertook this study in 1882 to study the fish migration patterns. In 1902, the members of the International Council for the Exploration of the sea, or ICES as famously known, held the first-ever meeting in Copenhagen. This meeting was a historic event in the discipline of oceanography. The ICES is the oldest inter-governmental marine organization in the world.

The 19th and 20th Century Expeditions

- The Challenger Expedition – The Circumnavigation Committee of the British Royal Society organized the most comprehensive oceanographic expedition. The *Challenger*sailed from England for a voyage that lasted nearly three-and-a-half years. The first lap of the journeytook the vessel to Bermuda, then to the South Atlantic Island around the Cape of Good Hope, and later to the eastacross the southernmost part of the Indian Ocean. It continued to Australia, New Zealand, the Philippines, Japan, and China. The vessel took deepestsounding at 26,850 ft., of what is now known asthe "*Challenger Deep*" in the Marianas Trench.

- The Voyage of the Fram – The late 19th and the early 20th centuries witnessed the transition of oceanographyfrom a descriptive science to a quantitativeone. The cruises now had the goal of gathering data. Development of theoretical models of ocean circulationand water movement happened. The Scandinavianoceanographers were active in this study of water movement. Fridtjof Nansen, one of the most incredible minds, was an explorer and zoologist interested in the currentsof the polar seas. He studied the direction of ice drift in the Arctic by freezinga vessel into the polar ice pack and driftingit to reachthe North Pole. For executing this, he had to design a uniquecraft – a wooded Fram of 128 ft ("to push forward) to survive the tremendous pressure from the ice.

- The Meteor Expedition – This expedition zigzagged between Africa and South America, exploring the region from 20°N to 60°S, and is better known for the first use of the echo sounder that produced accurate measurements of ocean depth.

Oceanography in Modern Times

Establishment of Oceanographic Institutions

Government agencies and private institutions took over the support of oceanography in the country during the 19th century. Alexander Agassiz, a mining engineer, marine scientist, and Harvard University professor, financed a series of expeditions to expand knowledge of deep-sea biology. In 1903, a group of professional people in San Diego establishedthe Marine Biological Association. Thus the University of California's Scripps Institution of Oceanography foundation. The Carnegie Institute funded investigations of the earth's magnetic field. The Rockefeller Foundation funded the establishment of the Woods Hole Oceanographic Institution in 1930on the east coast.

Oceanography studyincreased during World War II. The United States and its allies needed to move personnel and materials by sea to remote locations, predict ocean and shore conditions for landings, chart beaches and harbors from aerial surveillance, and use underwater sound to find the submarines. Academic studies ceased as oceanographers allocated their knowledge to the national war.

Large-Scale Exploration of the Oceans –

Post the Second World War; scientists used new, sophisticated instruments - radar, sonar, automated wave detectors, and temperature-depth recorders. Some prominent programs and institutions are -

- *Deep-Sea Drilling Program (DSDP), 1968* - a cooperative venture among research institutions, began to sample the "earth's crust beneath the sea" using the specially built drillship *Glomar Challenger*,named after the ship used duringthe Challenger expedition.

- *Ocean Drilling Program (ODP), 1983* - The DSDP became ODP and was managed by an international partnership of 14 science organizationsin the U.S. and 21 international organizations called the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES).

- *National Oceanic and Atmospheric Administration (NOAA), 1970* - The U.S. government reorganized its earth science agencies – the National Ocean Survey, National Weather Service, National Marine Fisheries Service, Environmental Data Service, National Environmental Satellite Service, and Environmental Research Laboratories.

Satellite Oceanography and Remote Sensing of the Oceans –

Data collection of currents, biological productivity, sea-level changes, waves, air-sea interactions, sea surface temperature, etc., using satellites allowed researchers to observe the ocean and other water bodies globally. Satellite sensors used for oceanography have continued to evolve in the last few decades. NIMBUS-7 satellite, launched in 1978 by NASA, carried a sensor package called the Coastal Zone Color Scanner (CZCS), which gave us the first global view of the ocean's chlorophyll distributions and productivity. It was eventually replaced by the Sea-viewing Wide Field Sensor (SeaWiFS) and the Moderate Resolution Imaging Spectrometer (MODIS). These provide information about ocean color and details about the dynamic changes in the oceans. Other satellites were

TOPEX/Poseidon, Jason-1, and Jason-2. Presently, a constellation of satellites orbits each,gathering valuable information for all aspects of oceanography.

1.6. ORIGIN OF OCEANS

The ocean may be defined as "the vast body of saline water that occupies the depressions of Earth's surface." More than 97% of the water on Earth's surface is contained in the ocean. About 2.5% is held in ice, groundwater, and all the freshwater lakes and rivers. Traditionally, the ocean has been divided into, oceans and seas, by using the boundaries of continents and the equator.

Table 1: Statistics for the World Ocean

Total area	331,441,932 square kilometers (127,970,445 square miles)
Total volume	1,303,155,354 cubic kilometers (312,643,596 cubic miles)
Total mass	1.41 billion metric tons (1.55 billion tons)
Average depth	3,682 meters (12,081 feet)
Greatest depth	10,994 meters (36,070 feet)
Mean ocean crust thickness	6.5 kilometers (4.04 miles)
Average temperature	3.9°Celsius (39.0°Fahrenheit)
Average salinity	34,482 grams per kilogram (0.56 ounces per pound); 3.4%
Average elevation of land	840 meters (2,772 feet)
Age	4.5 billion years

Certain theories believe that most of the atoms that make up Earth and its inhabitants were formed within stars. Stars form in the dusty spiral arms of galaxies and spend their lives changing hydrogen and helium to heavier elements. As and when they die, some stars eject these elements into space by cataclysmic explosions. The sun and the planets, including Earth, probably condensed from a cloud of dust and gas enriched by the recycled remnants of exploded stars. The Nebular Hypothesis which was propounded by the German philosopher Immanuel Kant in 1755, believed that the earth and our solar system have condensed from a rotating cloud of primordial matter of dust and gas. However, Laplace disagreed with the theory. He assumed the sun as a rotating disc. The continuous cooling and contraction led to an increase in the speed of rotation. This in turn increased the centrifugal force which caused the separation of rings and ultimately formed the planets. The same process led to the formation of the moon. In course of time, the earth and the moon cooled down resulting in a rocky crust. The superficial layer, cooled more rapidly than the internal layers, thus leaving the upper crust unsupported. The lower layers sank. The higher areas thus became continents and lower areas gave birth to oceanic depressions. The ocean formed later, as water vapor trapped in Earth's outerlayers escaped to the surface through volcanic activity or rain. Comets may also have brought some water to Earth. Life originated in the ocean very soon after its formation.

The most accepted regarding the origin of oceans is that of Alfred Wegener, a German meteorologist, and polar explorer. In 1912, he proposed a theory called **continental drift or Displacement Hypothesis**. Wegener suggested that the entire Earth's land had once been joined into a single supercontinent surrounded by an ocean. The landmass was called Pangaea (pan - "all"; Gaea - "Earth, land") and thesurrounding ocean Panthalassa (pan - "all"; Thalassa - "ocean"). Pangaea had broken into pieces about 200 million years ago. Since then, the pieces had moved to their present positions and were still moving. Wegener's evidence included the shoreline fit of continents across the North and South Atlantic, the alignment of mountain ranges, their similar age, composition, and structure, and fossils on both sides of the Atlantic. He believed that the heavy continents were slung toward the equator by a centrifugal effect. Wegener postulated 2 main directions of movement –

- Towards the west
- Towards the equator

The drifting apart of the two Americas led to the formation of the Atlantic Ocean. Further, a part of the Gondwanaland moved northwards creating the Indian Ocean. The evolution of the Pacific Ocean is marked by the three-sided movement of the earth's crust.

1.7. OCEAN MORPHOLOGY

The floors of the oceans are not simple, but rugged and complex. The theory of plate tectonics puts forth that Earth's surface is not a static arrangement of continents and oceans. But it is a dynamic mosaic of jostling lithospheric plates. Continental crust is thicker than oceanic crust. The continental lithosphere is less dense than the oceanic lithosphere.

Thesubmerged outer edges of continents i.e. the *continental margins* are greatly influenced by various tectonic activities.In other words, the edges of the landmasses below the ocean surface and the steep slopes that descend to the seafloor are known as the *continental margin*.The deep-sea floor beyond the continental margin is called the *ocean basin*.There are two types of continental margins: **passive margins** and **active margins**. Passive margins are found where the transition from continental crust to oceanic crust occurs within a single plate. Passive margins have little seismic (earthquake) or volcanic activity. These relatively wide margins form after continents are drifted apart (diverging plates), thus, creating a new and growing ocean basin between them. Because passive margins surround the Atlantic, they are often referred to as the *Atlantic-type* margins. Continental margins near the edges of converging plates or near places where plates are slipping past one another are called active margins. Active margins are often associated with earthquakes and volcanic activities and are relatively narrow.Because of active margins prevalence in the Pacific, they are sometimes referred to as *Pacific-type*margins.Continental margins have three main divisions: a shallow, nearly flat continental *shelf* close to shore; a more steeply sloped continental *slope* seaward, and the continental *rise*—that blends the continental margins into the deep-ocean basins.

Continental Shelf

The continental shelf is the shallow, submerged extension of a continent. These shelves are underlain by granitic continental crust.Taken together, the area of the continental shelves is 7.4% of the earth's ocean area.

The width of a continental shelf is usually determined by its proximity to a plate boundary.Continental shelves are flat borders of varying widths, from a few kilometers to as much as 1500kms.The average width of the continental shelves is about 80 km. This variation can be seen even in the context of the Indian peninsula.The continental shelf of the eastern coast of India is much wider than the western coast.Similar variations are seen all over the world. For example, the shelves are almost absent or very narrow along margins like the coasts of Chile, the west coast of Sumatra, etc. On the contrary, the Siberian shelf in the Arctic Ocean, the largest in the world, stretches up to 1,500 km inwidth. Even the depth of the shelves varies. It may be as shallow as 30 m in some regions, while in some it is as deep as 600 m.Shelves along the margin of the Atlantic Ocean often reach 350 kilometers in width and end at a depth of about 140 meters.

There are various types of shelve based on different sediments of terrestrial origin:

1. Glaciated shelf (surrounding Greenland),

2. Coral reef shelf (Queensland, Australia),

3. Shelf of a large river (around Nile Delta),

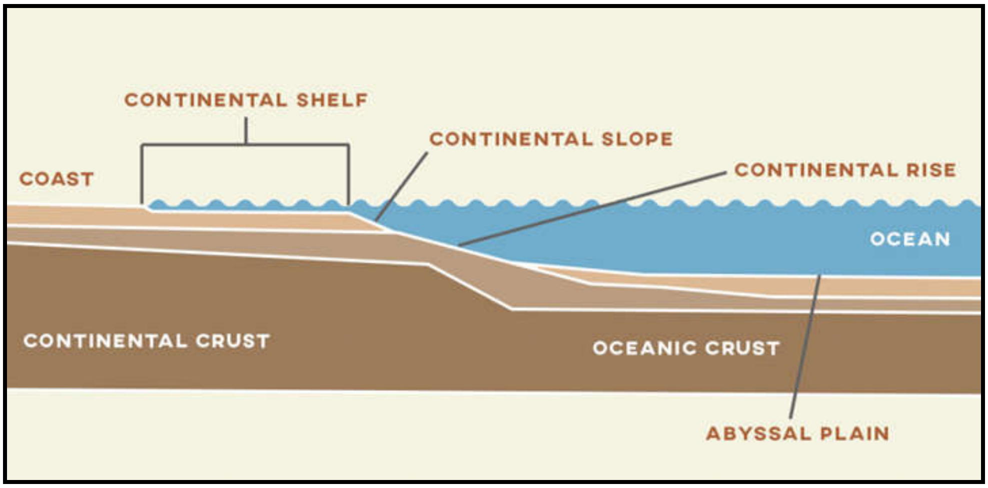
4. Shelf with dendritic valleys (at the Mouth of Hudson River)

5. Shelf along with young mountain ranges (shelves between the Hawaiian Islands).

Previously, the shelves have been covered and uncovered by fluctuations in sea level. Today, continental shelves are covered with thick deposits of silt, sand, and mud sediments derived from the land, river, glaciers, etc.The shelves have been the focus of intenseexploration for natural resources by humans. Because these shelves are sources of oil, minerals, and petroleum. A large quantity of the world's petroleum is obtained from these shelves. For example – the Bombay High.

The shelf typically ends at a very steep slope, called the shelf break. In other words, the *continental shelf break* is an abrupt change in the slope of the seafloor that occurs at the outer edge of the continental shelf. This marks the point at which there is a rapid increase in depth with distance from the coast.

Fig 1. Cross-section of continental margin depicting the particular elements



Source: Wikimedia Commons

Continental Slope

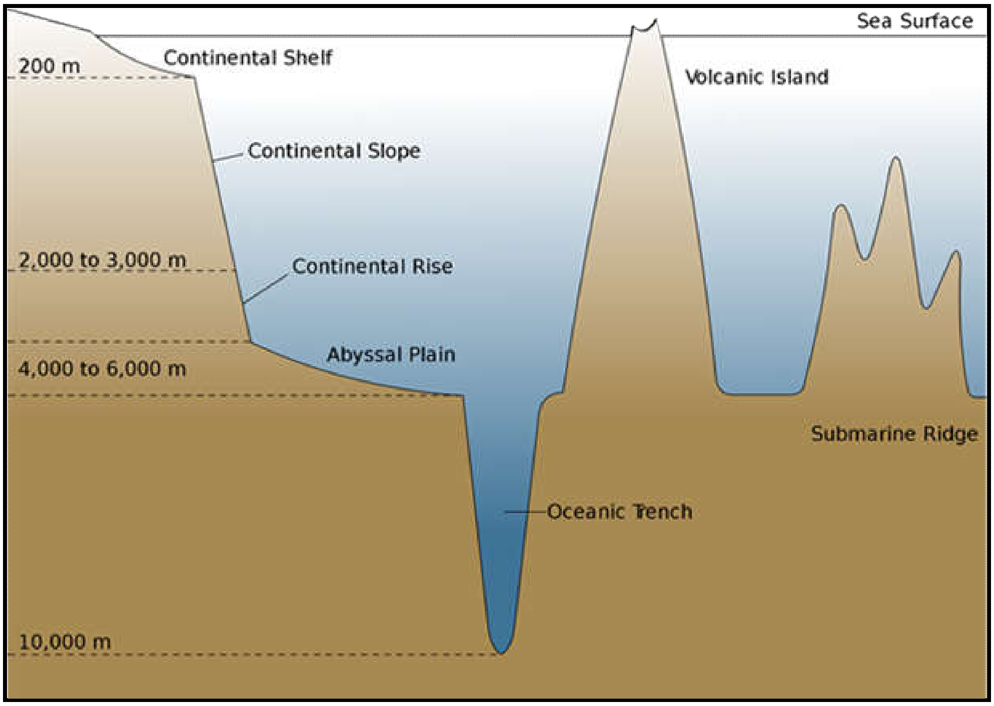
The transition between the gently descending continental shelf and the deep-ocean floor is known as the continental slope. The gradient of the slope varies between 2^0 and 5^0. The average inclination of a typical continental slope is about 4°**.** Generally, continental slopes at active margins are steeper than those at passive margins. The depth of the slope varies between 200 and 3,000 m. The Continental slope boundary indicates the end of the continents. Mainly due to their steepness and increasing distance from the land, slopes have very few deposits of sediments on them. Sealife is far less here than on the shelf.There are 5 types of slopes –

- Fairly steep with the surface dissected by canyons.
- Gentle slopes with elongated hills and basins
- Faulted slopes
- Slopes with terraces
- Slopes with seamounts

Continental Rise

Along the base of the continental slope liesa deposit of sediments. This belt of sedimentary deposits forms the ***continental rise***. Continental rise begins from the end of the continental slope. The average slope of continental rise ranges between 0.5^0 and 1^0. Its general relief is low. In some regions, the rise is very narrow but in others, it may extend up to 1,000 kilometersin width. With increasing depth, the rise becomes virtually flat and it merges with the abyssal plain. One of the widest and thickest continentalsrises has formed in the Bay of Bengal at the mouths of the Ganges and Brahmaputra rivers. Deep-ocean currents are an importantfactor in shaping continental rises, especially along the westernboundaries of most ocean basins.

Fig 2. Diagrammatic cross-section of an ocean basin, showing the various geographic features



Source: Wikimedia Commons

Submarine Canyons

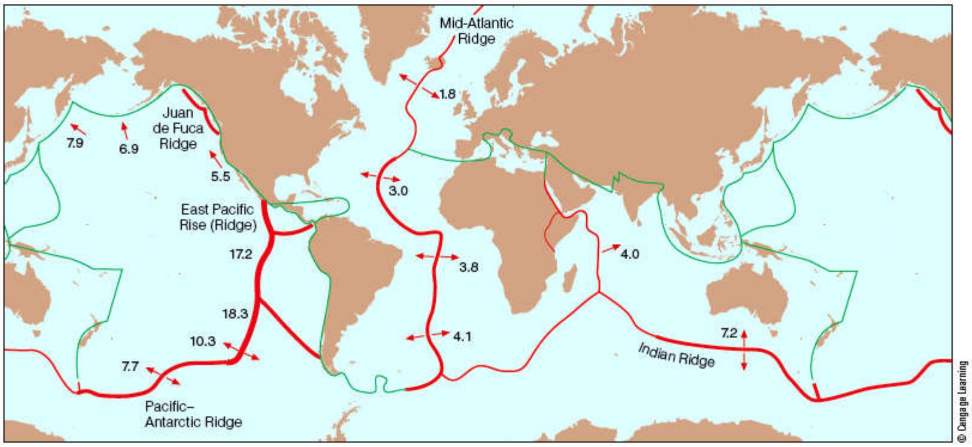
The most outstanding features of the continental slopes are submarine canyons. They are formed at the junction between Continental Shelf and Continental Slope. Submarine canyons sometimes extend up, into, and across the continental shelf. It is steep-sided and has a V-shaped cross-section. The canyons generally trend at right angles to the shoreline. However, at times it begins very close to shore and can be quite large.For example - Congo Canyon extends into the African continent as a deep estuary at the mouth of the Congo River. Submarine canyons similar in size and profile to the Grand Canyon have been discovered! Another example is the Hudson Canyon, located just offshore of the mouth of the HudsonRiver in New York. Locallandslides triggered by earth quakes some times cause an underwater avalanche of sediments, known as turbiditycurrents. Geologists believe that the canyons have been formed by abrasive turbidity currents plunging down the canyons.

Away from the margins ofcontinents the structure of the ocean floor/basin is different. The deep-ocean floor mainly consists of sediment-covered plains made of basaltic rocks. These deep ocean basins constitute more than half of Earth’s surface.Flat expanses of the basins are interrupted by islands, hills, active and extinct volcanoes, and active zones of seafloor spreading.

Oceanic Ridges

An oceanic ridge refers to a mountainous chain of young basaltic rock at the active spreading center of an ocean. Stretching around 65,000 kilometers of oceanic ridges encircles the globe (map 7). The rugged ridges often rise about 2 km above the seafloor. In a few places on the earth, they project above the surface to form islands such as Iceland, the Azores, and Easter Island. Oceanic ridges along with their associated structures account for 22% of the world's solid surface area. These features are often called ***mid-ocean ridges***. A mid-oceanic ridge, in simpler terms, is explained to be composed of two chains of mountains separated by a large depression. Iceland is a part of the Mid- Atlantic Ridge.These oceanic ridge systems are of tectonic origin and provide evidence in support of the Plate Tectonics theory.For example, the Mid-Atlantic Ridge does not run in a straight line. It is offset at more or lessregular intervals by transform faults.

Map 7- The oceanic ridge system (in red*) stretches some 65,000 kilometers (40,000 miles) around Earth.



*The thickness of the red lines indicates the rate of spreading

Source: Canges Learning

Abyssal Plains and Abyssal Hills

Both Abyssal plains and hills cover a quarter of the Earth's Surface. Abyssal is derived from a Greek word meaning "without bottom." Abyssal plains are extraordinarily flat, smoothest, featureless expanses of sediment-covered ocean floor found on the periphery of all the oceans. They are common in the Atlantic, less in the Indian Ocean, and relatively rare in the Pacific ocean. Abyssal plains are found between the continental margins and the oceanic ridges at a depth of around 3,000 to 6,000 meters (12,000 to 18,000 feet) below the surface. For example, the Canary Abyssal Plain is a huge plain that lies west of the Canary Islands in the North Atlantic. It covers an area of about 900,000 square kilometers.

Sediment deposits are thinnest near the mid-ocean ridge, because, the ocean crust here is the youngest and sediments had less time to accumulate. With increasing distance from the center of seafloor spreading, the ocean crust is older and the overlying sediment blanket is thicker. As sediment thickness increases, abyssal hills appear to grow. These hills are small, sediment-covered extinct volcanoes that areusually less than 200 meters high. Abyssal hills are thus defined as “an isolated (or tract of) small elevation(s) on the deep seafloor”. These abundant features are associated with seafloor spreading.

Seamounts

Ocean floors are dotted with thousands of volcanic projections that do not rise above the sea surface. These projections are called seamounts. They are circular or elliptical, more than 1 km in height, with relatively steep slopes of 20° to 25°. Seamounts are volcanic in origin and may be found alone or in groups. Most of them are submerged inactive volcanoes. There are more than 10,000 seamounts in the Pacific, which is about half the world's total. The Emperor seamount, an extension of the Hawaiian Islands in the Pacific Ocean, is an example.

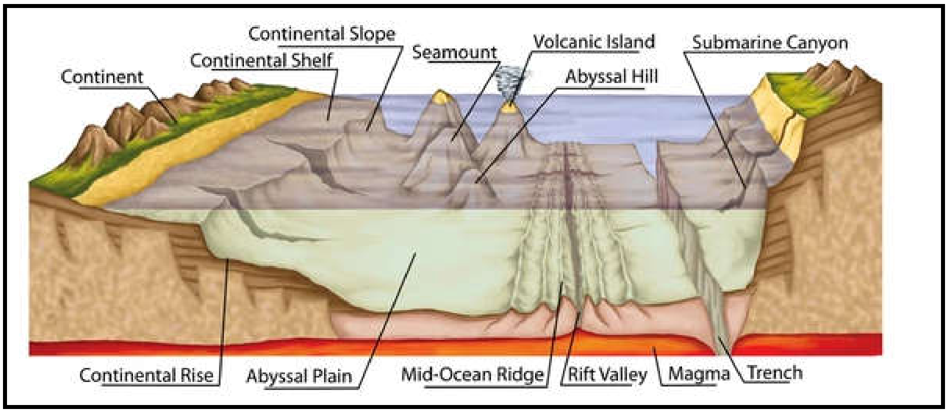
Guyots

Guyots are flat-topped seamounts that wereonce tall enough to penetrate the sea surface. They show evidence of gradual subsidence through stages to become plateau-like topped submerged mountains. Guyots are confined to the west-central Pacific.

Atoll

Atolls are ring-shaped low islands found in the tropical oceans consisting of coral reefs surrounding a central depression. It may be a part of the sea (lagoon), or sometimes form enclosing a body of fresh, brackish, or highly saline water.Sometimes, atolls and lagoons protect a central island. Atolls develop with seamounts.

.Fig.3 – Relief of Ocean Basin



Source: http://www.physicalgeography.net/

Trenches

Ocean trenches are long, arc-shaped narrow depressions on the deep-ocean floor. These are the deepest parts of the ocean and often the deepest natural spots on Earth. Ocean trenches are a result of tectonic activity. Precisely they are features of convergent plate boundaries, where dense lithosphere melts or slides beneath less-dense lithosphere in a process called *subductio*, creating a trench. Trenches are among the most active geological features on Earth, as great earthquakes and tsunamis often originate in them. They are curving chains of V-shaped indentations.

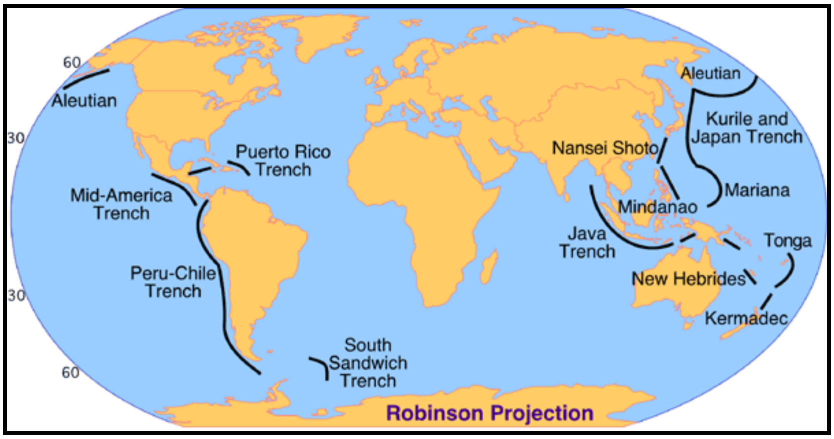
Ocean trenches are found in every ocean basin. For example, the Mariana Trench is about 70 km wide and 2,550 km long. The Mariana Trench depth is 36,163 feet. The Peru-Chile Trench off the west coast of South America is formed by the oceanic crust of the Nazca plate subducting beneath the continental crust of the South American plate. The Ryukyu Trench, stretching out from southern Japan, is formed as the oceanic crust of the Philippine plate subducts beneath the continental crust of the Eurasian plate. The deepest ocean trenches ring the Pacific as part of the so-called "Ring of Fire" which also includes active volcanoes and earthquake zones.

Island Arcs

Island arcs are chains of oceanic islands formed by volcanoes located along the subduction zone.Island arcs are associated with intense volcanic and seismic activity and orogenic processes. An island arc typically has a landmass or a partially enclosed, shallow sea on its concave side. Along the convex side, there exists a long, narrow deep-sea trench.

Most island arcs consist of two parallel rows of islands. The inner row is composed of a string of explosive volcanoes, while the outer row is made up of non-volcanic islands. Destructive earthquakes occur frequently at the site of island arcs. The majority of island arcs occur along the western margin of the Pacific Basin. The Ring of Fire is an island arc.

Map 8– Major Oceanic Trenches of the World



Source: http://www.physicalgeography.net/

1.8. DISTRIBUTION OF TEMPERATURE, SALINITY, AND DENSITY OF OCEANS

The Temperature of the Ocean Water

The study of ocean temperature is essential for marine organisms at various depths and affects the climate of the coastal land. There are three types of instruments used for recording the ocean's Temperature -

- Standard type thermometer for measuring the surface temperature.
- Reversing thermometers for measuring sub-surface temperature
- The thermographs.

Concerningtemperature, there are three layers in the oceans, from the surface to the bottom in the tropics –

1. The first layer is the toplayer of warm oceanic water. It is 500m thick, and its temperature ranges between $20^0$and 25^0C.
2. The thermocline layer is the vertical zone of oceanic water. This layer is below the first layer and is characterized by a rapid temperature decrease with increasing depth.
3. The third layer is icy and extends up to the ocean floor.

The sun is the principal source of energy for oceans. Generally, the ocean is heated by three processes – absorption of radiation from the sun, convectional current in the water body, and kinetic energy produced due to friction caused by the surface wind and the tidal currents. The ocean water is cooled by three processes – back radiation, exchange of heat between the sea and the atmosphere, and evaporation.

Daily Range of Temperature - Daily range of temperature is defined as the difference betweenthe maximum and minimum temperature of a day (24 hours). The daily temperature range of the ocean's surface water is almost insignificant as it is only around 1^0C. The daily temperature range is usually 0.2^0 to 0.3^0C at higher altitudes and 0.3^0C at lower altitudes.

Annual Range of Temperature – the ocean's water'syearly averagetemperature range is -12^0C. However, there is a lot of regional variation. For example, the annual temperature range is higher in enclosed seas than in open seas. Insolation, location, size of oceans,and prevailing winds are factors causing regional variations in ocean water's annual range of temperature.

Distribution of Temperatures of Oceans

The temperature of surface water of oceans varies strikingly from one place to another. The factors which cause striking variations are –

- *Latitude* – The temperature of surface water decreases from the equator towards the poles because the sun's rays keep slanting, causing a decrease in insolation polewards.

- *Unequal distribution of land and water* – Temperature in the enclosed seas of low latitudes becomes higher than in open seas because of the influence of the surrounding land areas. The northern hemisphere is warmer than the southern hemisphere due to the dominance of the land.

- *Prevailing wind* – winds blowing from land towards the oceans drive warm surface water away from coasts, thus resulting in the upwelling of cold water from the bottom (offshore winds). Sometimes wind pile up warm water near the coast causing temperature rise (onshore winds).

- *Ocean currents* – while warm breezes raise the temperature, cold winds reduce a place's temperature.

- *The ocean's location and shape* – the extensive latitudinal seas of low latitudes have warmer surface water than vast longitudinal seas.

- *Physical characteristics of the sea surfaces* – for example, the boiling point of seawater increases due to higher salinity.

- *Local weather conditions like cyclones, storms, etc.*

- *Presence of sub-marine ridges* because the temperature is affected due to lesser mixing of waters on one side and greater mixing on the other side.

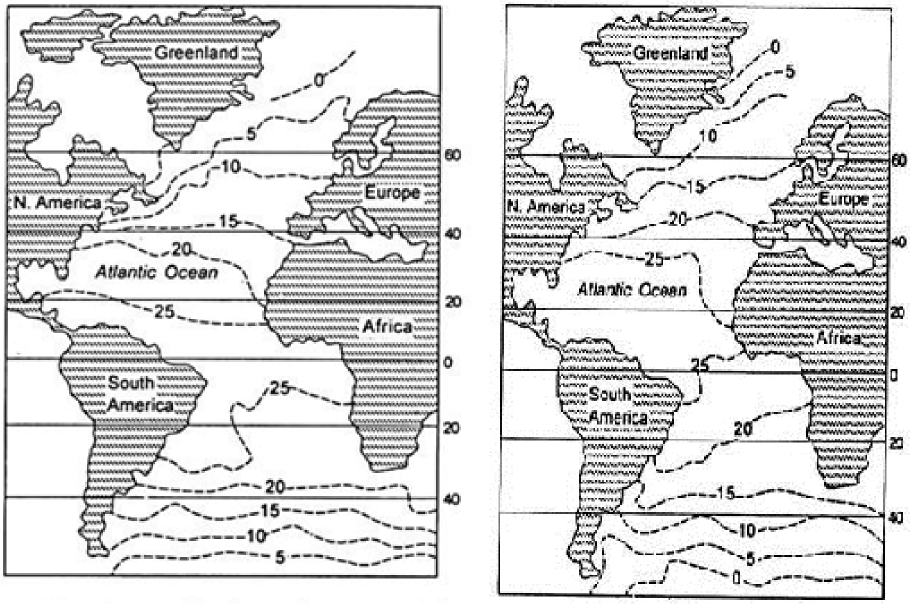
Horizontal distribution of temperature

The mean temperature of the oceans' surface water is 260C (800F), and it gradually decreases from the equator towards the pole. With increasing latitude, the rate of temperature decrease is generally 0.5^0F per latitude. For instance, the average temperatures become 22^0C at 20^0 latitudes and 0^0C near the poles. Northern hemisphere oceans record a relatively higher average temperature than the southern hemisphere due to unequal land and ocean water distribution. The average annual Temperature of all the Oceans is 17.2^0C. The mean yearlytemperature for the northern hemisphere is 19.4^0C, and for the southern hemisphere, it is 16.1^0C. Lines joining places of equal temperature are known as isothermal lines.

The distribution of Temperature in the north and South Atlantic Oceans is unsymmetrical. The decrease of temperature with increasing latitudes in the northern Atlantic Ocean is very low because of warm ocean currents (Gulf Stream). The reduction of temperature with increasing latitude is high in the southern Atlantic Ocean. For example – in the northern Atlantic 5^0C,the isotherm touches 50^0-70^0N latitude, while in the South Atlantic Ocean, it never crosses 50^0S latitude. The annual average temperature of the Pacific Ocean is slightly higher than the Atlantic Ocean (16.9^0C) and the Indian Ocean (17^0C).

Map 9–Isothermal lines showing Horizontal Distribution of Temperature in the Northern and Southern Atlantic Ocean

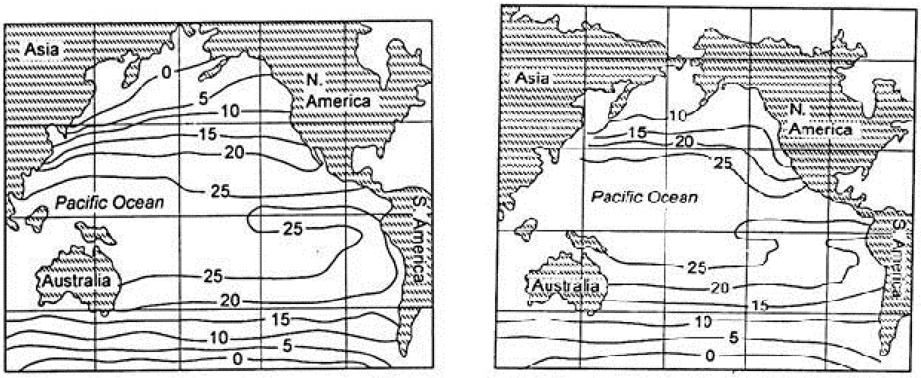
(February and August)



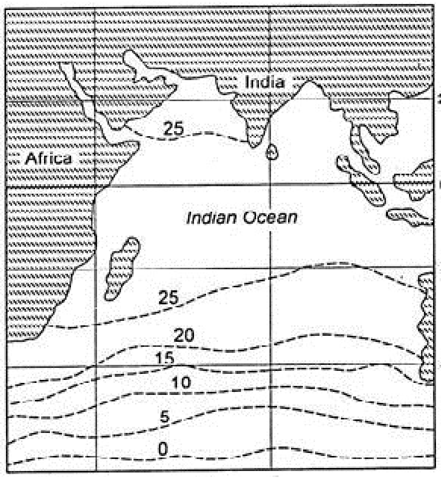
Source: Savindra, S. (1998). Physical geography. PrayagPustakBhavan, Allahabad.

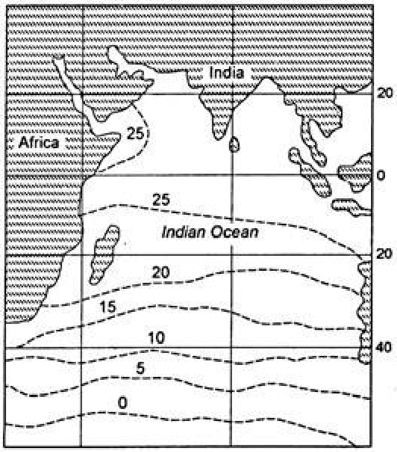
The oceans' lowest and highest temperatures are recorded near New Scotland and in the western Pacific ocean. The highest temperature of the Indian Ocean is recorded in the Bay of Bengal and the Arabian Sea.

Map 10– Isothermal lines showing Horizontal Distribution of Temperature in the Pacific Ocean(February and August)



Map 11– Isothermal lines showing Horizontal Distribution of Temperature in the Indian Ocean(February and August)





Source: Source: Savindra, S. (1998). Physical geography. Prayag Pustak Bhavan, Allahabad.

Vertical distribution of temperature

The maximum temperature of oceans is always at their surface because oceans directly receive the insolation and heat transmission to the lower sections of the oceans through the conduction mechanism. Solar rays penetrate up to 20m to 200m deep. Thus, the temperature decreases from the ocean surface with increasing depth; however, it is not uniform everywhere. Till 200m depth, the temperature falls rapidly. Beyond which decrease of temperature slows down. Oceans are vertically divided into two zones –

- ***Photic or euphotic zones*** - extends from or represent the upper surface to ~200 m. This zone receives adequate solar radiation.

- ***Aphotic zones*** -extend from 200 m to the ocean bottom. This zone does not receive adequate solar rays.

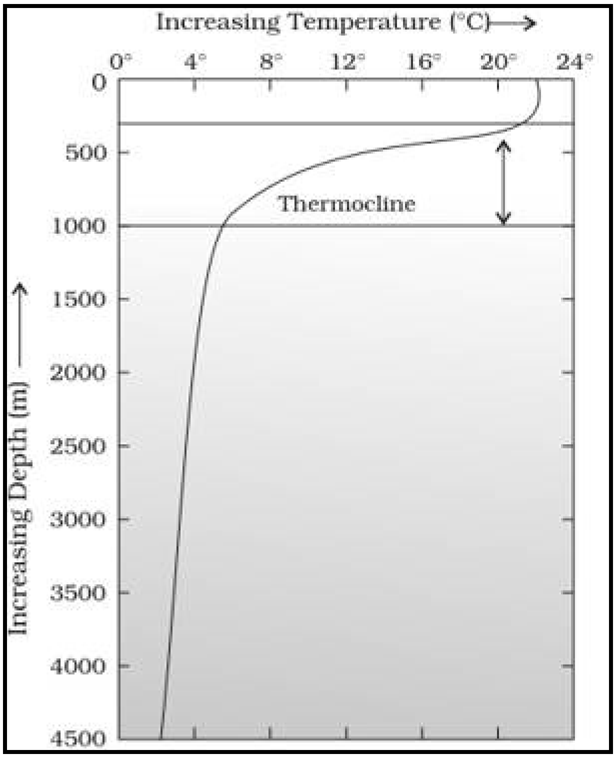
  Vertically, based on the temperature structure of the oceans, in the middle and lower latitudes, the oceans are divided into three layers –

- The *first layer* represents the top layer of warm oceanic water,which is about 500m thick. Here temperatures range between 20° and 25° C. This layer develops only during summer in mid-latitudes, while it is present throughout the year in the tropical region.

- The second layer is called the thermocline layer. It is characterized by a rapid decrease in temperature with increasing depth. The thermocline is 500 -1,000 m thick. About 90% of the total volume of water is found below the thermoclines.

- The *third layer* is icy and extends up to the deep ocean floor. Here the temperature becomes almost stagnant.

Fig. 4 - Thermocline



Source: Wikipedia

The characteristics feature of the vertical distribution of ocean water are –

- Even though the ocean's temperature decreases with increasing depth, the rate is not uniform. Below 2000m, the change is negligible.
- Annual and diurnal temperature ranges cease after 600 feet and 30 feet, respectively.
- At the equator, the rate of temperature decrease is greater than at the poles. The surface temperature decrease is not uniform, but the ocean's bottom temperature is uniform from the equator to the poles.
- The constant decrease of surface water is due to the upwelling of bottom water by offshore winds.
- The sinking of cold water and its movement towards lower latitudes is observed in the Arctic and the Antarctic regions
- Generally,surface water sometimes exhibits lower temperatures in equatorial regions due to high rainfall, whereas layers below have higher temperatures.
- In both the higher and lower latitudes, enclosed seas record higher temperatures at the bottom (for example - the Sargasso Sea, the Mediterranean Sea, and the Red Sea) due to increased insolation throughout the year and lesser mixing of the warm and cold waters.

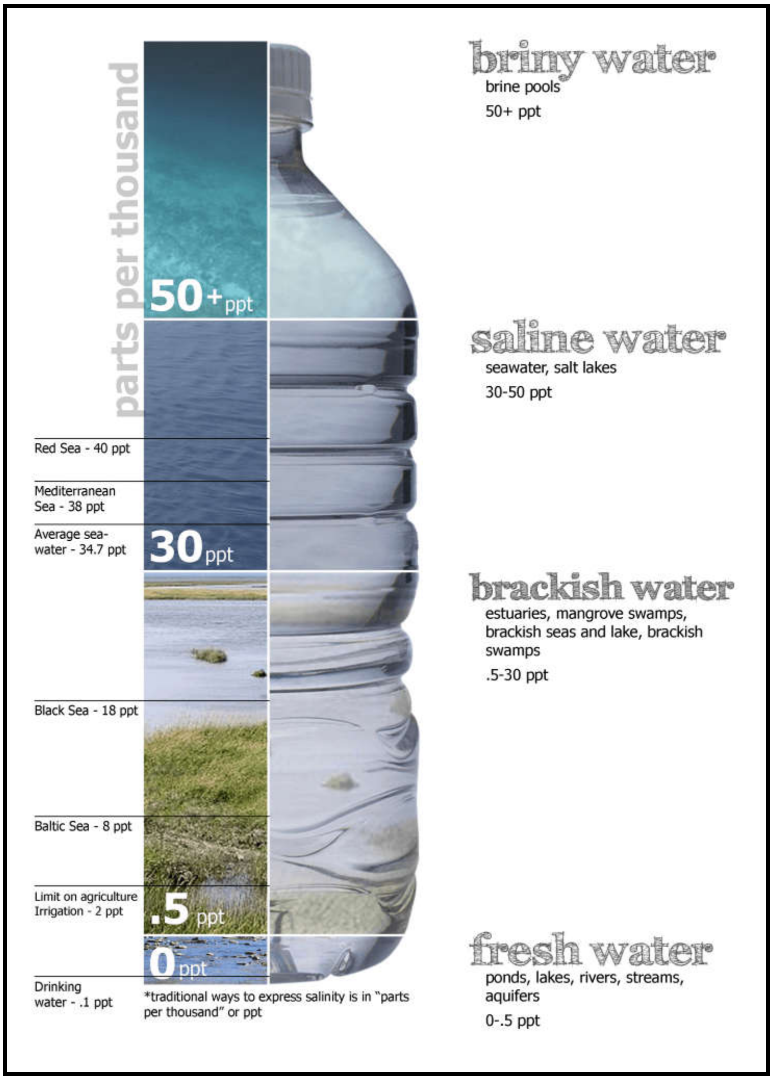
The Salinity of the Ocean Water

Salinity is defined as 'the total amount of solid material in grams contained in one kilogram of seawater and is expressed as part per thousand.' In simpler words, salinity is the term used to define the total content of dissolved salts in seawater. Salinity is calculated as the amount of salt (in gm) dissolved in 1,000 gm (1 kg) seawater. It is usually expressed as *parts per thousand* or *ppt*. For example, $40^{o}/_{oo}$ salinity means 40 grams of salt in 1000 grams of seawater. Ocean's salinity affects marine organisms. Even the freezing point of ocean water depends on salinity. Salinity increases water density, and variation in the salinity causes ocean currents.

Salinity determines temperature, density, evaporation, compressibility, thermal expansion, absorption of insolation, and humidity. It also influences the composition and movement of the ocean, water, and the distribution of fish and other marine resources. While salinity of 24.7 (24.7 $^{o}/_{oo}$) has been considered the upper limit to demarcate 'brackish water,' the average salinity in the sea and ocean is 35 $^{o}/_{oo.}$ However, the rate of salinity varies spatially and temporally. Isohalines, defined as lines joining places having an equal degree of saltiness, are used on maps to show the salinity of different areas.

The land is the primary source of oceanic salinity. Rivers from the continental areas bring Salts in solution form. There is a lot of variation in the composite of sea salt. Both ocean and sea waters contain a complex solution of several minerals in dilute form, as it is an active solvent. The total amount of salt in the ocean and seawater gradually increases as it is brought from the land every year. The different types of salt present in ocean water are represented in the table. These salts are of terrestrial origin. If all the significant salts are removed from the oceans and seas, the sea level will fall by 100ft. Besides, numerous salts, gold, silver, and radium are also in minute quantities.

Fig. 5 - Levels of Salinity in Water Bodies



Source:https://lotusarise.com/

Table 2– Significant Salts in the Ocean

Salts	**Amount (%)**	**Amount ($^o/_{oo}$)**
Sodium Chloride (Nacl)	77.8	27.213
Magnesium Chloride ($Mgcl_2$)	10.9	3.807
Magnesium Sulphate ($MgSO_4$)	4.7	1.658
Calcium Sulphate ($CaSo_4$)	3.6	1.260
Potassium Sulphate ($K2SO_4$)	2.5	0.863
Calcium Carbonate ($CaCO_3$)	0.3	0.123
Magnesium Bromide ($MgBr_2$)	0.2	0.076

Source: Savindra, S. (1998). Physical geography.

Factors controlling the Salinity of Oceans

Salinity varies spatially in oceans and seas. The factors leading to this differentiation in salt amount are –

- The salinity of water in the surface layer of oceans depends mainly on **evaporation and precipitation**. A *direct positive relationship is found between the rate of evaporation and salinity*. To explain further, the greater the rate of evaporation, the higher the salinity and vice versa. Evaporation due to high temperature with low humidity, i.e., dry conditions, causes more salt concentration. Thus overall salinity becomes higher. For example, salinity is higher in the tropics than at the equator. This is because both the areas record a high evaporation rate, but there is dry air over the Tropic of Capricorn and Cancer.Therefore, the oceans between 20°N and 30°N latitudes have higher salinity because of a higher evaporation rate (because of high temperature). *Precipitation is inversely related to salinity.* The higher the rate of rainfall, the lower the salinity, and vice versa. Like the equatorial zones, regions with high rainfall record comparatively lower salinity than the region with low rainfall. Even areas with high relative humidity and addition by freshwater have low salinity.The Baltic, Antarctic,andArctic waters have a salinity of <32 ppt because freshwater is added from the melting of icebergs.

- **Ocean currents** *mix seawater, and this affects the spatial distribution of salinity.* For example, warm equatorial currents drive salts away from the western coastal areas and accumulate them along the eastern coastal regions. The presence of high salinity in the Mexican Gulf is due to this factor. Similarly, Gulf Stream increases salinity along the north-western coast of Europe. The cool Labrador Current reduces salinity on the north-eastern shores of North America. Land-locked regions have higher salinity because of no mixing of freshwater and continuous evaporation. E.g., the Black Sea, Caspian Sea, Red sea, etc.

- The oceans into which huge rivers like Amazon, Congo, Ganges, etc., drain have lower salinity. *Because the rivers carry voluminous water and pour them into the ocean/sea, thus, salinity reduces at the mouth of the river.* The **influx of river water** effect is more pronounced in the enclosed seas like the Danube, and other rivers reduce salinity in the Black sea (18 $^{o}/_{oo}$). Moreover, an increase in salinity also increases at a place where the evaporation rate exceeds the influx of fresh river water: the Mediterranean sea (40 $^{o}/_{oo}$).

- Anti-cyclonic conditions (**atmospheric pressure**) increase the salinity of the ocean's surface water. The subtropical high-pressure belts represent such conditions for causing high salinity. **Winds** also influence the salinity of an area by transferring water to other places. For example, trade winds drive away saline waters from the western coasts of the continent or eastern margins of the oceans and pile them up near the eastern shores or western margins of the oceans, causing low salinity in the former areas and high salinity in the latter.

Distribution of Salinity

The average salinity for the ocean is 35 $^{o}/_{oo}$. But it ranges spatially and temporally. Salinity also varies from enclosed seas to partially closed ones and then to open seas. Thus, understanding the spatial distribution of salinity is studied in 2 ways – a) horizontal distribution and b) vertical distribution.

a) Horizontal Distribution – Horizontal distribution of oceanic salinity can be studied concerning latitudes. Generally, salinity decreases from the equator towards the poles. The highest salinity is recorded near the 20^{0}-40^{0}N latitudes (36 $^{o}/_{oo}$), as this zone is characterized by high temperature and high evaporation, but significantly low rainfall. The equator accounts for 35 $^{o}/_{oo}$salinity. The same value is recorded between 10^{0}-30^{0}S latitude. The zone between 40^{0}-60^{0} latitudes in both hemisphere records low salinity. The latitudinal distribution of salinity has been divided into four zones –

- Equatorial zone – low salinity due to excessive rainfall
- Tropical zone (20^{0}-30^{0}) – maximum salinity due to low rainfall and high evaporation
- Temperate zone – low salinity
- Sub-polar or Polar zones- there is minimum salinity due to the influx of ice-melting water.

The marginal areas of the oceans bordering the continents have lower salinity than their central parts due to the addition of freshwater to the marginal areas through the rivers. In the landlocked Red Sea, salinity is high as 41 $^{o}/_{oo}$. In the estuaries and the Arctic, the salinity fluctuates from 0 – 35 $^{o}/_{oo}$, seasonally as freshwater comes from ice caps.

Regional Distribution

- *Pacific Ocean* – The salinity variation in the Pacific Ocean is due to its shape and larger areal extent. Salinity remains 34 $^{o}/_{oo}$ near the equator. It increases to 35 $^{o}/_{oo}$ between 15^{0}-20^{0} in the northern hemisphere and around 36 $^{o}/_{oo}$ in the southern hemisphere.

- *Atlantic Ocean* - The average salinity of the Atlantic Ocean is around 36 $^{o}/_{oo}$ - 37 $^{o}/_{oo}$. The equatorial region of the Atlantic Ocean has a salinity of about 35 $^{o}/_{oo}$. Salinity increases from the equator towards the tropic of Cancer and Capricorn due to heavy rainfall, high relative humidity, cloudiness, and calm air of the doldrums. Polar Regions have low levels of salinity, ranging between 20 $^{o}/_{oo}$ and 32 $^{o}/_{oo}$ due to very little evaporation and receiving large amounts of freshwater from the melting of ice. Maximum salinity of 37 $^{o}/_{oo}$ is observed between 20° N and 30° N and 20° W – 60° W. Salinity gradually decreases towards the north.

- *Indian Ocean* - The average salinity of the Indian Ocean is 35 $^{o}/_{oo}$. But it gradually decreases towards the Bay of Bengal. The low salinity is observed in the Bay of Bengal due to the influx of river water by the

Ganges. On the contrary, the Arabian Sea has higher salinity due to high evaporation and a low influx of freshwater.

- *Marginal seas* - The North Sea, despite its location in higher latitudes, records higher salinity due to more saline water brought by the North Atlantic Drift. The Baltic Sea records low salinity due to the influx of river waters in large quantities. The Mediterranean Sea records higher salinity (37 $^{o}/_{oo}$ – 39 $^{o}/_{oo}$) due to high evaporation. In the Black Sea, salinity is very low due to the enormous freshwater influx by rivers.

- *Inland seas and lakes* – The amount of salt in the inland seas and lakes is controlled by the high rate of temperature, evaporation, the influx of river water, and the presence and absence of outlets. Whenever a river comes out of a lake, its salinity is reduced. For example, the northern part of the Caspian Sea records 14 $^{o}/_{oo}$, due to the influx of voluminous water from river Volga, Ural, etc. The highest salinity in water bodies is recorded in - the Great Salt Lake (Utah, USA), the Dead Sea, and the Lake Van in Turkey, with 220 $^{o}/_{oo}$, 240 $^{o}/_{oo}$, and 330 $^{o}/_{oo}$, respectively.

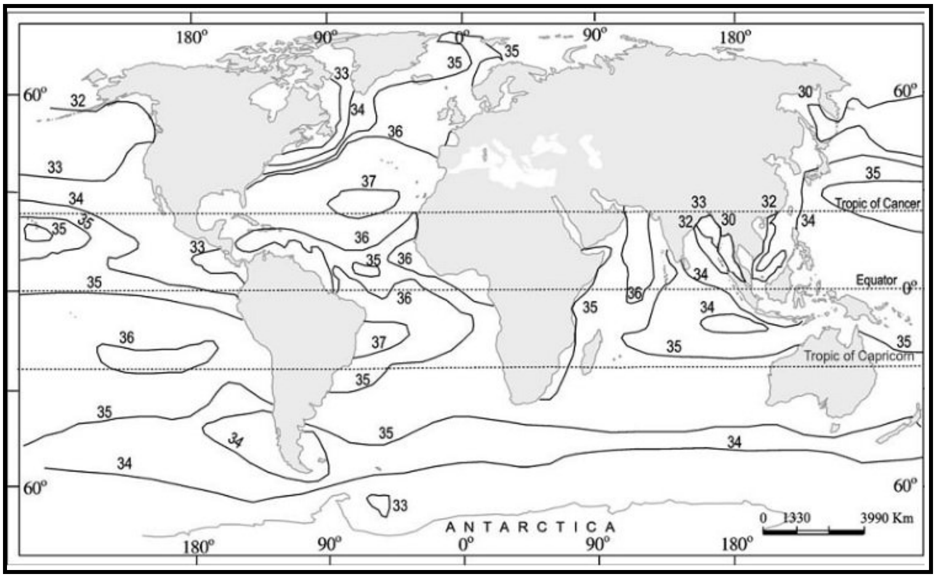
- *Cold and warm water mixing zones* **-** Salinity decreases from 35 $^{o}/_{oo}$ to 31 $^{o}/_{oo}$in the western parts of the northern hemisphere because of the influx of melted water from the Arctic region.

Vertical Distribution

Salinity also varies according to the depth of oceans, seas, rivers, lakes, and other water bodies. However, even this variation again is subject to latitudinal differences. The decrease is also influenced by cold and warm currents. In high latitudes, salinity increases with depth. While in the middle latitudes, it increases up to 35m and then decreases. At the equator, surface salinity is lower.

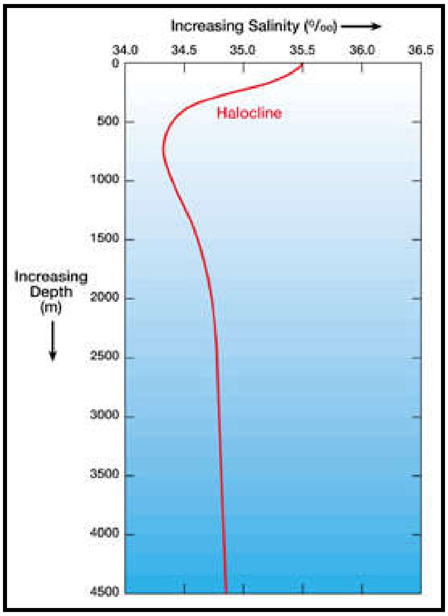
- Salinity changes with depth, but the changes depend upon the location of the ocean.
- Salinity at the surface increases by the loss of water due to the formation of ice or evaporation or decreases by the input of freshwaters, such as the rivers.
- Salinity at depth is fixed because there is no way that water is 'lost', or the salt is 'added.' There is a marked difference in the salinity between the surface zones and the deep zones of the oceans. For example, salinity in the southern boundary of the Atlantic Ocean is 33 $^{o}/_{oo}$ at the surface. But it increases to 34.5 $^{o}/_{oo}$ at the depth of 1200 ft.
- The lower salinity water rests above the higher salinity dense water.
- Generally, the salinity increases with depth and there is a distinct zone called the halocline (fig) where salinity increases sharply.
- The increasing salinity of seawater causes its density to increase.

Map 12 – Surface Salinity of the World's Oceans



Source: https://www.pmfias.com/

Fig 6 - Halocline



Source: https://www.windows2universe.org/

The Density of the Ocean Water

Density is a very important physical property of seawater. The density of a substance is the mass per unit volume of the substance. It is usually measured in grams per cubic centimeter of volume (g/cm^3). The density of distilled water is $1.00 g/cm^3$at a temperature of 4^0C. When two water masses having different density meets; the denser sinks downwards (subsidence) and then spreads out at a place where a similar density is found. As sea or ocean water carries many dissolved items, its density is slightly higher than pure water, i.e. $1.0278 g/cm^3$. Temperature and salinity both affect the density of the water. The density of ocean water gradually increases with decreasing temperature and the highest density is recorded at the temperature of -1.3^0C.

Density determines the dynamics of ocean water i.e. whether seawater will sink (subsidence and hence the downward vertical movement of seawater) or will float (expansion and horizontal movement). The density of seawater is related to the following 3 factors –

- Temperature → thermal expansion
- Pressure → Compressive effects
- Salinity → Addition of dissolved substances

1. **Temperature** is the primary controlling factor forthe density of ocean water, even though they are inversely related. That is, the higher the temperature, the lower the density and vice versa. Sea or ocean water is heated through insolation. Thus when more insolation is received on the sea surface, seawater expands. This phenomenon is commonly known as *thermal expansion*. On the other hand, low temperature causes cooling of ocean water, and hence thermal contraction results in a decrease in volume but an increase in density of ocean water. The role of temperature in controlling ocean water density is more pronounced in low latitude areas. Whereas, the importance of temperature in controlling seawater decreases towards the poles.

2. The effect of **pressure** is minor, even though it is directly positively related to ocean water density through compressive effects. Thus, ocean water density increases with increasing pressure and decreases with decreasing pressure. The pressure effect of thick water mass on density may be observed only in deep-sea mainly in deep-sea trenches.

3. **Salinity** is directly positively related to ocean water density. Because dissolved salt in seawater becomes denser than pure water. The density of pure water is 1.00g/cm^3 at 4^0C temperature. Whereas, the density of seawater carrying $35^0/_{00}$ is 1.028g/cm^3 at the same temperature.

Relationship between Density, Salinity, and Temperature

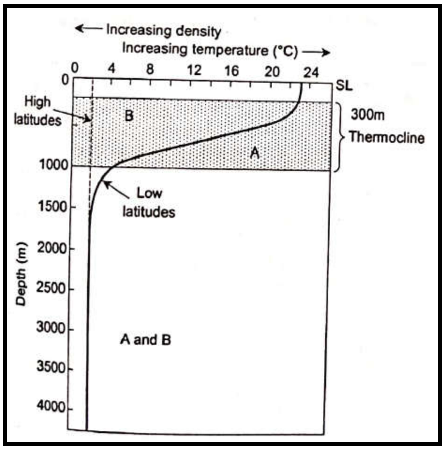
The density of seawater and temperature is inversely proportional. In fig. 7 (1) it is apparent that the temperature of seawater sharply declines from 200m depth to 1000m depth in tropical and sub-tropical regions (low latitude areas) and thereafter there is no variation in seawater temperature with increasing depth, as represented in curve A of fig. 7 (1). Whereas, there is no change in seawater temperature with increasing depth in Polar Regions (high latitudes areas) as represented in curve B. The zone of sharp change of seawater temperature between 200m and 1000m is called the *thermocline*.

The density of seawater increases with increasing depth between 200m and 1000m in tropical and sub-tropical regionsas represented in curve Afig.7 (2). In high latitudes, there is no change in ocean water density (as represented in curve B of fig. 7 (2). The zone (200m to 1000m depth) characterized by a sharp change in density of the seawater in low latitude regions is called *pycnocline.* Here pycno means density and cline means slope or gradient. It is evident from fig. that the density of ocean water and temperature are inversely proportional in sub-tropical and tropical oceans.

The coincidence of thermocline and pycnocline in the same depth zones denotes the close relationship between the density of ocean water and temperature. Fig. demonstrates a decrease in seawater temperature and increases in ocean water density with increasing depth (from 200m to 1000m depth).

As mentioned earlier, salinity decreases with increasing depth between 200m and 1000m in tropical and sub-tropical regions whereas it increases with increasing depth in high latitude areas. The zone of a sharp decline of seawater salinity (200m - 1000m) is known as *halocline*. If fig. 7(1), (2), and 8 (3), (4), are compared, it is evident that the salinity factor has minor control over ocean water density in tropical and sub-tropical regions oceans. On the contrary, ocean water temperature emerges as a crucial factor affecting density.

Fig. 7 - Variations of seawater temperature (1) and seawater density (2) with increasing depth in low and high latitude regions



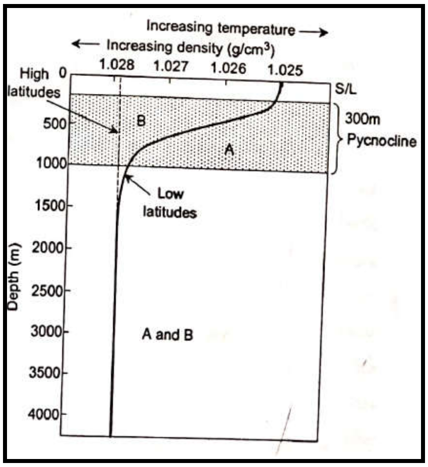
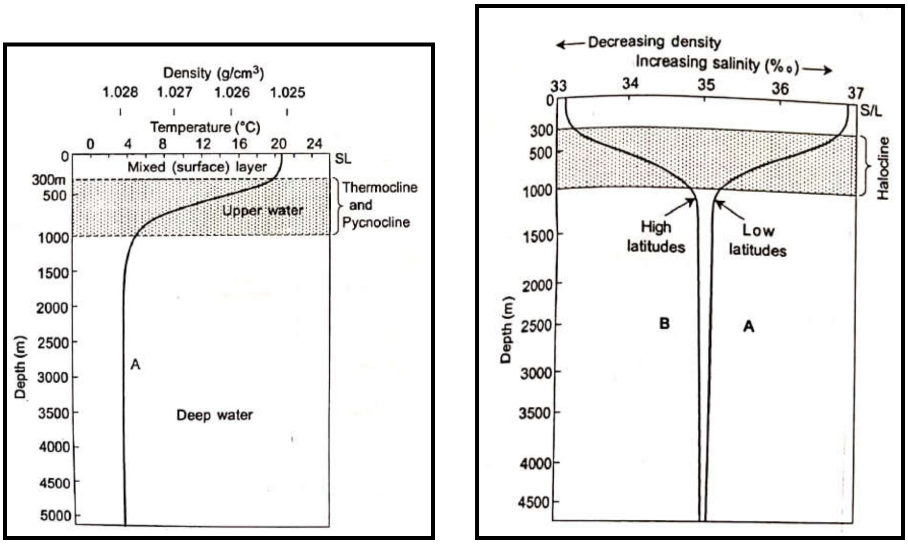
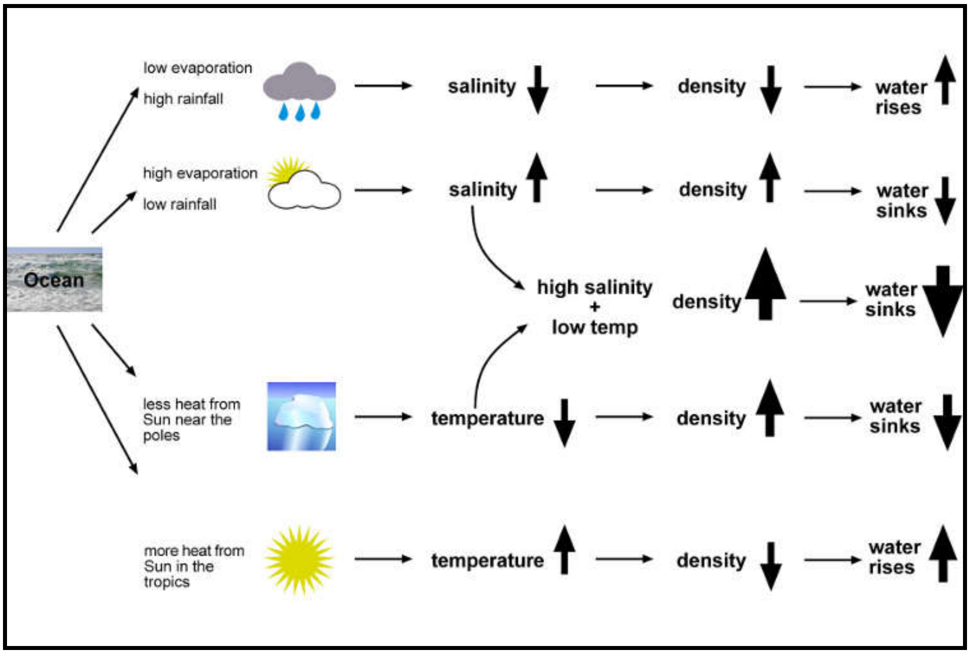


Fig. 8 - Relationship between ocean water temperature and density (3); Relationship between ocean depth, ocean water salinity, density, and halocline (4)



Source: Savindra, S. (1998). Physical geography. PrayagPustakBhavan, Allahabad.

Fig.9 -Salinity and temperature of the ocean rise or fall (indicated by arrows) in response to rainfall, evaporation, and solar radiation.



Source: https://www.sciencelearn.org.

Density Stratification of Oceans

There are three strata of ocean water columns from the sea surface to the ocean bottoms as follows –

- *The surface layer of the lowest density*
- *Pycnocline layer of sharp density gradient*
- *Deep or bottom layer of highest but the uniform density*

Surface layer

This layer represents the top thinnest layer of the oceans ranging in thickness from 100 to 200m. The surface layer is also called a photic zone where solar radiation directly penetrates and illuminates it. This layer carries 2% of the total volume of ocean water. Due to thermal expansion, density minimizes in this layer in the tropical oceans. Density rises in the same layer in sub-tropical regions due to evaporation. The surface layer is extremely significant for marine plants (phytoplankton) due to the presence of photosynthesis. Extremely low temperature due to the least insolation of sea surface water in the polar region causes a higher density of water, resulting in the dense water sinking in the polar oceans.

Pycnocline layer

This layer represents a transition zone of rapidly changing ocean water density, between the low-density upper surface water layer and the high-density deep ocean water below. The pycnocline layer carries 18% of the total volume of ocean water.

Deep layer

This layer represents high-density water mass which extends from 1000m depth to the ocean floor. The layer carries 80% of the total volume of ocean water. Low to extremely low temperatures in the polar areas are responsible for the contraction of water, causing an increase in seawater density. This causes the sinking of high-density water mass of polar regions which in turn causes the undersea flow of water towards low latitudes.

1.9. SUMMARY

Earth is a water planet. The ocean covers 71% of its surface and has greatly influenced its rocky crust and atmosphere. The average depth of the ocean is about 41⁄2 times the average height of the continents above sea level. Life on Earth almost certainly evolved in the ocean. Oceanography or Marine science applies the scientific method to study the ocean, and the living organisms dependent on it. Various hypotheses and theories have tried to explain the origin of the ocean. The earth is composed of concentric spherical layers. The layers may be classified by chemical composition into crust, mantle, and core or by physical properties into the lithosphere, asthenosphere, mantle, and core. Geologists have confirmed the existence of the layers by analysis of seismic waves, generated by the forces causingearthquakes. The theory of plate tectonics explains the curious jigsawpuzzle fit of the continents and the formation of oceans. While the continents are old; the ocean floors, are young. Seafloor features are a result of a combination of tectonic activity and the processes of erosion and deposition.The ocean floor can be divided into two - the continental margins and deep-ocean basins.The continental margin is the shallow ocean floor nearest the shore, and it consists of the continental shelf and the continental slope.The deep-ocean floor which is away from land has a much different origin and history. Prominent features of the deep-ocean basins include rugged flat abyssal plains,oceanic ridges,deep trenches, and curving chains of volcanic islands. The temperature, salinity, and density of ocean water vary both spatially and temporally. The density of seawater and temperature is inversely proportional. The density of seawater increases with increasing depth.

Voyaging for necessity evolved into voyaging for scientific and geographical discovery. The rise of the great oceanographic institutions, today marked the path into the future.

1.10. CHECK YOUR PROGRESS OR EXERCISE

1. **True or False**

a. The salinity for normal open ocean ranges between 33°/oo and 37 °/oo.
b. The actual boundary of a continent is its coastline.
c. The zone characterized by a sharp change in density of the seawater in low latitude regions is called a halocline.
d. The horizontal distribution of oceanic salinity can be studied concerning latitudes.
e. Mathew Maury published the book "The Physical Geography of the Sea."

2. **Fill in the Blanks**

a) ___________ is composed of two chains of mountains separated by large depression.
b) _______________ dips steeply into the ocean basins at an average angle of around 4°.
c) ________________ described the reversal of the currents due to the seasonal monsoon winds.
d) The zone of sharp decline of seawater salinity is known as _______________.
e) ____________ is formed at the junction of Continental Shelf and Continental Slope

3. **Multiple Choice Question**

1. The average depth of continental slope varies between_____________
a. 200-2000m
b. 3000-6000m
c. 300-750m
d. 3000-30,000m

2. ______________ is not a minor relief feature in the oceans
a. Seamount
b. Oceanic Deep

c. Atoll
d. Guyot

3. The density of Ocean Water ________ at the temperature of ______
a. 1.0278 g/cm^3 , 4^0C
b. 1.0278 g/cm^3 , 6^0C
c. 1.0356 g/cm^3, 4^0C
d. 1.0478 g/cm^3 , 10^0C

4. The zone of sharp change of seawater temperature _________
a. Halocline
b. Thermocline
c. Pycnocline
d. Isothermal lines
5. The average salinity for the ocean is _________
a. 36 ^{o}/oo
b. 37 ^{o}/oo
c. 34 ^{o}/oo
d. 35 ^{o}/oo

4. **Answer the following Questions**

1. Examine the factors that influence the temperature distribution of the ocean.
2. Write a detailed note on the reliefs of ocean basins. Cite examples.
3. "Oceanography is a broad field in which many sciences are focused on the common goal of understanding the oceans." Explain.
4. Explain how temperature, salinity, and density of oceans are related.
5. Briefly describe the history of oceanography.

1.11. ANSWERS TO THE SELF-LEARNING QUESTIONS

1.a. True

1.b. False

1.c. False

1.d. True

1.e. True

2.a.Mid-oceanic Ridge

2.b. Continental Slope

2.c. El-Mas'údé

2.d. Halocline

2.e. Submarine Canyons

3.1. b

3.2. b

3.3. a

3.4. b

3.5. d

1.12. TECHNICAL WORDS AND THEIR MEANING

- **Aphotic zone –** Represents the non-illuminated portion of the oceans extending between 200m depth to the ocean floor.
- **Halocline** – Denotes a zone of sharp salinity change in the vertical section of the oceans between 300m-1000m depth.
- **Insolation** – The radiant energy received by the earth and its atmosphere from the sun is called insolation.
- **Photic zone** – Represents the upper 200m deep water layer of the oceans, which is directly penetrated by solar radiation.
- **Pycnocline layer –** It is characterized by a sharp increase in seawater density.
- **Salinity** –Defined as a ratio between the weight of the dissolved solid materials and the weight of the sample seawater, usually one kilogram. It is expressed as part per thousand or ppt ($^{0}/_{00}$).
- **Thermocline layer** – It is characterized by the sharp decrease in seawater temperature.

1.13. TASK

With the help of an atlas, mark the ocean floor reliefs on an outline map of India.

1.14. REFERENCES FOR FURTHER STUDY

1. Stewart, R. H. (2008). *Introduction to Physical Oceanography*.

2. Garrison, T. (2012). *Essentials of Oceanography* (Sixth Edit). Brooks/Cole, Cengage Learning.

3. Singh, S. (2014). *Oceanography*. Allahabad: Pravalika Publications.

❖❖❖❖

2

OCEAN CURRENTS AND RESOURCES

Unit Structure

2.0 OBJECTIVES

Learning Outcomes: After the study of this module learners will be able to

- Understand the concept of ocean currents and their distribution.
- Understand processes involved in formation of oceanic waves, tsunami and tides.
- Understand the formation and characteristics of marine sediments and deposits.
- Understand food and mineral resources of the sea.

2.1 INTRODUCTION

Oceans occupy almost three fourth of the total earth surface. Oceanic dynamics play significant role in various oceanic processes continuously operating in oceans. Sea waves, tides, ocean currents, tsunami, coastal dynamics etc. are some of the important oceanic movements. Different kinds of oceanic movements give rise to formation of different landforms both in the ocean floor and coastal areas. Ocean water dynamics also play significant role in socio-economic progress of human being. This is mainly due to the fact that various human activities such as fishing, tourism, water transport, mining, power plants etc. are associated with oceans. Hence it is important to understand the ocean water dynamics and its role in shaping economic activities and also the geomorphic landforms resulted from such movements. This module aims at discussing the ocean water dynamics from the view point of landform generation and socio-economic implications of these dynamics.

2.1.1. Ocean currents: meaning

Movement of ocean water is an important form ocean water dynamics. Oceans are never static. Different kinds of movements take place in ocean continuously. Sea waves, tides and ocean currents are important movements of sea water. Ocean currents refer to as the general movement of mass of surface water in a fairly defined direction. Ocean currents may be defined as any persistent and dominantly horizontal flow of ocean water. Unlike oceanic waves, ocean currents comprise not only surface waters but also the movement of water up to the depth of 1000 meters. Hence ocean currents are considered to the most extensive type of ocean water movements.

Ocean currents are the continuous, predictable, directional movement of seawater driven by gravity, wind (Coriolis Effect), and water density. Ocean water moves in two directions: horizontally and vertically. Horizontal movements are referred to as currents, while vertical changes are called upwellings or downwellings. This abiotic system is responsible for the transfer of heat, variations in biodiversity, and Earth's climate system (National Geographic). Ocean Current is a horizontal movement of seawater that is produced by gravity, wind, and water density. Ocean currents play an important role in the determination of climates of coastal regions. The streams of water that flow constantly on the ocean surface in definite directions are called ocean currents.

Ocean currents are one of the factors that affect the temperature of ocean water. The magnitude of the ocean currents ranges from a few centimeters per second to as much as 4 meters (about 13 feet) per second. The intensity of the ocean currents generally decreases with increasing depth. The speed of ocean currents is more than that of upwelling or downwelling which are the vertical movements of ocean water.

2.1.2 Dynamics of ocean currents:

Horizontal pressure-gradient forces, Coriolis forces, and frictional forces are important forces that cause and affect ocean currents.

Rise and fall of the tide

Tides give rise to tidal currents. Near the shore, tidal currents are the strongest. The change in tidal currents is periodical in nature and can be predicted for the near future. The speed of tidal currents at some places can be around 8 knots or more.

Wind

The ocean currents at or near the ocean surface are driven by wind forces. The process is called Thermohaline Circulation. 'Thermo' stands for temperature and 'Haline' stands for salinity. The variations in temperature and salinity at different parts of the oceans create density differences which in turn affect the ocean currents. The movement of water through the oceans is slowed by friction, with surrounding fluid moving at a different velocity. A faster-moving layer of water and a slower-moving layer of water would impact each other. This causes momentum transfer between both layers producing frictional forces.When the pressure gradient force on the ocean current is balanced by the Coriolis forces, it results in the geostrophic currents.

- The direction of geostrophic flow is parallel to an isobar.
- The high pressure is to the right of the flow in the Northern Hemisphere, and the high pressure to the left is found in the Southern Hemisphere.

2.1.3 North and South Equatorial Currents

1. North Equatorial Current

- North Equatorial Current flows from east to west in the Pacific and the Atlantic Ocean.
- North Equatorial Current flows between the latitudes of 10 degrees and 20 degrees north.
- It is not connected to the equator.
- Equatorial circulation separates this current between the Pacific and Atlantic oceans.

2. South Equatorial Current

- It flows in the Pacific, Atlantic, and Indian oceans.
- The direction of the south equatorial current is east to west.
- The latitudes in which the current flows are between the equator and 20 degrees south.
- It flows across the equator to 5 degrees north latitudes in the Pacific and Atlantic Oceans.

2.2 GLOBAL DISTRIBUTION OF OCEAN CURRENTS

The ocean currents flowing across the globe are distributed in Atlantic, Pacific and Indian oceans. Major ocean currents in the world are given below.

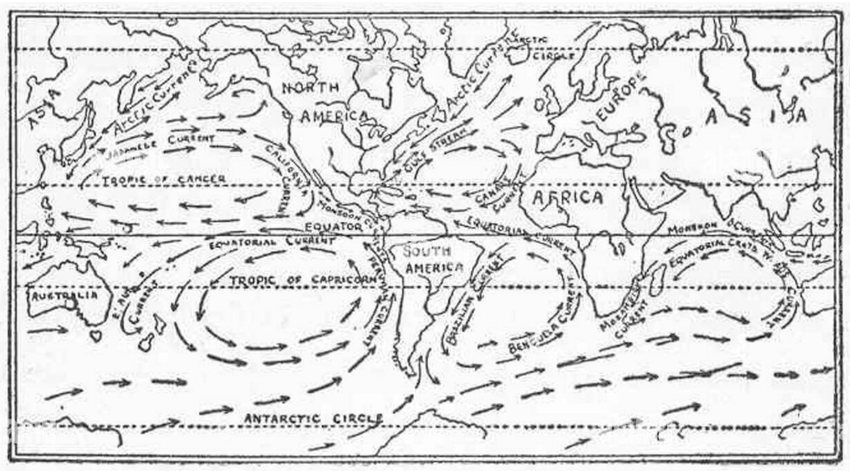
Ocean Currents in Atlantic Ocean	
Angola Current	Warm
Antilles Current	Warm
Benguela Current	Cold
Brazil Current	Cold
Cape Horn Current	Cold

Carribean Current	Warm
Falkland Current	Cold
Florida Current	Warm
North Atlantic Current	Warm
South Atlantic Current	Cold
Ocean Currents in Indian Ocean	
Agulhas Current	Warm
Leeuwin Current	Warm
Mozambique Current	Warm
West Australian Current	Cold
Ocean Currents in Pacific Ocean	
Alaska Current	Warm
Humboldt Current	Cold
Kamchatka Current	Cold
Kuroshio Current	Warm
North Pacific Current	Warm

2.2.1 Ocean currents in Pacific Ocean

Pacific Ocean is the largest ocean on planet earth. The movement of ocean currents in Pacific Ocean is mostly along the coastal areas. The distribution of ocean currents in Pacific Ocean is divided into three sections;

1. Currents in Mid-Pacific Ocean
2. Currents in North Pacific Ocean
3. Currents in South pacific Ocean



THE GREAT OCEAN CURRENTS

1. Currents in Mid-Pacific Ocean:

a) North Equatorial currents: This current of the Pacific Ocean runs from west coast of Mexico and flows towards the east and contuse up to Philippines. The transportation of water in this current is more than other currents in Atlantic and Indian oceans in equatorial regions. Near Mexico, this current is added to California Current.

b) South Equatorial current: This current is present on both sides of the equator. The formation of this current is caused by south-east trade winds. This current covers a total distance of about 13600 kms in south Pacific Ocean. Numerous small ocean currents meet this current on its left margin.

c) Equatorial counter current: It flows between north and south equatorial currents. It continues to flow from west to east throughout the year. It is interesting to note that this current always flows in northern hemisphere. During north summer the current velocity reaches to 100 cm/sec.

2. Currents in North Pacific Ocean:

Kurioshio currents is in fact is the extension of north Equatorial Current. In the Western part of the Pacific ocean, the North Equatorial Current bifurcates one joins counter current and one flows to Philippines. The one which flows along the north coast of Philippines is called Kuroshio current. Tsushima is warm current which generate on the left side of Kurioshio current. Oyashio, North Pacific, Aleutian, California currents are important currents flowing in North Pacific Ocean.

3. Currents in South Pacific Ocean:

Peru current, East Australia current and West wind drift are important currents flowing in South Pacific Ocean. Peru current is cold current that flows along west coast of South America from South to North. It is also called as Humboldt current. This current originates near Antarctica. The cold waters in Antarctica is carried by westerlies toward east. It bends near west coast of South America and then flows towards north. In January-March, Equatorial counter current is displaced to south. Due to this warm waters flowing along the coast of Equador converges with Peru Current. This south flowing current is refer to as “El Nino current”.

2.2.2 Ocean currents in Atlantic Ocean

Currents in North Atlantic Ocean include North Equatorial Current, The Equatorial Counter Current, Florida Current, Gulf stream, North Atlantic DriftThe Canaries Current and the Labrador current.

South Atlantic Ocean include South Equatorial current, Brazil current, Falkland current, South Atlantic current, Benguela current.

2.2.3 Ocean currents in Indian Ocean

Because of peculiar geographical location the Indian ocean is entirely different from the Pacific and Atlantic ocean currents. Northern part of the Indian ocean is different from other parts of it. North India ocean is under the influence of Indian monsoon. In southern part of Indian Ocean anti-cyclonic system of current is present.

The Winter Monsoon Drift, South Monsoon Drift are important ocean currents in North Indian Oceans whereas the South Equatorial Current, , Madagascar current, Mozambique current are dominant in South Indian Ocean.

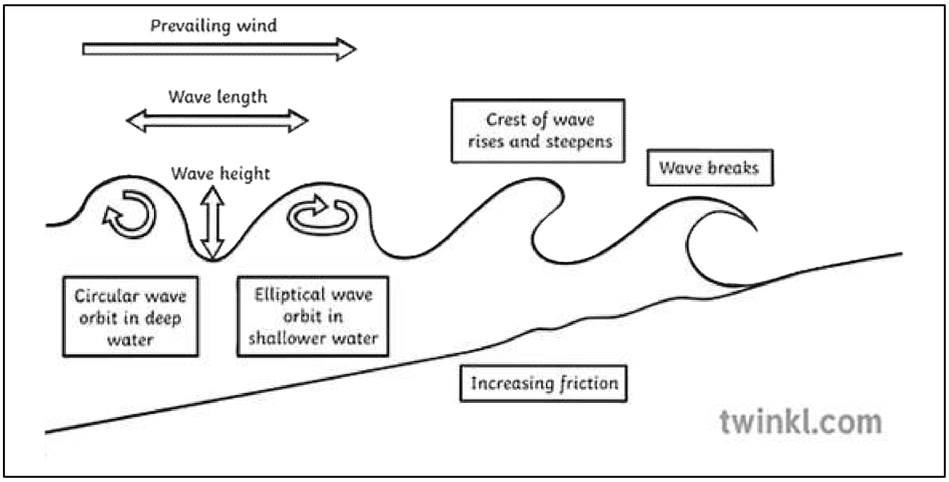
2.3 OCEANIC WAVES

Ocean waves (swell) are formed by transferring energy from the motion of atmospheric wind to the ocean surface and releasing a certain amount of energy to the shoreline, causing erosion and accretion of coastal landforms for long-term scale (Kaliraj et al., 2014).

Characteristics of oceanic waves

Wave characteristics

- Crest: the highest point of a wave
- Trough: the lowest point of a wave
- Height: the distance between a wave's crest and trough
- Amplitude: the distance between the crest or the trough to the still water line in between
- Period: the time between successive swell crests
- Frequency: the number of waves that cross a fixed point in a given amount of time



Causes of oceanic Wave formation

Waves are most commonly caused by wind. Wind-driven waves, or surface waves, are created by the friction between wind and surface water. As wind blows across the surface of the ocean or a lake, the continual disturbance creates a wave crest.

The ocean is never still. Whether observing from the beach or a boat, we expect to see waves on the horizon. Waves are created by energy passing through water, causing it to move in a circular motion. However, water does not actually travel in waves. Waves transmit energy, not water, across the ocean and if not obstructed by anything, they have the potential to travel across an entire ocean basin.

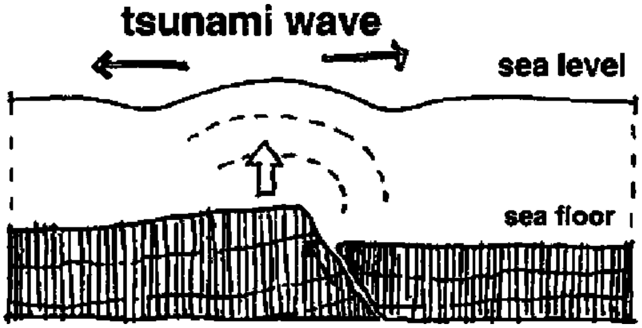
Waves are most commonly caused by wind. **Wind-driven waves**, or **surface waves**, are created by the friction between wind and surface water. As wind blows across the surface of the ocean or a lake, the continual disturbance creates a wave crest. These types of waves are found globally across the open ocean and along the coast.

More potentially hazardous waves can be caused by severe weather, like a hurricane. The strong winds and pressure from this type of severe storm causes storm surge, a series of long waves that are created far from shore in deeper water and intensify as they move closer to land. Other hazardous waves can be caused by underwater disturbances that displace large amounts of water quickly such as earthquakes, landslides, or volcanic eruptions. These very long waves are called tsunamis. Storm surge and tsunamis are not the types of waves you imagine crashing down on the shore. These waves roll upon the shore like a massive sea level rise and can reach far distances inland.

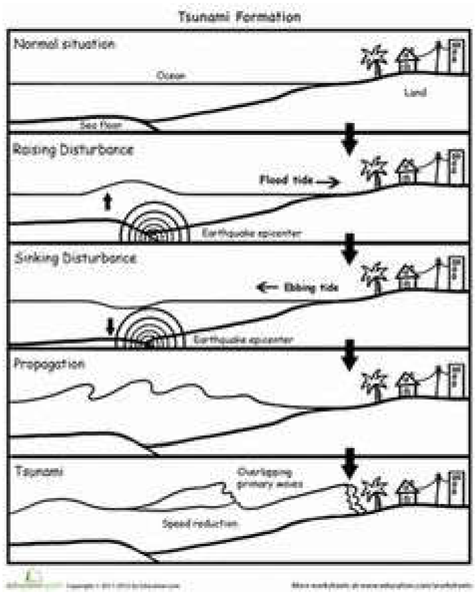
The gravitational pull of the sun and moon on the earth also causes waves. These waves are tides or, in other words, **tidal waves**. It is a common misconception that a tidal wave is also a tsunami. The cause of tsunamis are not related to tide information at all but can occur in any tidal state.

2.4 Tsunamis

How tsunamis are formed. A tsunami is a wave that spreads in the sea and is caused by an underwater earthquake, a landslide, a volcanic eruption or the fall of a meteorite. As the first cause is the most frequent one, we will focus on unravelling underwater earthquakes. The vast majority of earthquakes occur in faults.



What happens is that the two portions of the earth's crust separate, where one side slips over to the other side. That slide can be completely vertical, which literally means the fall of one of the sides of the fault, totally horizontal or something intermediate. In order for an underwater earthquake to cause a tsunami, the movement must have a vertical component; if it is totally horizontal it will not occur. The movement of the fault is so fast that the "step" that occurs on the ocean floor is instantly reflected on the surface of the sea, which deforms just like the bottom. We all know that a "step" in the water is not stable, the surface tends to recover horizontality. The higher water descends and vice versa, giving rise to a series of waves that propagate in all directions from the site of the earthquake: the tsunami.



Tsunami Characteristics

Most tsunamis are caused by a rapid vertical movement along a break in the Earth's crust (i.e., their origin is tectonic). A tsunami is generated when a large mass of earth on the bottom of the ocean drops or rises, thereby displacing the column of water directly above it. This type of displacement commonly occurs in large subduction zones, where the collision of two tectonic plates causes the oceanic plate to dip beneath the continental plate to form deep ocean trenches. Most subduction occurs along most of the island arcs and coastal areas of the Pacific, the notable exception being the west coast of the United States and Canada. Movement along the faults there is largely strike-slip, having little vertical displacement, and the movement produces few local tsunamis.

Volcanoes have generated significant tsunamis with death tolls as large as 30,000 people from a single event. Roughly one fourth of the deaths occurring during volcanic eruptions where tsunamis were generated, were the result of the tsunami rather than the volcano. A tsunami is an effective transmitter of energy to areas outside the reach of the volcanic eruption itself. The most efficient methods of tsunami generation by volcanoes include disruption of a body of water by the collapse of all or part of the volcanic edifice, subsidence, an accompanying or preceding the eruption. Roughly one-half of all volcanic tsunamis are generated at calderas or at cones within calderas. Submarine eruptions may also cause minor tsunamis.

Locally destructive tsunamis may be generated by subaerial and submarine landslides into bays or lakes. Lituya Bay, Alaska, has been the site of several landslide-generated tsunamis, including one in 1958 that produced a splash wave that removed trees to a height of 525 m. It also caused a tsunami of at least 50 m in the bay. The 1964 Prince William Sound earthquake triggered at least four submarine landslides, which accounted for 71 to 82 of the 106 fatalities in Alaska for the 1964 event. However, it is tectonic earthquake-generated tsunamis (those produced by a major deformation of Earth's crust) that may affect the entire Pacific Basin.

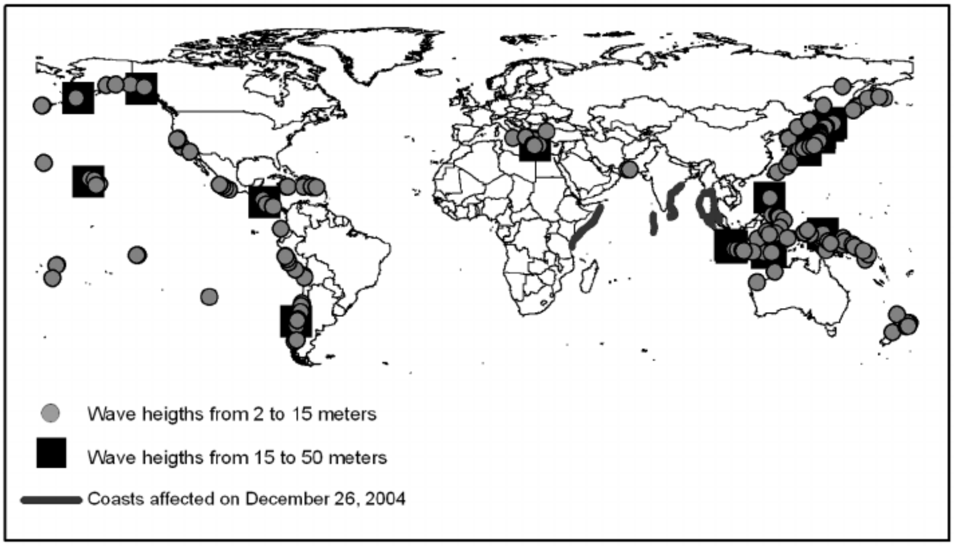
Other possible but less efficient methods of tsunami generation include: strong oscillations of the bottom of the ocean, or transmission of energy to a column of water from a seismic impulse (e.g., a deep-focus earthquake that has no surface rupture); transmission of energy from a horizontal seismic impulse to the water column through a vertical or inclined wall such as a bathymetric ridge; strong turbidity currents; underwater and above-water explosions. Several mechanisms commonly are involved in the generation of a tsunami (e.g., vertical movement of the crust by a seismic impulse or an earthquake, and a submarine landslide).

Worldwide Occurrence of Tsunamis

Tsunamis have been reported since ancient times. They have been documented extensively, especially in Japan and the Mediterranean areas. The first recorded tsunami occurred off the coast of Syria in 2000 B.C. Since 1900 (the beginning of instrumentally located earthquakes), most tsunamis have been generated in Japan, Peru, Chile, New Guinea and the Solomon Islands. However, the only regions that have generated remote-source tsunamis affecting the entire Pacific Basin are the Kamchatka Peninsula, the Aleutian Pacific.

Map - Distribution of tsunami

The Mediterranean and Caribbean Seas both have small subduction zones, and have histories of locally destructive tsunamis. Only a few tsunamis have been generated in the Atlantic Ocean. In the Atlantic Ocean, there are no subduction zones at the edges of plate boundaries to spawn such waves except small subduction zones under the Caribbean and Scotia arcs.



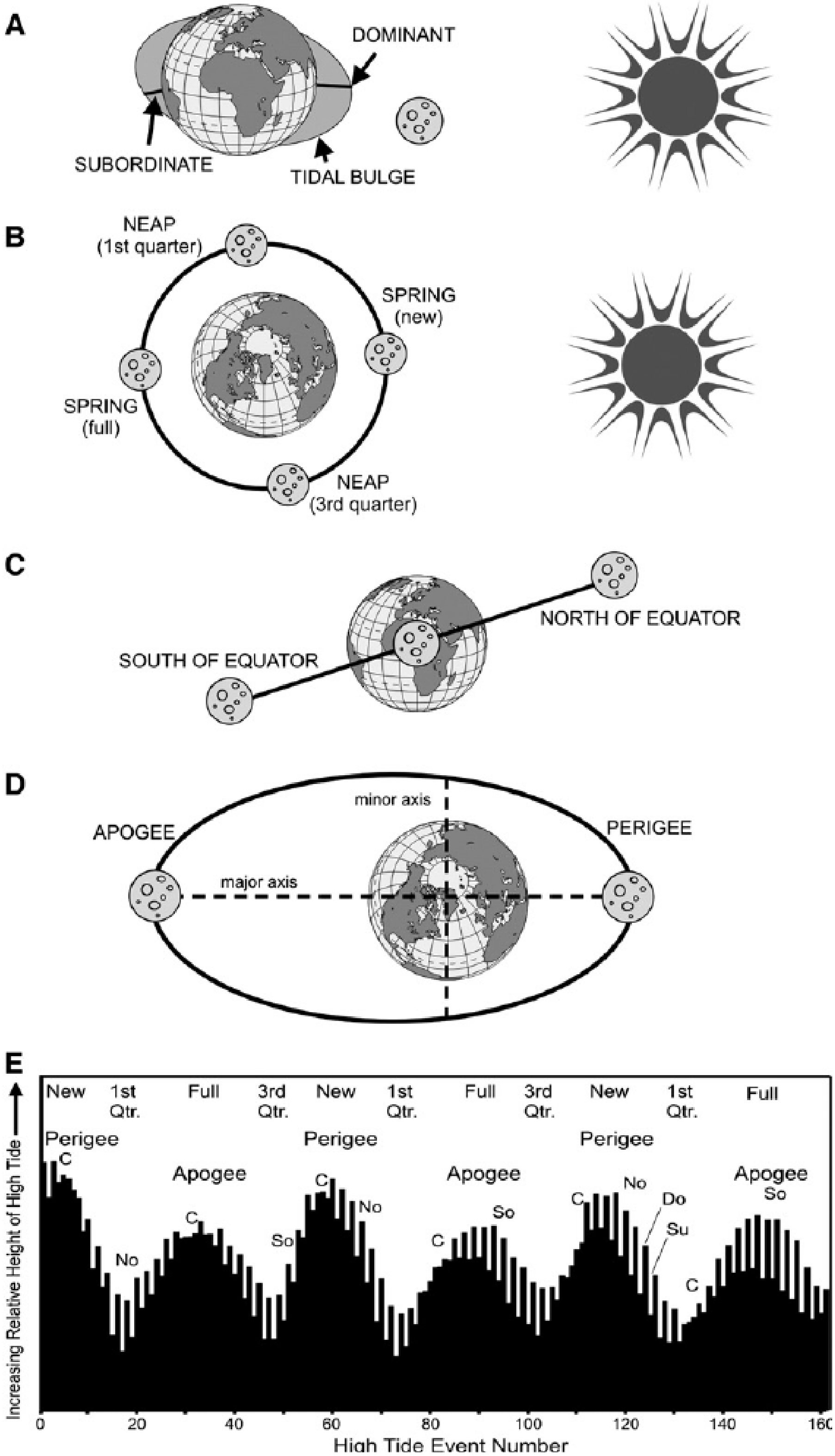
In the Indian Ocean, the Indo-Australian plate is being subducted beneath the Eurasian plate at its east margin. On December 26, 2004, an earthquake off the coast of northern Sumatra generated a tsunami that was recorded nearly world-wide and killed more people than any other tsunami in recorded history. More than 227,899 people were either killed or listed as missing and presumed dead and 1,126,900 were displaced by the earthquake and subsequent tsunami. The estimated economic losses exceed $10 billion. The devastating megathrust earthquake of December 26th, 2004 occurred on the interface of the India and Burma plates and was caused by the release of stresses that develop as the India plate subducts beneath the overriding Burma plate. The India plate begins its descent into the mantle at the Sunda trench which lies to the west of the earthquake's epicenter. The trench is the surface expression of the plate interface between the Australia and India plates, situated to the southwest of the trench, and the Burma and Sunda plates, situated to the northeast.

2.5 TIDES

Tide refer to as' any of the cyclic deformations of one astronomical body caused by the gravitational forces exerted by others'. The most familiar are the periodic variations in sea level on Earth that correspond to changes in the relative positions of the Moon and the Sun. The tides may be regarded as forced waves, partially running waves and partially standing waves. They are manifested by vertical movements of the sea surface (the height maximum and minimum are called high water [HW] and low water [LW]) and alternating horizontal movements of the water, the tidal currents. The words *ebb* and *flow* are used to designate the falling tide and the rising tide, respectively.

Equilibrium theory of Tides

Until now we have been referring to tides on an imaginary earth that is totally covered in water and has no land masses/ continents. This is the basis for the Equilibrium Tide theory. The Equilibrium tide theory is defined as the elevation of the sea surface that would be in equilibrium with the tide forces if the earth were covered with water to such a depth that the response to these forces is instantaneous. In reality this has no resemblance to the real tides, and the rise and fall predicted by it are too small compared to observed tides. This is however an important reference system for tidal analysis.



The dynamic theory/ real tide on the other hand, represents the tide as a wave "forced" by the tide-producing forces, and the rise and fall on the coast as a result of flow convergence or divergence. In theory, it allows calculations of tidal flows in the ocean, and the rise and fall on the shores. However, the real ocean basins have very complicated coastal and bottom topography and it is not possible to obtain exact solutions, except in the open sea.

There are several important factors that modify the movement of water in real tide situations:

1. **The Sun/Moon:** The moon's gravitational effect is greater than that of the suns due to it's closer proximity to the Earth, but acting sometimes in conjunction with the sun and sometimes in opposition it varies the amplitude and timing of the tides.

2. **Geography**: Land masses obviously impede and deflect movement of water on the Earth's surface.

3. **Friction**: Friction retards the movement of water particles across the Earth's surface – (the movement of tides across it is gradually slowing down the rotational speed of the Earth.)

4. **Basin Oscillation**: All bodies of water have natural periods of oscillation determined by their size and shape. All oceans are made up of a number of oscillating basins. The resultant oscillations at any one place affect the tidal movement or wave form depending upon the degree of resonance with the astronomic tidal curve.

5. **Lunar and Terrestrial Orbits**: The shape and plane of both the Earth's orbit around the Sun and the moon's orbit around the Earth are such that the distance between these bodies, their gravitational effect, varies continuously in cycles of months, years and even longer periods.

6. **The Earth's Orbit**: is in the form of an eccentric ellipse (eg or pear shaped). At perihelion the Earth is 91.3 million miles and at aphelion it is 94.5 million miles away from the sun respectively.

7. **The Earth's Declination/ Tilt**: 23° 27' off the vertical, hence the declination of the relative position of the sun and the moon as they appear to revolve around the Earth.

8. **The Moon's Orbit**: Also an eccentric ellipse with a varying apogee and perogee.

The Equilibrium theory explained above describes two bulges moving around the Earth from east to west at a steady rate. Their range would be 0.5m at the equator. This is not exactly what happens with the observed tides. The theoretical explanation of diurnal tides does not agree with the observations either. So why not?

The main reason for this complicated response to the tidal forcings is the fact that the land divides the world's waters into oceans, seas, gulfs etc. of different size, shape and depth. The only latitudes for the unimpeded circumpolar movement are around Antarctica and in the Arctic.

In addition, the water movements are affected by the rotation of the Earth. The Coriolis effect (which we will come to later) causes the water to take a curved path rather than a straight one and Kelvin waves produce different tidal ranges across channels. The best example of this is that of the English Channel where the French coast experiences a much larger tidal range than the British side

Natural Resonance

The various bodies of water have their individual natural periods of oscillation. This influences their response to the tide- raising force. The Pacific Ocean has, in general, a natural period of oscillation of about 25 hours, making it resonant to the diurnal components of the tide raising forces, so the tides tend to be diurnal there. The natural period of oscillation of the Atlantic is about 12.5 hours making it resonant to the semi- diurnal components and so the tides in that ocean are mainly semi-diurnal. Pacific tides are observed to have much more diurnal characteristics in general than Atlantic tides. There are also seas that have a natural period of oscillation that makes them unresponsive to either diurnal or semi-diurnal forces, these are known as non-tidal waters. Good examples of non-tidal waters are: Eastern Mediterranean, Baltic, Black and Caspian Seas

Coriolis and Friction.

Coriolis and friction are linked an understanding of both is important to understanding water movement. Newton's law of motion applies only when all measurements are made with respect to an inertial coordinate system, that is, one that is neither accelerating nor rotating. However the Earth is rotating and so allowances need to be made for this. This is done by providing two "fictitious forces", the centrifugal force and the Coriolis force. The centrifugal force is conveniently combined with the Earth's gravitational force (G) in what we commonly refer to as "gravity" (g).

The Coriolis force is rarely noticeable in laboratory-scale measurements, but it is very significant in large-scale geophysical motions such as winds, ocean currents and tides. In the upper wind driven layers of water bodies a balance is achieved between wind- stress, Coriolis force and pressure gradient field. The Coriolis force arises through relative motion on the rotating Earth and is proportional to the relative velocity and the sine of the latitude. It acts at right angles to the velocity, to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The Coriolis force without pressure gradients arising may balance the wind-stress. Thus a strong wind-stress leads to a strong Coriolis force.

Coriolis force acts in both the vertical and horizontal plane, but we will consider only the horizontal component. Imagine the earth to be covered with a frictionless film, the surface of which conforms to that of a level surface, ie is everywhere normal to the direction of gravity. As a body (or surface layer of water) moves to a higher latitude, the easterly velocity of the earth's surface decreases and so the easterly velocity of the body relative to the Earth increases. This is seen as an acceleration to the left in the Southern Hemisphere and an acceleration to the right in the Northern Hemisphere.

Now we need to ask the question, how does water move? Another major component of water movement is friction. But first we need to look at wind-stress.

The major current systems of the ocean are driven by the wind acting on the surface. The direct effect of the wind-stress is transmitted only to limited depth by viscosity and turbulence. The main surface current systems of the Atlantic and Indian oceans are in the form of large gyres that occupies most of the width of the ocean and are clockwise in the Northern hemisphere and anti-clockwise in the southern hemisphere. The Coriolis force is responsible for these circular patterns, deflecting both the winds and the currents driven by the winds.

The frictional forces that affect a particle in the ocean are:

1. **internal friction**, due mainly to eddy viscosity, which in shallow seas is often negligible compared with
2. **external friction**, due to stresses at the surface and at the sea-bed.

In 1905 V.W. Ekman, a Swedish mathematician and oceanographer, observed that icebergs in the Arctic ice pack were drifting at an angle to the direction of the wind. Ekman showed theoretically that the effect of wind blowing steadily over an ocean of infinite depth, extent and uniform eddy viscosity is to drive the surface layer at an angle ± 45° to the left of the wind direction in the Southern Hemisphere (to the right in the Northern Hemisphere) and to move the successive deeper layers of water more and more to the left until at a given depth the direction of the motion of water is opposite to that at the surface. In addition to the motion being directed more and more to the left (in the Southern Hemisphere), the speed of the motion decreases with depth, due to friction.

2.6 MARINE SEDIMENTS AND DEPOSITS

Marine sediment refers to any deposit of insoluble material, primarily rock and soil particles, transported from land areas to the ocean by wind, ice, and rivers, as well as the remains of marine organisms, products of submarine volcanism, chemical precipitates from seawater, and materials from outer space (e.g., meteorites) that accumulate on the seafloor.

Although systematic study of deep-ocean sediments began with the HMS *Challenger* expeditions between 1872 and 1876, intensive research was not undertaken until nearly 100 years later. Since 1968 American scientists, in collaboration with those from the United Kingdom, the Soviet Union, and various other countries, have recovered numerous sedimentary core samples from the Atlantic and Pacific oceans through the use of a specially instrumented deep-sea drilling vessel called the Glomar Challenger.

Marine sediments deposited near continents cover approximately 25 percent of the seafloor, but they probably account for roughly 90 percent by volume of all sediment deposits. Submarine canyons constitute the main route for sediment movement from continental shelves and slopes onto the deep seafloor. In most cases, an earthquake triggers a massive slumping and stirring of sedimentary material at the canyon head. Mixed with seawater, a dense liquid mass forms, giving rise to a density current that flows down the canyon at speeds of several tens of kilometres per hour. After reaching the base of the continental slope, the sediment-laden mass moves out onto the continental rise at the base of the slope. Deposits from turbidity currents (i.e., short-lived density currents caused by suspended sediment concentrations) can build outward for hundreds and sometimes thousands of kilometres across the ocean bottom. Large sediment-built plains commonly occur in the Atlantic Ocean, where turbidity currents flow from the base of a continent to the Mid-Atlantic Ridge.

Types of Marine Deposits

There are various types of ocean deposits that can be found in the oceans and these types are mentioned below:

Lithogenous Deposits

Lithogenous composed of small fragments. It is also known as terrigenous sediments. The small fragments are the part of preexisting sediments that have made their way into the ocean. These sediments can contain an entire range of particle sizes, from microscopic to clay to large boulders. They are found normally everywhere on the ocean floor. These sediments are created on land by the process of weather. Here rocks and minerals are broken down into tiny particles through the action of wind, rain, water flow, temperature or ice-induced cracking, and other erosive processes. Then these particles are transferred into the oceans.

Lithogenous sediments usually reflect the composition of whatever materials they were derived from. They are dominated by the main material that makes up most terrestrial rocks. Quartz, feldspar, clay minerals, iron oxides, and terrestrial organic matter. Quartz which is also known as silicon dioxide is one of the most common minerals found in all rocks. That's why it is the dominant component of the lithogenous sediments including sand.

- Various forms of deposits are found in oceans. About 90% of the lithogenous sediment in the oceans have come from rivers, particularly from Asia.
- Most of the sediments, mainly the larger particles, will be deposited and remain closer to the coastline.
- On the other side, small particles may be suspended in the water column for longer periods and may be transported a big distance from the source.

- The wind is such a fact which can transport small particles like dust and sand to the ocean and move to thousands of kilometres from the source.
- These small particles can fall into the ocean when the wind dies down or serve as the nuclei around which raindrops or snowflakes.
- Glaciers also have lots of soil and rock particles and large boulders which they get carried by the ice.
- When the glacier breaks out and melts and it meets with the ocean then these particles get deposited in the ocean.
- Landslides, mudslides, avalanches and other gravity-driven events can deposit large amounts of materials into the ocean.
- Wave action along a coastline will erode rocks and will push loose particles into the ocean and seashore.
- Volcanic eruptions emit large amounts of ash and other particles into the surroundings and are then transported to the oceans through the wind.

Biogenous Deposits

Biogenous sediments are sediments that are made from the skeletal remains of living organisms. These sediments include a wide variety of microscopic organisms, coral fragments, sea urchins and pieces of mollusc shells. Algae and protozoans are the sources of biogenous sediments. The biogenous sediments come from the tests of these one-celled organisms. They are living in the surface waters of the oceans. When these tests comprise greater than 30% of the particles then these particles are known as **ooze**. There are two types of oozes on the ocean floor are calcareous sediment and siliceous sediment. Oozes that are dominated by diatom or radiolarian tests are called siliceous oozes and calcareous sediment are produced from the tests of microscopic algae and protozoans.

Hydrogenous Deposits

Seawater contains many different types of dissolved substances. Sometimes, chemical reactions occur that cause these types of substances to precipitate out as solid particles, which accumulate as hydrogenous sediment. All these occur by the change in conditions such as a change in temperature, pressure or pH which reduces the amount of substance that can remain in a dissolved state. These kinds of sediment are normally found near hydrogenous vents. In these systems, seawater percolates into the seafloor where it becomes superheated by magma before being expelled by the vent. This water contains many dissolved substances and when it mixes with cold seawater after leaving the vent then these particles precipitate out mostly as metal sulfides. These particles make smoke that flows from the vent and eventually settle on the bottom as hydrogenous sediments.

Cosmogenous Sediments

Cosmogenous sediments are derived from extraterrestrial sources. These have mainly come in two primary forms - microscopic spherules and larger meteor debris. Spherules mostly consist of silica or iron and nickel and are thought to be ejected as meteors burn up after entering the atmosphere. Meteors come from the collision of meteorites with the earth. These types of collisions have a great impact on the earth's atmosphere that eventually settle back down to earth and contribute to the sediments. Meteor debris consists of mainly silica and nickel. One of the main forms of this debris from collisions are tektites which are small droplets of glass. They are composed of terrestrial silica that was ejected and melted during a meteorite impact. It forms solid after it becomes cool upon returning to the surface. Cosmogenous sediments are fairly rare in the ocean and it does not usually accumulate in large deposits. It comes from space dust which is present in the atmosphere which is continuously raining down on the earth.

Marine Soil

Soil deposits on ocean beds are known as marine soils. Though oceans are very violent the seabeds are very calm for the most part. A very small particle would deposit on the seabeds. The texture and composition depend on the proximity to the land and biological matter. The ocean floor is composed of three different types of soil also known as pelagic sediments or marine sediments. The names of the soils are calcareous ooze, red clay, and siliceous ooze.

Calcareous Ooze

It is the most common soil of the three soils. It covers approximately 48% of the whole ocean floor. It consists of the shells of foraminifera, coccolithophores, and pteropods. They are the tiny organisms that are living in the ocean.

Red Clay

It is the second soil that is found in the ocean. It covers approximately 38% of the ocean floor. It is brown in color. It is made up of quartz, clay minerals, and micrometeorites which are rocks that weigh less than a gram and have fallen to earth from the outer surface.

2.7 FOOD AND MINERAL RESOURCES OF THE SEA

The oceans hold a veritable treasure trove of valuable resources. Sand and gravel, oil and gas have been extracted from the sea for many years. In addition, minerals transported by erosion from the continents to the coastal areas are mined from the shallow shelf and beach areas.

These include diamonds off the coasts of South Africa and Namibia as well as deposits of tin, titanium and gold along the shores of Africa, Asia and South America.

Efforts to expand ocean mining into deep-sea waters have recently begun. The major focus is on manganese nodules, which are usually located at depths below 4000 metres, gas hydrates (located between 350 and 5000 metres), and cobalt crusts along the flanks of undersea mountain ranges (between 1000 and 3000 metres), as well as massive sulphides and the sulphide muds that form in areas of volcanic activity near the plate boundaries, at depths of 500 to 4000 metres.

Back in the early 1980s there was great commercial interest in manganese nodules and cobalt crusts. This initial euphoria over marine mining led to the International Seabed Authority (ISA) being established in Jamaica, and the United Nations Convention on the Law of the Sea (UNCLOS) being signed in 1982 – the "constitution for the seas". Since entering into force in 1994, this major convention has formed the basis for signatories' legal rights to use the marine resources on the sea floor outside national territorial waters.

After that, however, the industrial countries lost interest in resources. For one thing, prices dropped – making it no longer profitable to retrieve the accretions from the deep sea and utilize the metals they contained. Also, new onshore deposits were discovered, which were cheaper to exploit. The present resurgence of interest is due to the sharp increase in resource prices and attendant rise in profitability of the exploration business, and in particular to strong economic growth in countries like China and India which purchase large quantities of metal on world markets.

Even the latest economic crisis is not expected to slow this trend for long. The industrial and emerging countries' geopolitical interests in safeguarding their supplies of resources also play a role. In light of the increasing demand for resources, those countries which have no reserves of their own are seeking to assert extraterritorial claims in the oceans.

Manganese nodules

Covering huge areas of the deep sea with masses of up to 75 kilograms per square metre, manganese nodules are lumps of minerals ranging in size from a potato to a head of lettuce. They are composed mainly of manganese, iron, silicates and hydroxides, and they grow around a crystalline nucleus at a rate of only about one to 3 millimetres per million years. The chemical elements are precipitated from seawater or originate in the pore waters of the underlying sediments. The greatest densities of nodules occur off the west coast of Mexico (in the Clarion-Clipperton Zone), in the Peru Basin, and the Indian Ocean.

In the Clarion-Clipperton Zone the manganese nodules lie on the deep-sea sediments covering an area of at least 9 million square kilometres – an area the size of Europe. Their concentration in this area can probably be attributed to an increased input of manganese-rich minerals through the sediments released from the interior of the Earth at the East Pacific Rise by hydrothermal activity – that is, released from within the Earth by warm-water seeps on the sea floor and distributed over a large area by deep ocean currents.

2.8 SAMPLE QUESTIONS

Q.1. Fill in the following and complete the sentence.

1. ___________may be defined as any persistent and dominantly horizontal flow of ocean water. (Ocean currents)

2. The ocean currents at or near the ocean surface are driven by wind forces. The process is called____________. (Thermohaline Circulation)

3. North Equatorial Current flows between the latitudes of ____________degrees north. (10 degrees and 20)

4. ______________currents is in fact is the extension of north Equatorial Current. (Kurioshio)

5. The Winter Monsoon Drift, South Monsoon Drift are important ocean currents in_________________. (North Indian Oceans)

6. South Equatorial Current, Madagascar current, Mozambique current are dominant in_____________. (South Indian Ocean)

7. The distance between a wave's crest and trough is called ________of the wave. (Height)

8. The first recorded tsunami occurred off the coast of _____________in 2000 B.C. (Syria)

9. ___________ refer to as' any of the cyclic deformations of one astronomical body caused by the gravitational forces exerted by others'. (Tide)

10. Marine sediments deposited near continents cover approximately _______ percent of the seafloor.(25)

12. --------------sediments are sediments that are made from the skeletal remains of living organisms.(Biogenous)

Q. 2. Identify and tick the correct type of ocean currents.

Current	Warm Currents	Cold Currents
Antilles Current		
Benguela Current		
North Atlantic Current		
South Atlantic Current		
Agulhas Current		
West Australian Current		
Kamchatka Current		
Kuroshio Current		

Q. 3. Write Short notes on:

1. Characteristics of oceanic waves
2. Causes of tsunami
3. Types of ocean sediments
4. Types of tides
5. Ocean currents in Indian Ocean

Q. 4. Answer the following.

1. What do you mean by ocean currents how are they formed?
2. Explain causes and effects of tsunami.
3. Elaborate equilibrium theory of tides.
4. Write a note on ocean sediments.
5. Discuss mineral deposits found in the ocean.

❖❖❖❖

3

OCEANOGRAPHY AND HYDROLOGY

Unit Structure

3.1 OBJECTIVES

a. To provide the students with conceptual clarity about Hydrology, water cycle, water budget and water resources. This in turn will help them understand the various components of the hydrological cycle and how these components interact with each other to maintain an equilibrium on earth. These components and their interaction is a continuous cyclic process, commonly experienced by humans on a regular basis. The idea is to explain the mechanism behind the occurrence of such interactions between the atmosphere, land and underground water, so as to be able to relate to their occurrence.

b. To familiarize the students with the important aspects of the patterns of movement of water through the water cycle and the factors that influence this movement. All the components are sub-divided into 3 discrete compartments and all the three are very much related and dependent on one another to the extent that without the existence of any one of them the water cycle wouldn't be possible.

c. To acquaint the students with the diverse water resources present on the surface of the Earth in the form of saline as well as fresh water resources. The importance of these sources of water is further emphasized and elaborated for the convenience of the students and to generate better understanding. Moreover, the crucial concept of water budget is also presented herein.

3.2 INTRODUCTION

Water, by large is considered to be the lifeline that supports all forms of life on Earth, be it those creatures that live in water or those that survive on land, all biota is hugely dependent on water. Therefore, the vitality and resourcefulness of water can under no circumstance be undermined. Water is of two types- saline and fresh. The latter is of a higher significance in terms of human survival. The information presented here, highlights the occurrence of water in various forms (solid, liquid and vapor). It is rather necessary that water exists in these forms so as to keep the water cycle in motion. The water budget talks about the mechanism through which the Earth maintains and balances the available water on the continents and in the oceans. The patterns of movement adopted by water and the factors responsible for its movement through the atmosphere, land and underground aquifers help in generating a clear understanding about the role played by nature to present water in the usable and non-usable forms as well as the hindrances created though human intervention in the existing phenomena, in the mind of the readers. Knowledge about the global water supply and the existing fresh and salty water resources present on earth can be extracted from the information presented in the following pages.

3.3 THE HYDROLOGICAL CYCLE (Water Cycle)

The term Hydrology refers to the science or study of the water resources, inclusive of both fresh and saline water that exist on the planet Earth. Hydrology also encompasses the mode of occurrence, distribution/ movement and pattern of circulation of water in solid, liquid or gaseous state. Water that falls as precipitation, flows as surface water, is stored as ground water or hangs between the earth and its atmosphere as vapor all forms the content for the study of hydrology. This science has an inter-disciplinary nature and draws its matter from several disciplines like; physics, chemistry, geology, meteorology, statistics etc.

3.3.1 Hydrological Cycle or Water Cycle:

Water on Earth is constantly moving, changing state (from liquid, to gas, to solid) and being recycled. The water cycle describes this journey. There are 4 main stages in the water cycle: evaporation, condensation, precipitation and collection.

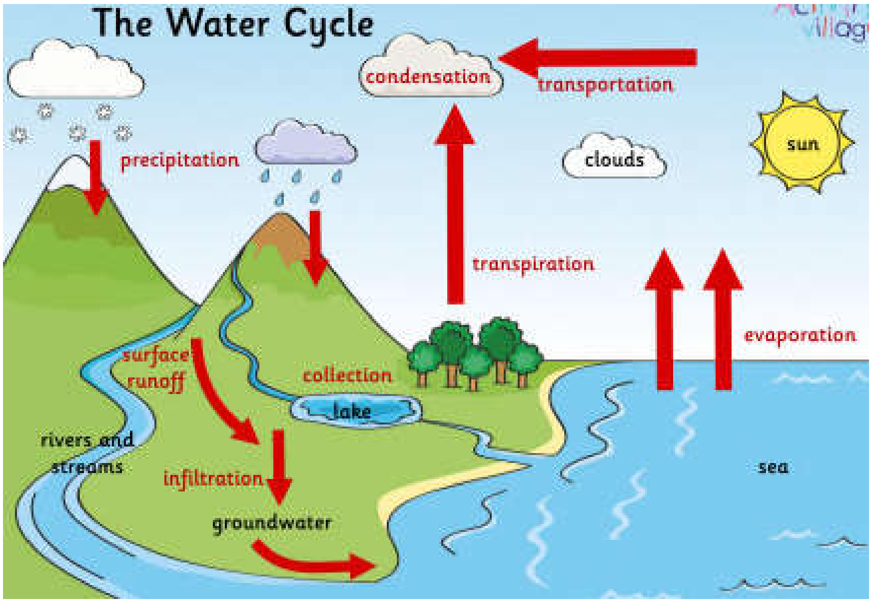


Fig. 3.3.1: Hydrological Cycle

Source: activityvillage.co.uk

Evaporation: When the sun heats the surface of Oceans, seas, lakes, rivers and ponds, some of the water changes state and becomes gaseous (water vapor), and mixes with the atmospheric air. Warm air has a tendency to rise upward and so the water vapor present in it rises too.

Condensation: When the air cools down after reaching a particular height, the vapor condenses back into water droplets. These water droplets collect together (coalesce) and form clouds.

Precipitation: The water droplets in clouds attract other water droplets towards them and they grow bigger. When they get too big and heavy they fall to the ground as rain. If the air is cold enough, the droplets remain frozen and then fall as snow or hail. Though maximum precipitation occurs over the oceans and seas but a small percentage of clouds are driven towards the land areas by the prevailing winds and the clouds heavy with moisture, cause precipitation in the form of rain, drizzle, snow, sleet or hail depending upon the existing temperature conditions of that region. This water coming from precipitation, is subsequently returned to the water bodies from where evaporation took place. It should be understood that the entire precipitation does not enter the surface water bodies but is deflected to different places i.e. a part of the water simultaneously evaporates while falling to the ground, a part of it is intercepted by the canopy of the vegetation, buildings, drains and sewers, a part of it falls in the farmlands, cultivable lands and increases the soil moisture and a portion of it even percolates through the soil and various layers of rocks to form the ground water and the water falling on metaled surfaces many a times does not reach the streams as stream flow but acts as surface runoff.

Collection: When the water falls on Earth it collects in the streams, reservoirs or lakes and even flows with the rivers. When it falls on land, some of it filters into the Earth and becomes groundwater or it can flow over the land as run off into the drains and may join the existing bodies of water like streams, rivers, lakes.

Some of the water may be taken up by plants and animals. Plants take up water from the soil through their roots. They then 'breathe' the moisture out of their leaves into the air through the process of transpiration. Evaporation accounts for about 90% of the water in the air while transpiration accounts for the remaining 10%. This cycle is continuous and constant (does not change).

This is a very simplistic and logical explanation of the water cycle. This cycle has been in existence since the very beginning i.e. since the formation of the Earth and its processes. It is continuous and never ending in nature but at the same time it is complex as well, since it involves various paths, time scales and change in gaseous, liquid or solid state. Also, no starting stages, end stages or pauses have ever been identified in this cycle and it is complete in all respects. If there is any human intervention at any given stage of the water cycle in the form of suppression of evaporation, modification in land-use and land cover, inducing artificial rain or over-exploitation of the ground water resource, the results and consequences shall be unprecedented and shall have disastrous repercussions in some other stage of the cycle, which in turn shall prove to be harmful for all forms of life existing on Earth.

The hydrological cycle not only exercises a significant control over the life forms, geography, economics, politics, sociology and engineering of any given place or region but also affects several individual departments functioning in a country, namely; activities pertaining to inland and marine navigation carried out by the navy and for coastal regulation, for forestry and allied undertakings, for irrigation and drainage, for water and power supply, for flood and salinity control, for recreation involving water sports etc.

3.4 MOVEMENT OF WATER

3.4.1 Patterns of Movement and Storage of Water:

Nature has its own unique design of storing and recycling fresh water in order to satisfy the needs and demands of all living organisms, because water serves as an essential commodity that is responsible for sustaining life on this planet. For this reason, nature has organized the creation of three major segments, namely; the '*surface of the Earth'* (land), *'sub-surface'* (underground) *and* the *'atmosphere'*. These facilitate the storage of water in the form of reservoir as well as movement of water in an orderly fashion and a set pattern, i.e. there is a specific *point of entry* into a given segment, be it land, atmosphere or subsurface, and there is also an *exit point* from that segment. Water follows the entry and exit points and in this manner the water budget is formed. This budget can be accounted for and calculated if, the entry and exit points are known and the amount of water entering through these points is recorded. In this manner, the relationship between the inflow and outflow and demand and supply of water can be properly established.

It should be noted: for the calculation of the water budget, the person in-charge of calculation may consider just one part from either of the 3 given segments like; a lake may be considered from the land segment. Or may consider all the three segments together e.g. an entire watershed, because it contains the components of all the segments. A description of the water present in the 3 segments is presented here.

a) ***Atmospheric Water***- water that exists in vapor form in the atmosphere, is referred to as 'atmospheric water'. This vaporization of water is due to the continuous evaporation process that takes place from the ground/soil, from vegetation (through transpiration) as well as from the water bodies, present on Earth (both oceanic and inland). This happens due to the impact of the solar radiation reaching the Earth. The evaporated water moves with the upward rising air to enter the lower layers of the atmosphere.

Note that: At any given time, the atmosphere can hold a very small amount of evaporated water. If collected together, this vapor is capable of forming a very thin layer barely 25 mm in thickness. This water vapor after reaching a given height, begins to cool down and the process of condensation begins. This leads to the release of latent heat from the vapor and it either converts to raindrops or ice crystals depending upon the altitude at which condensation occurs. This condensed water then falls as precipitation on Earth and is returned to the water bodies, soil surfaces, and sub-surface, through stream-flow and percolation of rain water downwards through the soil, respectively.

It should be clearly understood that, the water contained in the atmosphere, is a part and parcel of the hydrological cycle. In the absence of this cycle, the atmosphere would have remained devoid of water content. Moreover, the atmosphere acts as a brilliant transporter of water over several hundred kilometers, because of its water distribution tendency, wherein, it carries water from surplus areas (oceans and seas) to supply it to deficit areas (land surfaces).

Vaporized water helps in *maintaining the energy balance of the Earth and in regulating the temperature*. This happens because during the process of condensation -latent heat is released, cloud formation takes place and clouds are responsible for absorbing huge proportions of the incoming solar radiation. Besides, a higher percentage of vapor content present in the atmosphere, increases the humidity but decreases the heat by absorbing it. This greatly reduces the surface temperatures.

Movement of water in the atmosphere occurs in 2 ways. Firstly, through convection currents and secondly, through molecular diffusion method (this is the tendency of water vapor to travel from areas of high vapor concentration to low vapor density areas).

b) ***Land Surface Water***: Water on the surface of the Earth is usually in the form of fresh water. This flows on land as rivers, streams etc. or is found in a stagnant form in ponds, lakes, reservoirs and wetlands. It flows as underground (sub-surface) water after infiltrating through the pores of the soil. It is received from the clouds as precipitation. Most commonly, precipitation occurs in two forms, namely; Rainfall and Snowfall (though there are several forms of rain and snow that can be experienced on the Earth). Places having very low temperature, experience snowfall (because water vapor directly condenses into ice particles instead of rain drops) and those having high temperatures experience rainfall. Most of the fresh water present on Earth occurs as ice and snow, which is locked in the ice-caps, in glaciers and especially in Greenland and in the continent of Antarctica. Although the irony is that, these places are largely inaccessible and the fresh water trapped here is unavailable for human consumption, given their location, in the polar areas. But the nature's generosity is such that, the snow of the mid-latitude regions can be easily accessed and used by man for his various needs and requirements.

Note that: Glaciers, snow-fields and ice caps can typically be called as 'water suppliers' due to their ability to store tons and gallons of water, as snow, for very long time spans ranging from decades to even centuries. The melting of snow causes the water to change its state from solid to liquid which makes its utilization and consumption much easier. The glaciers and snow-packs are dependent on the atmospheric water (which condenses and falls as snow) since, this water is their actual source of water supply. The methodology employed by the researchers to measure the amount of water contained in a snow-pack involves snow surveys. This is done by digging a pit in certain demarcated areas that receive heavy snowfall and then, determining its depth as well as water content and chemistry. In the present times, due to advancement of technology, detailed snow surveys can be conducted using satellite and aircraft remote sensing techniques which also enable the construction of digital elevation models (DEMs).

I. **Lakes:** these are another prominent fresh water storage agencies on land. These contribute to the global water budget by acting as the 4^{th} largest store-house of water (both fresh and saline). Lakes can be termed as large or small, depending upon their volume, extent or location.

There are three important sources that supply water to lakes, namely; stream water inflow, ground water inflow and atmospheric (through precipitation) water inflow. It is possible that a lake may receive water through either of the three sources or all of these sources. Similarly, lakes even lose water. This also happens through three mediums, i.e. through evaporation, outflow of streams and sub-surface penetration of water. Some lakes are called *Terminal Lakes*, because they receive water from all the given three sources of water but lose water only through the process of evaporation. Lakes that are situated at high elevations, generally have just a single source of water supply i.e. precipitation, whereas the other two sources of water supply are absent here.

The span of time for which a specific quantity of water shall remain in the lake is called its residence time. This keeps varying from time to time and is different for large and small lakes. The residence time of very large lakes will be excessively large, i.e. 200 years or more. Whereas, the residence time of smaller lakes may range between 2-5 years. In case of glacial lakes it may stretch upto a decade or more. Whereas, very small lakes may have a residence time ranging from a few days to a few weeks.

II. **Wetlands**: these are similar to lakes in several ways, i.e. both contain standing water and the water loss and gain mechanisms for both is very much alike. Moreover, water stored in the wetland depressions gives the appearance of a lake. The most conspicuous difference lies in the fact that outflow of water from these areas is mostly in the form of transpiration from vegetation rather than by evaporation (as experienced by lakes). Secondly, the water in the wetlands is generally stored in their soils, unlike the lakes. In general, wetlands are places which, for a major part of the year, contain water saturated soils. This has a huge influence on the manner in which the soil development takes place as well as the flora and fauna inhabiting that area/wetland. There are certain types of wetlands which do not receive a continuous inflow of water from different sources throughout the year. Moreover, the presence of standing water is not a usual phenomenon, instead, water inflow occurs only for a given period of time or a part of the year. Such wetlands have one governing factor that remains constant i.e. 'saturation of the soil' meaning- 'soil remains covered with ample amount of moisture throughout the year'. The wetlands play a vital role in the hydrological cycle by majorly contributing to it. This takes place through constant exchanges, movement and storage of water (in its various forms), between the atmosphere, land surface and the sub-surface.

III. **Streams:** These hold a very small percentage of the total water content present as fresh water on the surface of the Earth. A very prominent feature displayed by streams is that they always begin their journey from places at higher elevations and end up in the plains. This journey of the streams can be divided into 3 discrete stages, namely; youthful stage, mature stage and senile (old) stage. They vary in size as well as the volume of water carried and area drained by them, ranging from small rivulets to huge perennial or seasonal rivers (area may vary from a few kilometers to thousands of kilometers and some of them even flow across international borders). Many streams, called as rivers, are even older than the early human civilizations and such major rivers after draining an extensive drainage basin eventually fall into the sea, E.g. Nile, Mississippi, Amazon, Indus, and Brahmaputra. Their main task is to transport water from their source to their mouth and thus, they cannot be considered as reservoirs or agencies of water storage. These may be interrupted at various places by natural or man-made features, which leads to changes in their natural courses or flow regimes. The flow velocity (speed) of streams is also quite variable i.e. ranging between 30 cm/second to 300 cm/second. Streams are not only an essential source of fresh water, but also act as facilitators in the water cycle by promoting evaporation and increasing the vapor content in the atmosphere which ultimately results in precipitation and filling of water bodies and by acting as an agent of exchange between the water present on land surface (including rainfall runoff) and under the surface (interflow/ discharge). During the wet months or late spring when the snow-melt begins, both, their flow velocity as well as discharge increases manifold. Large streams are less dynamic as compared to small streams- which display a sharp and rapid reaction to storm events.

c) ***Underground Water***: This flows in the sub-surface and forms the water table. The water received through precipitation and that which seeps into the ground passing through the different layers of the soil, ultimately ends up as ground water which is generally found stored in the crevices, open spaces or between two layers of the rocks found underneath the soft, porous and permeable soil. Several rock particles, minerals, gases, organic matter, solid rocks, water etc. collectively form the subsurface. The water present here is majorly in the storage form since it acts as a reservoir. Transportation of water takes place but to a limited extent. Underground water has a noticeable function of maintaining and regulating the water cycle like the other two segments discussed above. The rain water and surface runoff penetrates into the soil and moves downwards. Underground water can even be seen flowing on the surface after an outflow (as seen in karst topography), during human extraction or during instances when water escapes through openings in the surface e.g. hot springs.

Note that: More than 95 per cent of the global fresh water is stored in the underground aquifers as ground water. But due to excessive extraction and restricted recharge, the subsurface water has begun to show signs of depletion. This can be experienced whenever the need to dig deeper to obtain water, arises and during instances of land subsidence.

The sub-surface has 2 distinct zones, namely, saturated zone and the unsaturated zone. The former zone has pores and voids among the Earth materials which are completely full of water. This zone is located below the unsaturated zone and acts as a storehouse holding the largest amount of consumable freshwater. The water table lies just above this zone. Saline water can be found below it. Water table is said to be recharged when water from the unsaturated zone moves downward. In some regions, human extraction of ground water for domestic, agricultural, and industrial uses constitutes the major portion of outflow of underground water.

Whereas, the latter (unsaturated zone) is characterized by the presence of both air and water in the open spaces between the Earth materials located beneath the ground. This means that the pores and crevices are partially filled with air and partially with water. This zone may vary from 0-1000 m in thickness and thicker unsaturated zones are generally found in arid areas. Moreover, this zone makes water available for the plants and vegetation to grow and flourish, because, water here percolates very gradually allowing more water for a longer time for plants.

According to Healy, R.W., et al. (2007), out of the precipitation that falls on Earth, the amount of water that finds its way into the soil and downward into the subsurface, is around 76 per cent. 85 percent i.e. majority of water that percolates downwards, is returned to the atmosphere either through evaporation from the soil or through evapotranspiration through the flora.

Soils are capable of holding and retaining moisture in them. Different types of soils have varying capacities to hold moisture. Moisture obtained from rainfall, runoff or flow of the rivers, is retained in the upper layers of the soil and the excess water slowly moves downwards through the pores (open spaces) of the soil. Also, the water retained in the pores starts downward movement over a period of time or with addition of more water. This is known as the porosity of the soil. In other words, it refers to the presence of open spaces in between the soil particles. Certain soils are more porous as compared to the others. E.g. Sandy gravel soils and, loamy, clayey soils- are most porous whereas, limestone soil and silt are the least porous. Those soils containing more or less equal sized particles and sticky materials, have lower porosity and vice-versa.

In addition to porosity, permeability of the soil also plays a key role. This means- the rate at which water infiltrates downward to reach the water table is known as permeability. Particle size, water impurities, void ratio, the degree of saturation, trapped air and organic material all these greatly influence the soil permeability. To better understand the concept of permeability, the example of a pebble and a sponge can be assumed. On pouring water over a pebble, it is observed that the water flows without being absorbed. The pebble is incapable of retaining water whereas, if the same water is poured over a sponge, it retains the water. In doing so, the water is allowed to move down, towards the base of the sponge. Similarly, certain types of soils respond better to permeability than the others. These include- clayey soils and silt- these impede the flow of water downward. On the other hand, both sand and gravel are highly porous as well as permeable, thus, these act as excellent aquifer materials. Sandstone and limestone are also highly permeable.

The ground water is recharged and lost annually through several processes. The recharge processes are listed below.

- Recharge through precipitation i.e. rain water infiltration.
- Seepage of canal water downward through the soil.
- Percolation of water downwards from the irrigated fields and cultivable lands.
- Water seepage form overlying streams.

- Recharge through lakes, reservoirs, tanks etc.
- Artificial recharge schemes.

Following are the water loss mechanisms operating underground.

- Through outflow of subsurface water into the rivers or streams
- Through the process of transpiration from all flora.
- Evaporation processes.
- Extraction of water for domestic, industrial and agricultural activities.

***Note*:** The water that is available for consumption marks the difference between the annual recharge of ground water and the annual loss.

3.4.2 Factors Affecting Movement of Water:

As discussed earlier, water is in constant motion throughout this planet, via the water cycle- a perfect arrangement of nature, which facilitates and makes the existence of various life forms possible on Earth. This cycle ceaselessly operates day and night, thus continuously recycling the water between its three forms- solid, liquid and vapor. This movement entails the exchanges that take place between the three segments of water i.e. atmosphere, land and subsurface. The water that evaporates from the soil, vegetation, oceans and other inland water bodies, is returned to them, through precipitation, runoff, ground water inflow (from rivers, soil seepage, lakes, wetlands etc.) and ground water outflow (from springs, openings, evapotranspiration, extraction of ground water) and surface water inflow and outflow. In this way water completes the entire cycle of vaporization, condensation, storage and transportation through the surface and sub-surface medium. Numerous factors influence the movement and exchange of water on Earth. These are discussed below.

a) ***Climate/Precipitation*:** The climate and especially the degree of dryness or wetness of a region hugely impacts the movement of water in different forms, on Earth. This refers to the rate of precipitation (i.e. high, moderate or low) occurring in that region. But precipitation levels always vary with varying seasons. Heavy and frequent spells of downpour signifies abundance of water in all the 3 segments (air, land and underground). There is more water for transportation, storage and infiltration through soil. More the humidity, more will be the rate of condensation, resulting in precipitation. Higher precipitation levels result in larger streamflow, quicker rate of ground water recharge, more runoff, and more water reaching the sea. Thus, the climate and precipitation patterns of a place significantly influence the movement of water in the cycle by increasing or restricting its flow. The rivers carry abundant water during and after the rainy spells as compared to the rest of the year. In places which receive less or inconsistent amount of rain, the rivers show signs of intermittent flow regimens and the flow is generally restricted to the surface level only (not very deep), leaving the area dry. Even the ground water is found at greater depths than normal and there is little scope for ground water outflows into the rivers, lakes, ponds and wetlands. The sources of water storage tend to deplete over time due to insufficient precipitation.

***Note*:** Rivers only become perennial when the 'source of water' is consistent in supplying it. E.g. Snowmelt, enough access to ground water and longer rainy seasons or frequent precipitation.

b) ***Infiltration and runoff*:** Infiltration refers to the process of seepage of the precipitation water into the soil. This water travels downwards through the various layers to reach the water table. It is directly proportional to the type of soil in a given region because certain soils allow quicker infiltration as compared to the others. Moreover, if the precipitation is less than the capacity of the soil to hold, then almost all of the precipitation water will easily percolate downwards. The water runs off if, this capacity is exceeded. Runoff refers to the precipitation water that simply flows over the land surface. When the precipitation is more than the capacity of the soil to absorb it and allow further infiltration, then the excess water is called runoff. It usually does not necessarily become a part of the sub-surface. This water finally empties into the drains, or joins the small or major rivers as a minor streamflow in large open spaces in a watershed. It has an important role to play in the water cycle. In other words, infiltrated water becomes a part of ground water whereas, runoff water forms the surface flow. The combination of these two processes affect the manner in which water falling as precipitation, interacts with the surface and the sub-surface. Water stored in the surface water bodies (except glaciers and ice fields) is subjected to many changes in volume, over time. These changes also become predominant with the increase or reduction in the vegetation cover since, precipitation intercepted by vegetation also constitutes surface storage and it also affects the amount of water that infiltrates through the soil.

***Note*:** In hydrological studies, many scientists use the sum of infiltrated water and runoff water in order to calculate the total amount of precipitation that has occurred in a given place. In addition to this, there are certain elements like weather conditions, soil, land use, slope and depth of water table that greatly influence the rate of infiltration and runoff.

c) ***Evapotranspiration*:** When liquid or solid water converts into its gaseous state i.e. vapor, by absorbing latent heat, then that process is called as evapotranspiration. It is a combination of two words- evaporation and transpiration. This occurs in two ways during the day time, firstly, when the water evaporates from the soil, or from marine and fresh water bodies and moves upwards into the atmosphere (i.e. evaporation) and secondly when the excess or residual water evaporates from the surface of the leaves of vegetation (i.e. Transpiration) For the purpose of easing out the measuring process, both these terms are combined to form a single term- 'Evapotranspiration'. This process holds a vital place among the water budget components and accounts for 65 per cent of the total precipitation that falls on the global landmasses. Water and energy are the two major factors that hugely affect evapotranspiration. In simple terms it can be understood as- for the process of evapotranspiration to take place, it requires the availability of water in sufficient quantities as well as the availability of solar energy to cause the heating of water and start its conversion into water vapor. In dry regions, less availability of water and in cold areas less availability of energy pose a limitation on the process of evapotranspiration. Its rates are almost nil during the night time and maximum during the hours of highest solar radiation.

Note**:** It is important to know the difference between evapotranspiration and potential evapotranspiration. The latter is defined as an estimate which is calculated during times when, the water is plentiful. It gives us an idea of the amount of water that may evaporate from the vegetation, soil and water bodies in the presence of solar energy. Potential evapotranspiration rates are usually required when irrigation systems have to be planned, managed and monitored.

d) ***Flow Velocity*****:** When we talk about a river, we know that it is in constant motion. It starts moving from a given source and keeps flowing till it reaches its destination also called its mouth. During its flow, the river attains velocity, meaning the speed at which water in that river flows (flow velocity). This velocity keeps changing with the changes in its stages and the places over which it flows. It is rather important to understand that the velocity of a river directly depends upon 2 key factors. These include- Gravity and Friction. Gravity influences the speed of the river by employing the downward pull. E.g. river flows at a greater speed when moving down a slope and its speed increases with the increase in the gradient of the slope. On the contrary, its speed reduces significantly when it flows over a flat surface. As far as friction is concerned, it acts to reduce the velocity of the river by offering resistance. This resistance can be in the form of rocks, boulders, sand, silt or barriers to the flow. Most often it is observed that, there is least friction in the centre-most portion (below the surface) of the river, thus, it has the maximum flow velocity here. Whereas, the velocity becomes minimum at the banks of the river due the presence of hindrances. For this reason, those rivers which have a high flow velocity, tend to cut the riverbed more deeply and those with a low flow velocity, tend to bend and meander.

e) ***Human intervention*****:** this can be explained in the context of the everyday activities carried out by humans, merely due to their existence on Earth. These can be as miniscule (tiny) as cleaning the house, watering the garden or having a bath and as huge as performing construction activities (e.g. Dams), irrigating the fields or using water in industries. In all these situations we are borrowing water from the nature and in turn altering the water cycle. This means that the human beings act as a factor that influences the movement and exchange of water on Earth. There are three interrelated groups into which human intervention can be categorized, namely; water storage and conveyance structures, patterns of land-use and methods and quantity of ground water extraction. These 3 groups affect the entry and exit points and the flow rates of water. They also act as a medium for redistributing water within the 3 segments of the Earth (i.e. surface, sub-surface and atmosphere). It should be noted that changes in the water cycle gives birth to changes in the natural habitats giving rise to a few new and depleting a few old habitats. The following sub-heads shall further elaborate the concept of human intervention.

i. ***Water Storage and Conveyance Structures*****-** we should first know and understand the meaning of Water Conveyance Structures. These structures refer to such constructions which facilitate the storage, impoundment, transmission and diversion of water. These may include several man-made features, namely; reservoirs, dams, tanks, canals, pipelines, tunnels, ditches, aqueducts etc. or these can even be natural in origin, like; gullies, ravines, deep valleys, natural tunnels etc. these surface reservoirs are extremely beneficial and serve many purposes to facilitate several human activities. These include- provisioning of sufficient water supply for agricultural, industrial and domestic purposes, recreation, generation of electricity, altering of stream temperature, reducing events of flooding, giving rise to new ecosystems and fish habitats, accelerating the rate of evaporation and the rate of flow of surface water to the sub-surface. The manually constructed network of pipelines, canals, reservoirs etc. serve as important agents of transportation that carry water between various watersheds. These act as a valuable component of the water budget since they provide ample scope for the exchange of water between the land, atmosphere and the sub-surface.

ii. ***Land Use*****-** this term can be defined as- the methods in which 'land is used by different individuals with varying needs and in turn they draw benefit from it. Several activities and practices are carried out on the land surface depending upon the suitability of that portion of land for carrying out any particular activity. There are innumerable services that are provided by land to suit the interests or meet the needs of mankind, e.g. land can be used for agriculture, horticulture, developing public facilities, construction of buildings, residences, offices, shopping complexes, roads, railway lines, airports, harbors, warehouses, industries, godown, government buildings, silos etc. In other words, it can be said that, the manner in which man uses the surface of the Earth, to satisfy his requirements is known as land-use. The practice of subjecting the land surface to varying activities, goes a long way in altering the water cycle because it influences the exchange of water between the atmosphere and the Earth. It is worth mentioning here that, the 'land cover' which exists on the Earth in the form of hills, mountains, forests, grasslands, scrublands and wetlands are subjected to conversion activities in order to make room for agriculture and allied activities as well as secondary and tertiary services. This continuous conversion of land cover into land-use, prepares sufficient ground for the alteration of the water budget and hydrological cycle.

The reason behind this kind of a change is that- native forests, wetlands or grasslands have different rates of transpiration, evaporation, infiltration, and water-table recharge rate. These rates are completely dissimilar from those of the cultivable-agricultural lands or concrete lands into which these are converted. Clearing of the rainforests reduces the rate of evapotranspiration from these areas. On the other hand, irrigation of the farmlands increases the same in those portions of the Earth. Similarly, urbanization majorly changes the land's capacity to absorb water, since, water cannot infiltrate downwards through the impermeable surfaces, thus leading to runoff. This runoff needs to be properly channelized through the network of drains into the rivers or streams but in some cases if the runoff due to rainfall is too much then, it can lead to flooding of the rivers.

iii. *Ground Water Abstraction*- this is also known as the process of drawing of ground water from places in which it is available or the extraction of the ground water. This method of obtaining water is more than 200 years old and mankind has been extracting the ground water to satisfy innumerable needs. The underground water is stored in aquifers and can be drawn as per need, i.e. for irrigation, for domestic purposes in rural as well as urban areas and for industrial purposes. Whenever groundwater is extracted, it leads to a reduction in the level of water in that area. This reduction can be higher or lower than the recharge rate of water depending upon the precipitation pattern existing there. It is rather easier to monitor or measure the level of stored water as compared to the rate of extraction, discharge or recharge. This in turn leads to diminished rates of out flow of ground water towards the wetlands/rivers and they slowly dry up. This drying up, further has a negative impact on the riparian vegetation which shows signs of damage/loss. On the contrary, in some cases it is also seen that the water extracted from the ground for irrigation is returned to the atmosphere through evapotranspiration. It may even travel to the sub-surface again through the process of infiltration into the soil or may flow towards the wetlands or streams and become a part of the surface water. Thus in this manner the water cycle is maintained. Water abstracted for domestic purposes is returned to the ground through leakage in septic tanks or is left to join the surface water bodies through water disposed from waste water treatment plants.

3.5 WATER BUDGET

Water budgets provide a means for evaluating availability and sustainability of water supply. A water budget simply states that the rate of change in water stored in an area, such as a watershed, is balanced by the rate at which water flows into and out of the area. An understanding of water budgets and underlying hydrologic processes provides a foundation for effective water-resource and environmental planning and management. Observed changes in water budgets of an area over time can be used to assess the effects of climate variability and human activities on water resources (Healy. R, et al., 2007).

Certain scholars have defined the water budget by stating that this budget is the means through which the difference between the flow rate of water inside and outside of an '*accounting unit*' can be balanced by understanding the rate at which changes occur in the water storage. An accounting unit of the water budget can be in the form of an agricultural field, a watershed, a reservoir, or an underground aquifer. This can be better understood with the help of an equation; *In flow of water - Out flow of water = Change in water Storage.*

It is important to note that, water budget depends on water storage and movement processes, therefore, it is projected as simple and universally accepted.

Water budget studies carried out in different parts of the world hint towards the fact that, there is always a scope for assessing and comparing the effects and outcomes of different natural and man-made factors on water budgets. The natural factors can be in the form of geology, soils and vegetation which can alter the water cycle in many ways. Other methods of alterations include man-made changes in land-use like; clearing land for agriculture, carrying out construction activities, building dams on rivers, installing irrigation and drainage systems etc. all these hugely impact the water budget and water cycle. Water budgets provide a basis for assessing how a natural or human-induced change in one part of the hydrologic cycle may affect other aspects of the cycle.

Water Budget also referred to as the '*Water Balance'* is a means for calculating the quantity of water that enters into and exits from, the various components of the water cycle (I.e. land, sub-surface and the atmosphere) as mentioned in the preceding sections. A water budget assists us in studying and understanding the sources of water supply, the places where sources of water storage can be found and the quantity of water present in them.

While studying the Water budget, one is required to know the process of evapotranspiration and the working of the water cycle, along with the places (reservoirs) where water is stored on the ground and under the ground. The amount of water present in them, their movement patterns from discharge to recharge and the inter basin (import and export) transfers of water. This provides essential information about land's carrying capacity with regard to water resources. Table 3.5.1 depicts the global water supply and table 3.5.2 depicts the water budget for the global landmass.

Table 3.5.1: Estimated global water supply.

Water storage	Volume, in thousands of km^3	Percentage of total water
Ocean water	1,320,000	97.1
Atmosphere	13	0.001
Water in land areas	37,800	2.8
Freshwater lakes	125	0.009
Saline lakes and inland seas	104	0.008
Rivers	1.25	0.0001
Icecaps and glaciers	29,200	2.14
Soil root zone	67	0.005
Ground water (to depth of 4,000 meters)	8,350	0.61

Source: Healy. R, et al., 2007

Table 3.5.2: Water budget for global land mass.

Water-budget component	Annual rate, in milli-meters	Percentage of annual precipitation
Precipitation	834	100
Evapotranspiration	540	65
Total discharge to oceans	294	35
Discharge to oceans from surface runoff	204	24
Discharge to oceans from base flow	90	11
Infiltration of precipitation	630	76

Source: Richard W. Healy, 2007

(Note: Evapotranspiration is the sum of evaporation and plant transpiration.)

3.5.1 Water Budget Components:

The components of a water budget are quite similar to those of the water cycle. These can be understood from the following equation.

$P = I + ET + R$

Here, P means precipitation, I means infiltration, ET means evapo-transpiration, R means runoff.

Mathematically, the water budget can be expressed as follows:

$$P = RO + AET + I + D + A \pm \Delta I \pm \Delta s \pm \Delta g$$

Here, P means precipitation, RO means surface runoff, AET means actual evapo-transpiration, I means interflow, D means groundwater discharge, A means anthropogenic inputs (septic systems) and/or supplies/abstractions, ΔI means change in land surface storage, Δs means change in soil moisture storage, Δg means change in groundwater storage.

In those conditions where a natural watershed/basin is undisturbed for a long time (i.e. no human influence is there in terms of pumping or withdrawing water), the inputs and outputs of water are naturally balanced and there is zero change in the water storage. Although the moisture stored in the soil may vary on a day to day basis but the net change will remain negligible for the year as whole.

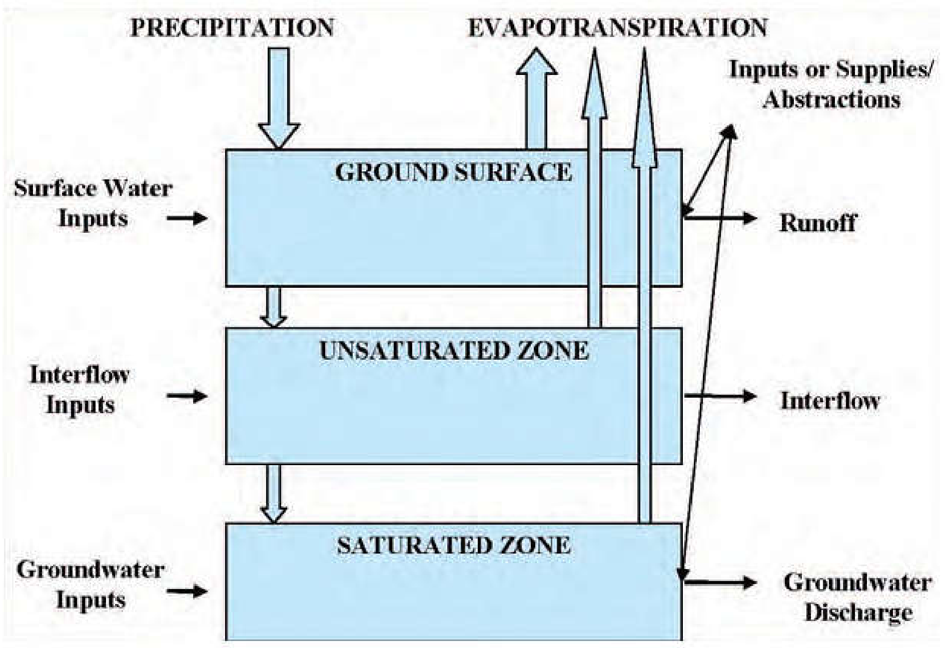


Fig. 3.5.1 Components of Water Budget

Source: ecoursesonline.iasri.res.in

3.5.2 World Water Balance:

All the water present on the Earth either in the form of fresh water or saline water is in a state of balance. This is nature's way of maintaining equilibrium on Earth, which is maintained through the hydrological cycle among different components where water is stored, recharged and discharged,through inflow and outflow mechanism. Water balance is dependant on three important components namely; evaporation (including transpiration), precipitation and runoff.

It varies over the landmasses and over the ocean bodies.

On Earth, the percentage of saline water is fixed, i.e. 97 per cent of all the water existing on earth in solid or liquid forms is salty (nearly 1386 million cubic kilometers) and the remaining 3 per cent of water is fresh or non saline. This means that we have just a small quantity of 35 million cubic kilometers of fresh water available. Out of this, 24.4 million cubic kilometers of water is fresh but is found in solid form (as ice fields in areas of perma –frost or polar areas and in glaciers and on mountain tops) which not readily usable and the rest i.e. 10.6 million cubic km of water is in liquid and usable form as rivers, streams, lakes, ponds or underground water.

It has been observed that the rate of evaporation on an yearly basis, taking place over the ocean surface comes out to be 0.505 million cubic km and *water received through precipitation by the ocean/seas is 9 per cent less than the water evaporated from them*. Similarly, water also evaporates from the inland water bodies or fresh water bodies and this evaporated water comes out to be 0.072 million cubic kilometers. The difference lies in the fact that water falling as precipitation on land areas is more in quantity as compared to the water that evaporates from here and thus land receives more atmospheric water in comparison to the ocean bodies even though more water evaporates from oceans/seas.

It is also observed that nearly 0.047 million cubic kilometers of water flows from the land areas as runoff. This runoff water may join the rivers/streams or it may enter the fields and be stored in the soil as soil moisture, or it may infiltrate into the soil and form ground water or may even join the sea. Note that, the amount of river water that is used for irrigational purposes is merely 4 per cent and the remaining water flows into the seas or oceans. The figures mentioned above are just estimated and approximate values and not exact values due to lack of enough and relaible data. They are subject to change over a period of time and vary among different studies.

The water balance of the continents and the oceans can be understood by carefully studying the following tables i.e. Table 3.5.3 and 3.5.4.

Table 3.5.3: Water balance of Continents (in sq. mm/year)

Continent	Area (M km^2)	Precipitation	Total runoff	Runoff as % of precipitation	Evaporation
Africa	30.3	686	139	20	547
Asia	45.0	726	293	40	433
Australia	8.7	736	226	30	510
Europe	9.8	734	319	43	415
N. America	20.7	670	287	43	383
S. America	17.8	1648	583	35	1065

Source: K. Subramanya, 2013

Table 3.5.4: Water balance of Oceans (in sq. mm/year)

Ocean	Area ($M\ km^2$)	Precipitation	Inflow from adjacent continents	Evaporation	Water exchange with other oceans
Atlantic	107	780	200	1040	−60
Arctic	12	240	230	120	350
Indian	75	1010	70	1380	−300
Pacific	167	1210	60	1140	130

Source: K. Subramanya, 2013

3.6 WATER RESOURCES

3.6.1 World Water Resources:

The world comprises of a huge quantity of water in the form of seas and oceans which enguf the continents and islands. This water although present in enormous proportion on the Earth's surface, but is unworthy of consumption/usage due to its saline nature. The water that eventually plays the role of satifying human needs is none other than fresh water. Humans with passage of time and development of technology have been able to convert some portion of the salty marine water into usable forms through reverse osmosis and allied processes. These are mainly in practice in the water deficient countries like UAE (Dubai). For developing a sound understanding of the water resources present around the world, the area occupied by them and the volume of water contained within them can be developed from table 3.6.1.

Table 3.6.1: Water Resources present in the world.

Item	Area ($M\ km^2$)	Volume ($M\ km^3$)	Percent total water	Percent fresh water
1. Oceans	361.3	1338.0	96.5	—
2. Groundwater				
(a) fresh	134.8	10.530	0.76	30.1
(b) saline	134.8	12.870	0.93	—
3. Soil moisture	82.0	0.0165	0.0012	0.05
4. Polar ice	16.0	24.0235	1.7	68.6
5. Other ice and snow	0.3	0.3406	0.025	1.0
6. Lakes				
(a) fresh	1.2	0.0910	0.007	0.26
(b) saline	0.8	0.0854	0.006	—
7. Marshes	2.7	0.01147	0.0008	0.03
8. Rivers	148.8	0.00212	0.0002	0.006
9. Biological water	510.0	0.00112	0.0001	0.003
10. Atmospheric water	510.0	0.01290	0.001	0.04
Total: (a) All kinds of water	510.0	1386.0	100.0	
(b) Fresh water	148.8	35.0	2.5	100.0

Source: K. Subramanya, 2013

(Note: $M\ km^3$ means- Million cubic kilometers)

3.6.2 Global Fresh Water Resources:

Fresh water, also known as potable water exists in three forms on Earth, namely; liqiud, solid and vapour. Water in all these forms accounts for a total of 2.5 per cent. The water that is readily available for human use (i.e. water in rivers, streams, ponds, lakes, canals or tanks) is even limited in extent since a significant proportion of this water is present in the atmosphere as vapour and in solid form as ice fields of Antarctica, Greenland, Arctic Ocean, on the mountains tops as ice caps or in the form of glaciers. A small portion of this water is also present as sub-surface water and can only be extracted through wells, tube wells or springs and gysers.

a) **Precipitation** - rain, snow, dew etc. - plays the key role in renewing water resources and in defining local climatic conditions and biodiversity. Depending on the local conditions, precipitation may feed rivers and lakes, replenish groundwater, or return to the air by evaporation. (Facts on Water Resources: A summary of the United Nations World Water Development Report 2, 2016). The atmosphere contains the amount of water which if collected together would form a thin layer of just 25 mm in thickness. This atmospheric water is a result of the continuous evaporation that takes place from the fresh and saline water bodies as well as from the soil and vegetation i.e. transpiration. This water then condenses or freezes and returns to the Earth as precipitation.

b) **Glaciers** - store water as snow and ice, releasing varying amounts of water into local streams depending on the season. But many are shrinking as a result of climate change. (Facts on Water Resources: A summary of the United Nations World Water Development Report 2, 2016). Glaciers are capable of supplying water to the rivers/streams throughout the year, through snowmelt. They are the largest sources of fresh water on Earth, carrying 29.2 million km^3 of water in the form of snow and polar ice. Glaciers are fed by solid atmospheric water (i.e. precipitation in the form of snowfall).

c) **River basins** - are a useful “natural unit” for the management of water resources and many of them are shared by more than one country. The largest river basins include the Amazon and Congo Zaire basins. River flows can vary greatly from one season to the next and from one climatic region to another. Because lakes store large amounts of water, they can reduce seasonal differences in how much water flows in rivers and streams. (Facts on Water Resources: A summary of the United Nations World Water Development Report 2, 2016). The rivers/streams carry only a small fraction of the total water present on land, though these serve as the most useful water bodies since the water contained in them is potable and ready for any human or animal consumption or utilization at any given time. The volume of water contained in them is approximately 1,250 km^3. These are generally classified as water transport agents rather than water storage agents of the Earth. They majorly aid in exchange of water between the surface and the sub-surface.

d) **Wetlands** - including swamps, bogs, marshes, and lagoons - cover 6% of the world's land surface and play a key role in local ecosystems and water resources. Many of them have been destroyed, but the remaining wetlands can still play an important role in preventing floods and promoting river flows. (Facts on Water Resources: A summary of the United Nations World Water Development Report 2, 2016). The water in the wetlands is supplied by rivers/streams or underground water. Many a times, the water here is in the form of soil moisture or is stored in the vegetation. Water that evaporates from here contribues to the water cycle.

e) **Lakes** – these occupy the fourth position among the largest sources of water on land, in the global water budget. An estimated quantity of 229,000 km^3 is stored in the natural lakes. of this total quantity, stored in the lakes, approximately 125,000 km^3 volume of water is fresh in nature and 104,000 km^3 is stored in the form of salty water. 95 per cent of the total salty lake water is present in the Caspian Sea alone.

f) **Groundwater** - Of the freshwater which is not frozen, almost all is found below the surface as groundwater. Generally of high quality, groundwater is being withdrawn mostly to supply drinking water and support farming in dry climates. The resource is considered renewable as long as groundwater is not withdrawn faster than nature can replenish it, but in many dry regions the groundwater does not renew itself or only very slowly. Few countries measure the quality of groundwater or the rate at which it is being exploited. This makes it difficult to manage. (Facts on Water Resources: A summary of the United Nations World Water Development Report 2, 2016). It should be noted that water stored in the sub-surface accounts for nearly 95 per cent of the total fresh water present in the readily usable form, which can be utilised for satisfying any human need just after being extracted from its source.

Note: The average amount available per person varies from less than 50 m^3 per year in parts of the Middle East to over 100 000 m^3 per year in humid and sparsely populated areas. (Facts on Water Resources: A summary of the United Nations World Water Development Report 2, 2016).

3.7 HISTORY OF HYDROLOGY

Water is the prirne requirernent for lhe exiscence of life and thus it has been man's endeavor from time immemorial to utilise the available water resources. History has instances of civilizations that flourished with the availability of dependable water supplies and then collapsed when the water supply failed. Numerous references exist in the Vedic literature regarding ground water availability and its utility. During 3000 BC ground, watcr development through wells was known to the people of the

Indus Valley civilization, as revealed by arehaeological excavations at Mohenjodaro. Quotations in ancient Hindu scriptures indicate the existence of the knowledge of the hydrological cycle even as far back as the Vedic period. The first description of the rainguage and its use is contained in Chanakya's Arthashastra written in 300 B.C. Varahamihir's Brihatsamhita, contains description of the rainguage, wind-vane and prediction procedures for rainfall. Egyptians knew the importance of the stage measurements of the rivers and records of the stages of the Nile dating back to 1800 B.C. have been located. The knowledge of the hydrological cycle came to be known in Europe much later, in around 1500 A.D.

Most of the present day science of hydrology has been developed since 1930, thus giving hydrology the status of a young science. The worldwide activities in water resources development since the last few decades by both developed and developing nations aided by rapid advances in instrumentation for data acquisition and in the computer facilities for data analysis have contributed towards the rapid growth of this young science.

3.8 EXERCISES

3.8.1 Fill Ups.

a) There are _____ main stages in the water cycle.

b) The process of conversion of water vapor back into water is called _______.

c) The constructions which facilitate the storage, impoundment, transmission and diversion of water are known as ______.

d) Saturated zone and unsaturated zone are a part of _____.

e) _____ is the largest source of fresh water on Earth.

3.8.2 Multiple Choice Questions (MCQs)

a) The energy and heat balance of the Earth is maintained by:

i. Evaporation
ii. Condensation
iii. Precipitation
iv. Vaporized water

b) The tendency of water vapor to travel from areas of high vapor concentration to areas of low vapor concentration is called:

i. Transportation
ii. Convection
iii. Molecular diffusion
iv. Suspension

c) Lakes that receive water from different sources but lose it only through the process of evaporation are:

i. Small Lakes
ii. Terminal Lakes
iii. Saline Lakes
iv. Shallow Lakes

d) Wetlands generally have saturated soils. This means that the soils are covered with ample:

i. Water
ii. Trees
iii. Crops
iv. Silt and clay

e) 65 per cent of the total precipitation that falls on the global landmasses is the result of:

i. Runoff
ii. Infiltration
iii. Evapotranspiration
iv. Interflow

3.8.3 Answers to Exercises

For fill ups

a) 4

b) Condensation

c) Water conveyance structures

d) Sub-surface

e) Glaciers

Answers for MCQs

a) Vaporized water

b) Molecular diffusion
c) Terminal Lakes
d) Water
e) Evapotranspiration

3.8.4 Task

a) Discuss the hydrological cycle in detail with appropriate diagram

b) Human intervention is responsible for altering the water cycle. Justify.

c) Elaborate the concept of the water budget, highlighting its components.

3.9 SUMMARY

Water is regarded as the most essential resource for humans and all living entities. Its importance has been underscored since the very beginning of civilizations. Not only is it significant for maintaining life on Earth but it is the fundamental contituent for regulating the temperature on our planet, fuelling the hydrological cycle and sustaing the countries of the world. The information presented in this fold will paly a role in generating a better understanding of the worldwide water resources, water budget and the water cycle. It is of particular relavance to realize the significance of the water cycle as it forms the foundation of this fold. Every aspect of the sub-heads covered here, are coherrently correlated with this cycle. The storage and movement of water through the atmosphere, land and sub-surface and the factors responsible for this movement throughout the length and breadth of the Earth need to be studied with reference to the continuous cyclic motion of water. These factors have been vividly elaborated for the convenience of the readers. Furthermore, the global water supply, fresh water resources and types as well as the mechanism of world water balance hae been optimally explained.

3.10 REFERENCES

Facts, G. (2016). Facts on water resources. A summary of the United Nations World Water Development Report 2.

Subramanya, K. (2013). *Engineering hydrology, 4e*. Tata McGraw-Hill Education.

Healy, R. W., Winter, T. C., LaBaugh, J. W., & Franke, O. L. (2007). *Water budgets: foundations for effective water-resources and environmental management* (Vol. 1308). Reston, Virginia: US Geological Survey.

https://study.com/academy/lesson/factors-that-influence-water-movement-in-river-systems.html

https://study.com/academy/lesson/factors-that-influence-groundwater-movement.html

http://ecoursesonline.iasri.res.in/mod/page/view.php?id=425

❖❖❖❖

4

WATERSHED ITS CHARACTERISTICS AND EAPORATION PROCESS

After going through this chapter following aspects of watershed its characteristics and evaporation process will help you to understand the concept of watershed and get details information about various physiographic agro – pedo and geological characteristics along with the concept of evaporation.

Unit Structure

4.1 OBJECTIVE

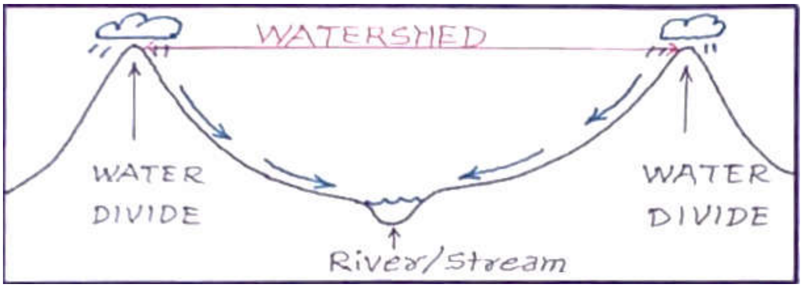
Watershed is an important concept in the study of hydrology. It is necessary to understand difference in the topographical and effective watershed. The study of watershed is useful in the field of agriculture water supply, settlement etc.

The main objective of this topic is to understand the concept of watershed and get details information about various physiographic agro – pedo and geological characteristics along with the concept of evaporation.

4.2 TOPOGRAPHIC AND EFFECTIVE WATERSHED

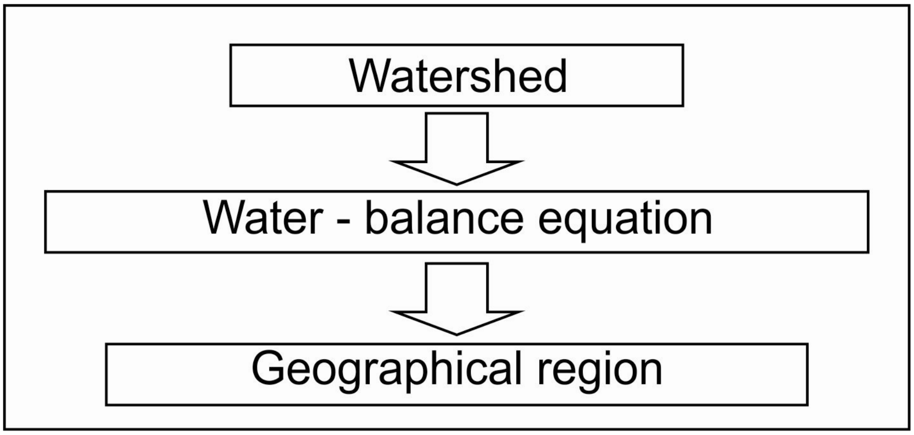
Definition of watershed.

Watershed is defined as the area that appears on the basis of topography, to contribute all the water that passes through a given cross section of a stream.

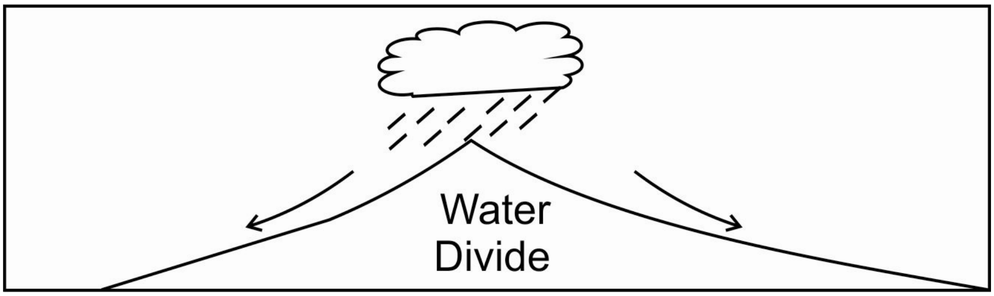


A watershed is a geographical unit in which the hydrological cycle and its components can be analysed.

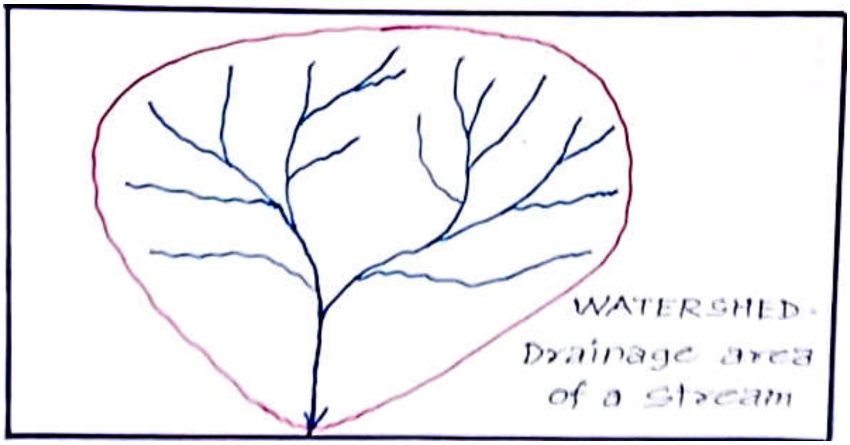
In order to establish the basic hydrologic characteristics of the region, the equation is applied in the form of water – balance equation to a geographical region.



The boundary that delimits a watershed is called a **divide**. These are mountain ranges or hilly areas. Water always flows in the downward direction of slope due to the gravitational pull. Rain water that falls on the hilly area or mountain ranges is divided by them and hence the mountains or hill ranges are also termed as **water divide.**



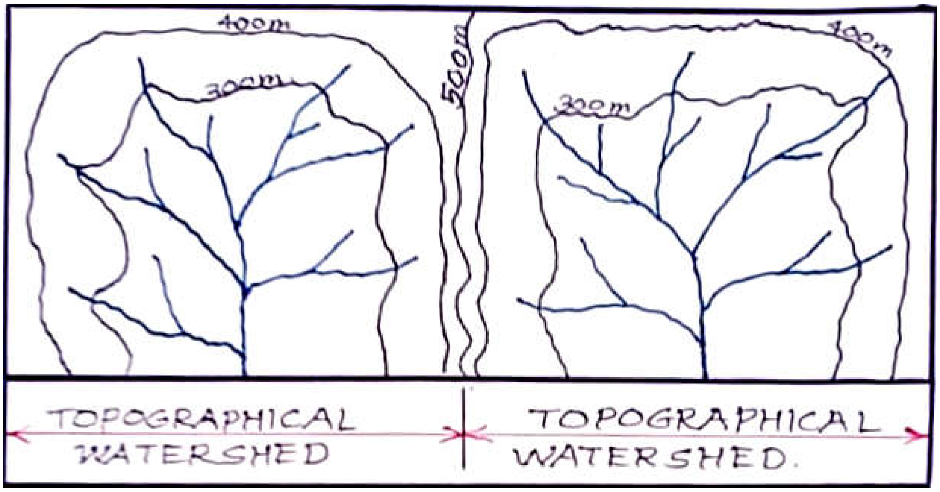
The horizontal projections of the area of watershed is called the drainage area of a stream at that cross section.



Topographic and Effective Watershed

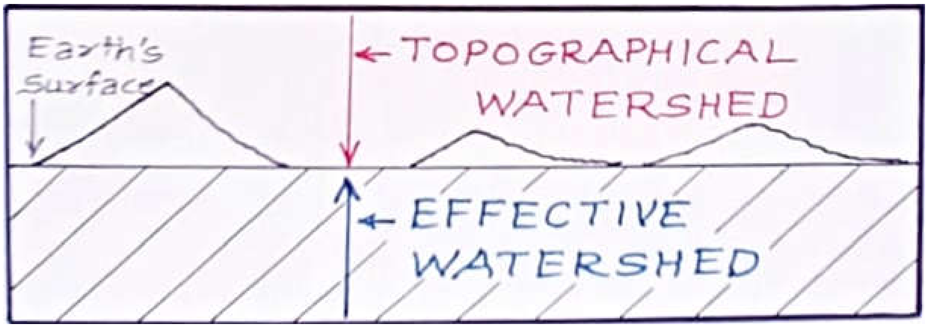
To topographic watershed can be identified with the help of topographical map. It we can identify crest line of the regions of higher elevations / mountain hill ranges surrounding stream or river, the crest line of mountains or water divide determine the topographic watershed.

Topographical watershed is represented in the diagrams given below.



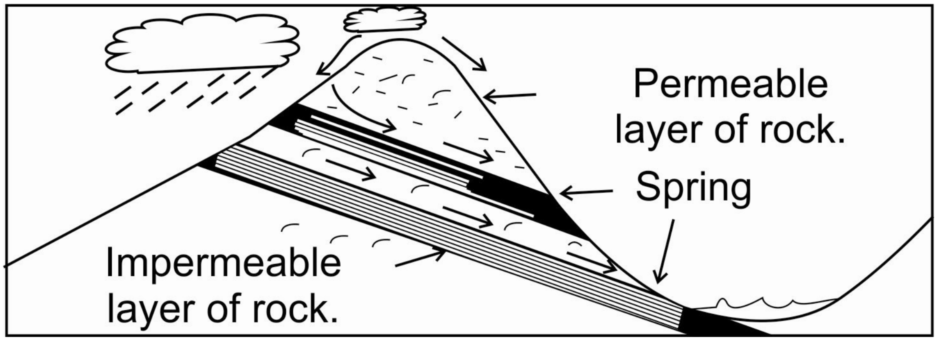
Effective Watershed

Topographical watershed can be decided on the basis of elevations marked on the topographical map. In this case we view watershed from the top i.e., above earth's surface but effective watershed can be identified on the basis of underlying geological factors that divert the flow of water below the earth's surface. Hence the effective watershed is based on the geological characteristics found in the region below the earth's surface.



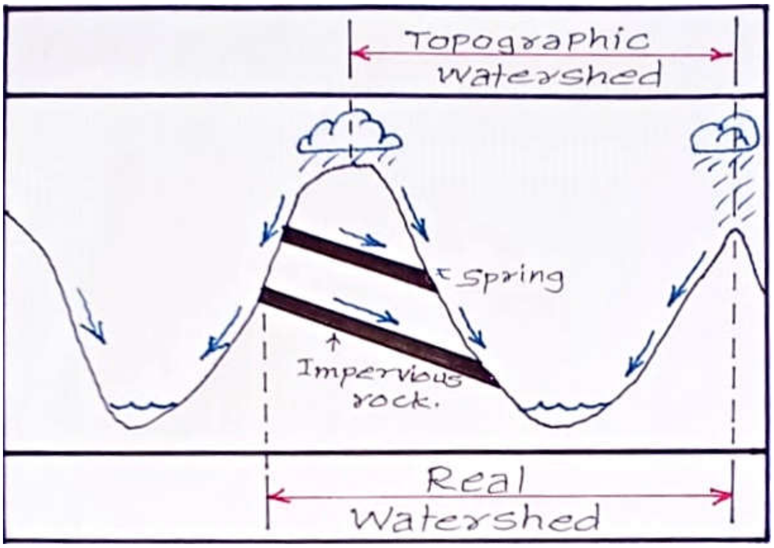
Water flows in the direction of slope & so even after percolating through surface layers of soil, water can flow in the direction of slope formed due to underlying geological structure.

If there is a impermeable layer of rock below the porous or permeable rock, then the water cannot percolate through this impermeable layer of rock and this underground water will flow in the direction of slope.



Hence the topographical and effective watershed may be different & the effective watershed is more important & usefull is decided on the basis of various factors like geological factors which decide the effective flow of water.

The following diagram represents topographical and effective watersheds.



Many underground streams are found in the karst region and hence this difference between the topographic watershed and real watershed is more common in these region.

The surface flow of water is affected by the construction of man – made features like roads, real ways embankments, artificial takes etc. Hence it is important to study watershed of any region before constructions of man-made features.

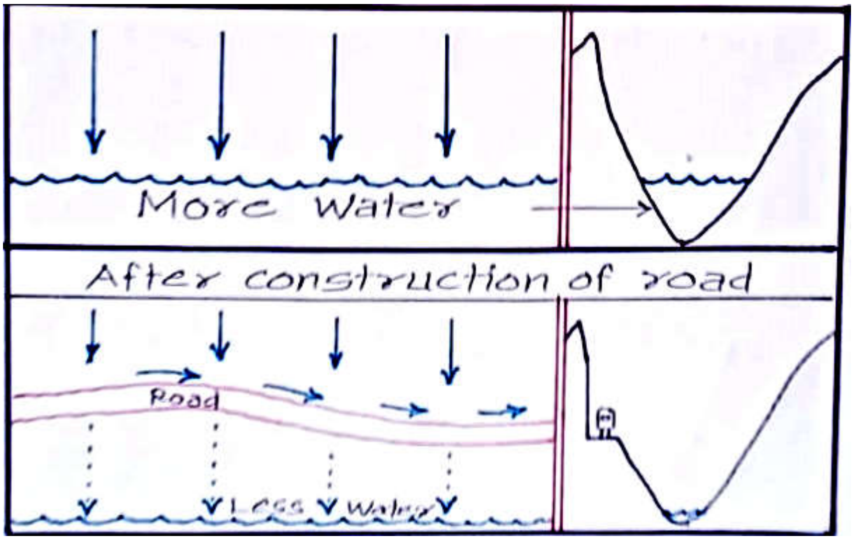
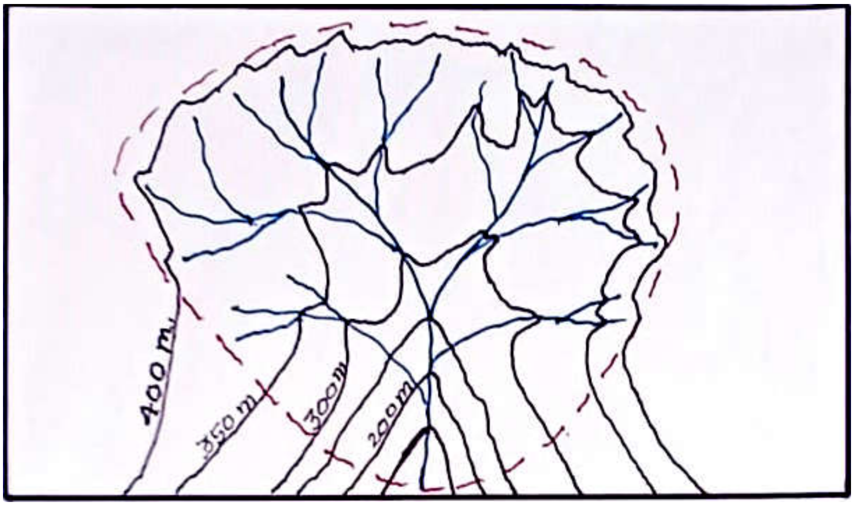


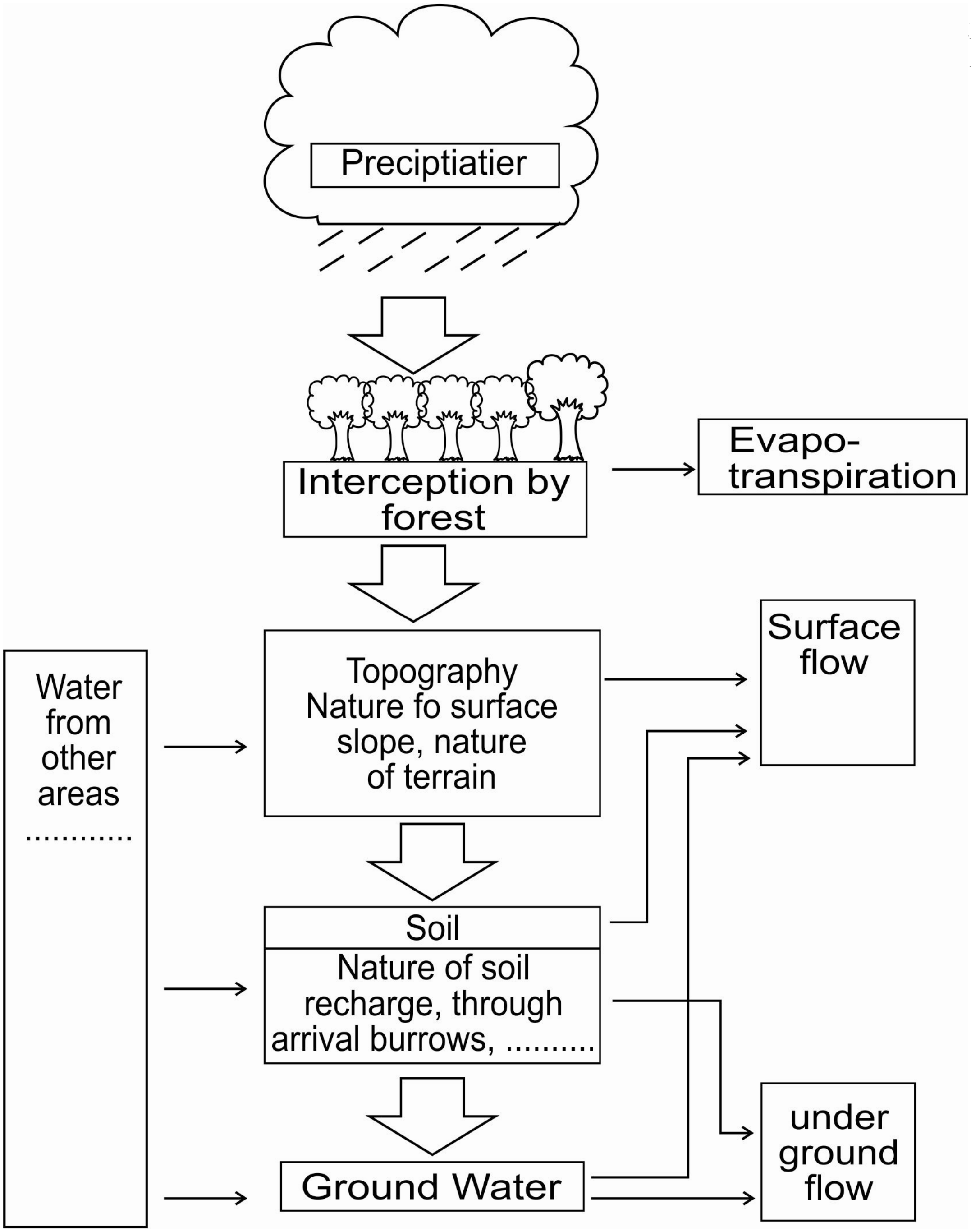
Fig impact of man-made features on watershed.

4.2.1 WATERSHED DELINEATION

It is possible to delineate watershed area with the help of topographical Map.

Identity stream and its tributaries on the topographical map. Draw line at an angle of about 90° to the contour lines to include stream and its tributaries. We draw this line with respect to water divide-area of higher elevation – Finally we return to the starting point and enclose entire watershed area.





4.3 PHYSIOGRAPHIC CHARACTERISTICS OF WATERSHED

4.3.1 Geometric & Drainage Network :

The physiographical characteristics of watershed influences hydrological responses especially during flood and drought periods.

The concentration time, which is related to the speed and intensity of the watershed's reaction to rainfall is influenced by different morphological characteristics.

4.3.2 Geomorphological characteristics :

a) Watershed surface :

A watershed is the area of reception of rainfall and of supplying the watercourse.

The outlet flows depend on its surface. the surface of watershed can be measured using a variety of methods

(1) by using a planimeter

(2) by superimposing grid over the watershed map.

(3) By using digitalizing methods.

Watershed shape :

The shape of a watershed influences the shape of its characteristics hydrograph. e.g. a long shaped watershed generates lower outlet flow as the concentration time is higher.

A watershed having a fan-shaped presents a lower concentration time & so it generates higher flow.

Graveliu's index is used for the analysis of a watershed according to its shape.

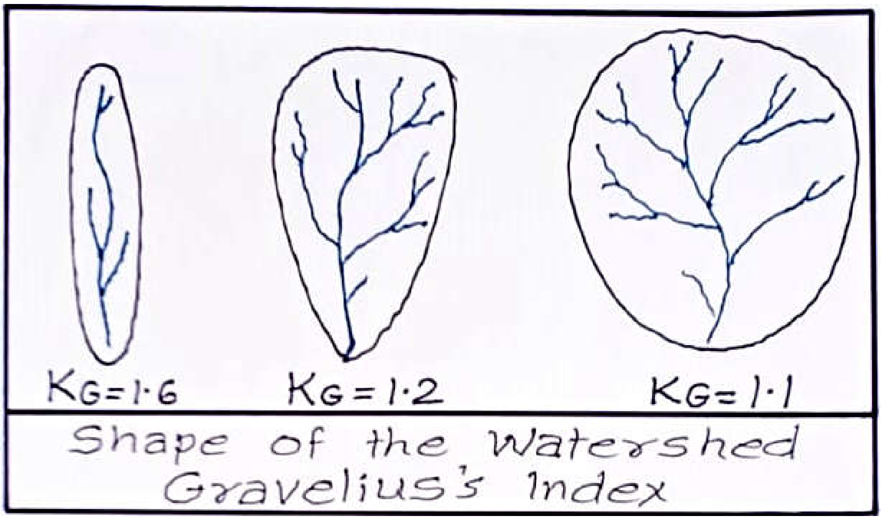
$$K_G = \frac{P}{2\sqrt{\pi A}}$$

$$= 0.28\frac{P}{\sqrt{A}}$$

$K_G =$ Gravelius's shape index

P = Watershed perimeter (in km)

A = Watershed Area (Km^2)



4.3.3 Watershed Orientation :

In the temperate region orientation of watershed influences the melting speed of snow.

Watersheds developed in north-south direction have an alternative exposure to sunrays, the melting speed of snow is less than in case of watersheds developed towards east-west.

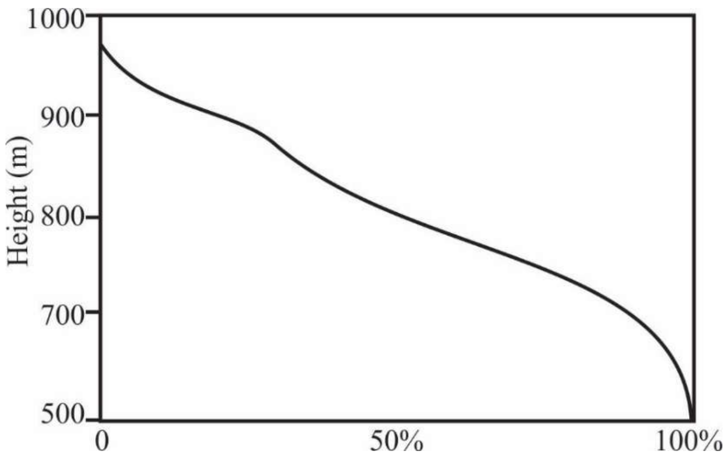
It is also necessary to know the direction and frequency of the dominant wind.

Topography :

The nature of terrain or relief influences the reaction of the watershed through the following characteristics.

a) Hypsographical Curve :

Watershed Hypsographical curve gives a general idea of the watershed relief. Attitude is taken along 'y' axis and surface area - cumulated surface is represented along x axis in this curve.



Hypsography curve in Watershed :

Hypsographical curve has practical utility in the comparison of different watersheds or of different sections of watershed.

The hypsographic curve also helps to establish the average amount of precipitation over the watershed and can give about its hydrographic network.

Altitude of the Watershed :

The extreme altitudes of the watershed, such as maximum and minimum are obtained as a starting step for topographic maps.

The maximum altitude is the elevation of the highest point of the watershed while the minimum altitude is the elevation of lowest point, which is generally the outlet section of the watershed.

These values determine the altimetry amplitude of a watershed and help to calculate the slope.

Average slope of watershed :

The average slope of watershed provides us information about the watershed topography.

The average slope of a watershed influences radically the value of the time of concentration and directly the runoff generated by a rainfall. Following formula proposed by Carlier and Leclerc is used for finding out average slope of watershed.

$$i_a = \frac{D.L}{A}$$

i_a = Average slope of the watershed (m/km) or (‰)

D = Equidistance between two consecutive contour lines (m)

L = Total length of the contour lines (Km.).

A = Surface of the watershed (Km^2)

Topography :

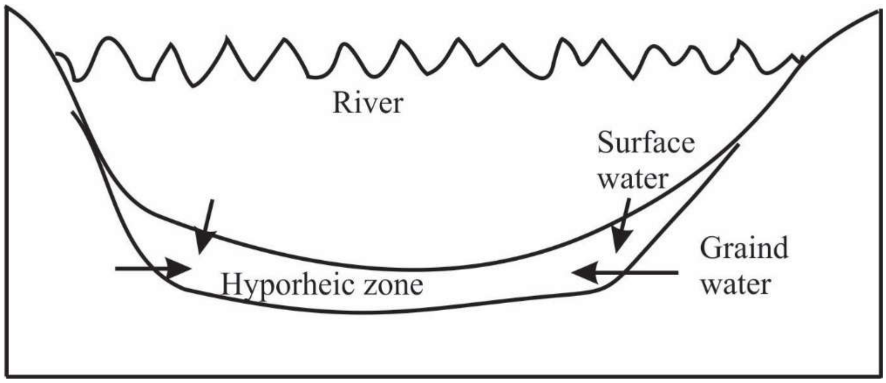
Topography of the region has greater control on baseflow - both directly and indirectly. The influence of topography is most pronounced in relatively high relief region.

Exceptions exist in highly porous regions e.g. Volcanic or glacial terrain or Karst region, where water can move more freely in the subsurface region.

Topographic gradients control the rate at which soil water moves downslope, which is either stored in the soil or joins stream channel.

Hyporheic Zone :

The hyporheic zone is the region of sediment and porous space beneath and alongside a stream bed, where there is mixing of shallow groundwater and surface water.



Base flow :

Base flow is the flow of water below Earth's surface. It includes groundwater hyporheic flows, drainage of near surface valley soils.

Factors that promote infiltration and recharge of subsurface soft storage will increase baseflows, but factors associated with higher evapotranspiration will reduce baseflow.

Factors influencing baseflow

1) Amount of water storage in river channels and groundwater aquifers.

2) Physiographic characteristics of the Basin.

3) Evapotranspiration from streams / rivers in the catchment area.

4) Geomorphology of the landscape and stream network.

5) Nature of aquifers and near surface soils.

These factors can be altered with human impact on the landscape. Similarly, climate chance can also contribute to the base flow & watershed in the region.

Hydrography :

The hydrographic network is defined as the sum of all the water courses, natural or artificial permanent or temporary, which contribute to the runoff.

The characteristics of hydrographic network of watershed is influenced by four main factors.

1) Geology

2) Climate

3) Relief

4) Environment

The hydrographic network is one of the most important characteristics of a watershed.

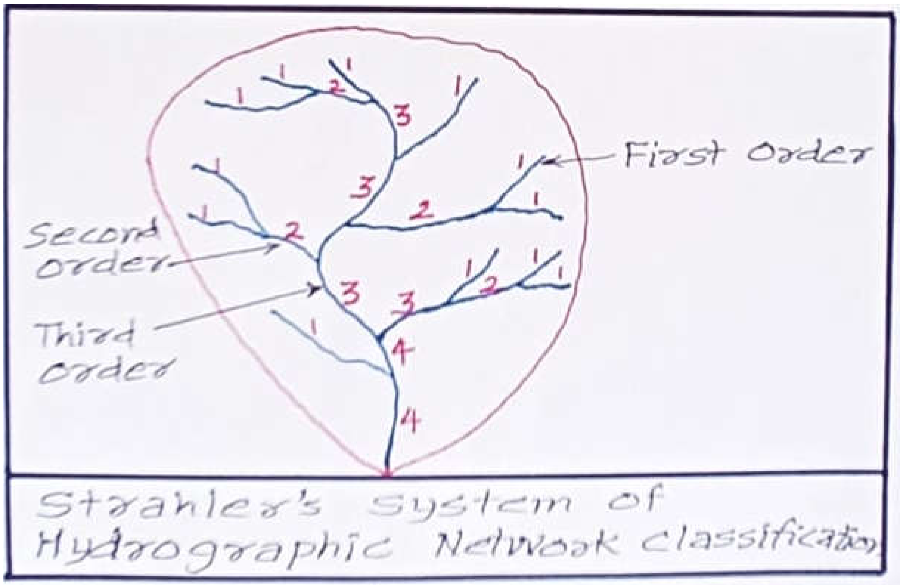
Hydrographic network topology:

The classification of the water courses or streams was introduced by Strahler (1957) The order of the watercourses reflects the degree of ramification of the hydrographic network from upstream to downstream and it is based on the following principles.

1) All water courses / streams without tributaries are of **first** order.

2) Watercourses formed by the confluence of two water courses of different order is going to keep the highest order of the **two**.

3) The watercourse formed by the confluence of two watercourses of same order is going to have an order higher with one (+1) than the other two.

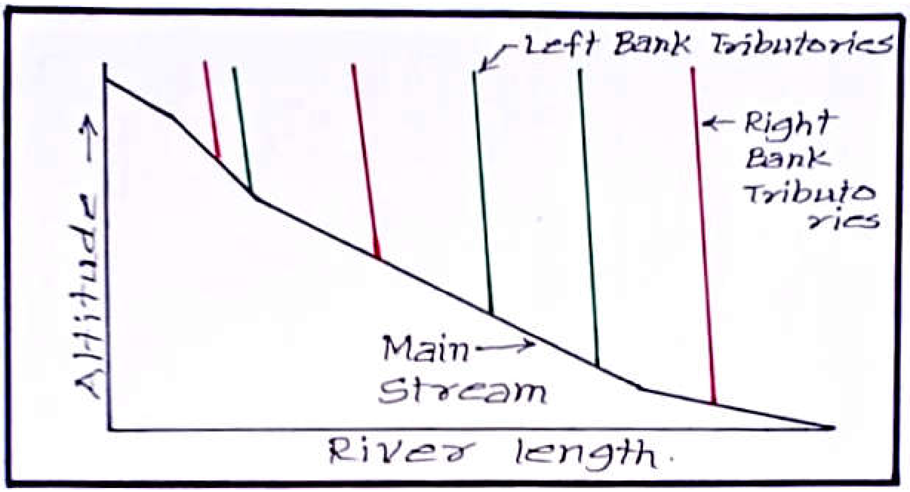


Strahler's System of Hydrographic Network classification

Slopes and length for Hydrographic network.

Runoff is rapid when the slope is steep. Gentle slope gives the water the necessary time to infiltrate totally or partially into the soil.

The calculation of the average slope is obtained from the longitudinal profile of the main stream and its tributaries.



Longitudinal profile of a hydrographic network

The most common method used to calculate the longitudinal slope of a watercourse consists of correlating the difference of altitude of the extreme part of the stream with its length.

Following formula is used to calculate longitudinal slope of stream.

$$S_i = \frac{\Delta H}{L}$$

S_i = Longitudinal slope of stream (m/km) or (‰)

ΔH = Difference of altitude of the extreme points of the stream. (m)

L = Total length of the stream between its extreme points (km)

4.4 AGRO – PEDO – GEOLOGICAL CHARACTERISTICS OF WATERSHED

Soil types and vegetation cover.

The type of soil influences

1) The infiltration rate.

2) The retention capacity

3) The runoff coefficient

The humidity degree of the soil is one of the main factors that determine the concentration time.

Soil Types -

Generally soils can be subdivided into three main groups.

A) Zonal Soils
B) Intrazonal Soils
C) Azonal Soils

A) <u>Zonal Soils –</u>

This type of Soils are formed under conditions of goods soil drainage trough the prolonged action of climate and vegetation. These are most important and wind-spread type of soil.

Distinctive soil profile is found in the zonal soils.

Examples of zonal soils.

1) Podzol soils - Hight coloured podzol soils & forested region.
2) Lateritic soils – Lateritic soils of warm moist subtropical, tropical and equatorial regions .
   (a) Reddish brown lateritic soils.
   (b) Black and drak-gray tropical soils.
3) Soils of the forest-grassland transition- Degraded chernozem soils.
4) Dark coloured soils of the semi-arid and Humid grasslands –
   Prairie Soils
   Chernozem soils
   Chestnut soils
   Reddish brown soils

5) Light Coloured soils of arid region –
   Brown Soils
   Gray Desert Soils
   Red Desert Soils

B) INTRAZONAL SOILS.

1) Hydromorphic soils of marshes, swamp, bog and flat upland
   Bog soils
   Meadow soil
   Planosols

2) Halomorphic soils of poorly drained arid regions and coastal deposits.
   - Saline Soils
   - Alkali Soils
   - Soloth
3) Calcimorphic Soils- Rendzina Soils

C) AZONAL SOILS

1) Lithosols

2) Regosols – Alluvial Soils Sands (Dry)

Azonal (A means not + zonal, which means a soil which is not formed in that zone, which is a transported soils)

Azonal soils do not have well developed profiles, either because they have insufficient time to develop or because they are on slopes too steep to allow profile development.

Azonal soils include thin stony mountain soils (lithosols)

Freshly laid alluvial materials or sand dunes (Regosols)

Subsurface Topography & soil characteristics.

Baseflow and water storage capacity is influenced by the sub-surface topography in addition to surface topography or relief.

The influenced of subsurface to topography is of particular importance during low moisture conditions when the topography of the confining layers may be the predominant control on moisture retention, and hence an important factor for baseflow.

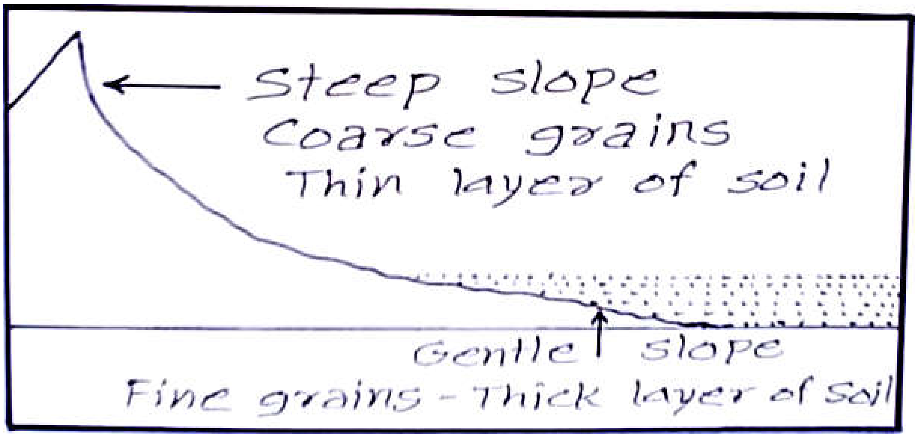
Subsurface strata that induce through flow are widely varied, but are most often associated with the parent material –

1) Bedrock with negligible porosity and fracturing.
2) Heavily compacted till.
3) Impermeable layer.

Tree root growth, animal burrowing and other bioturbation processes affect soil horizon, soil properties influence the distributions, of water storage.

Variation in soil texture plays a significant role in the rate of moisture loss due to surface or subsurface topographic gradients.

We find correlations between topography and soil textures.



Soil hydrology is strongly affected by the regional variations in the amount of soil moisture which is mainly controlled by surface and subsurface topography.

Vegetation Cover

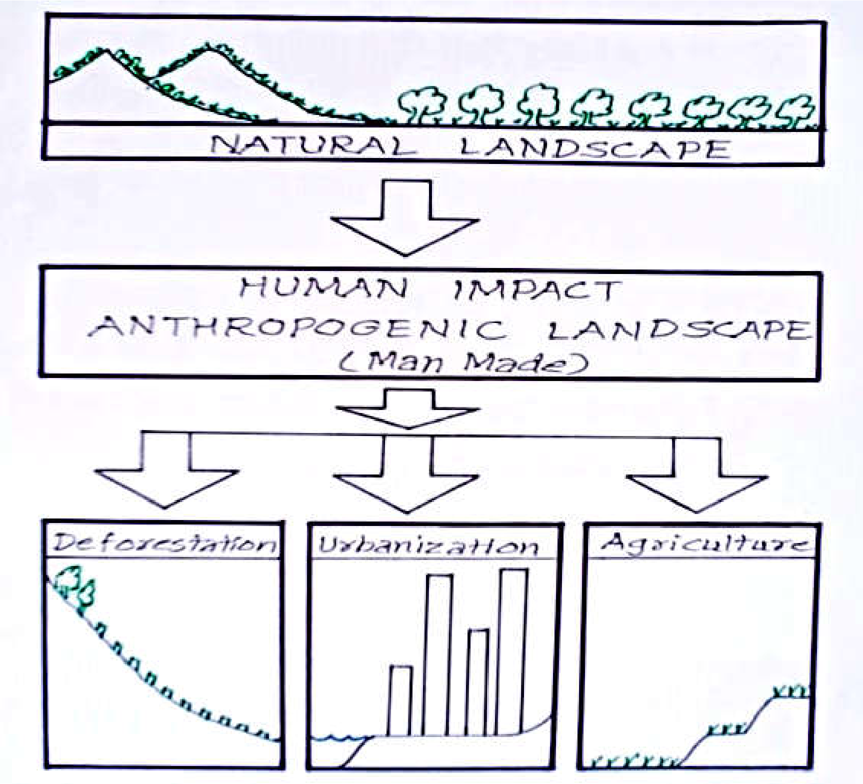
The type and density of vegetal covering directly determines the quantity of water intercepted and retained by the soil e.g. the forest retains a certain part of the precipitation by the tree canopy.

Vegetation regularizes the runoff in normal climatic conditions. During flood & droughts (extreme conditions) its action is relatively reduced.

The absence of vegetation cover reduces water retention capacity of the soil. In this case runoff is very rapid & it also erodes river beds.

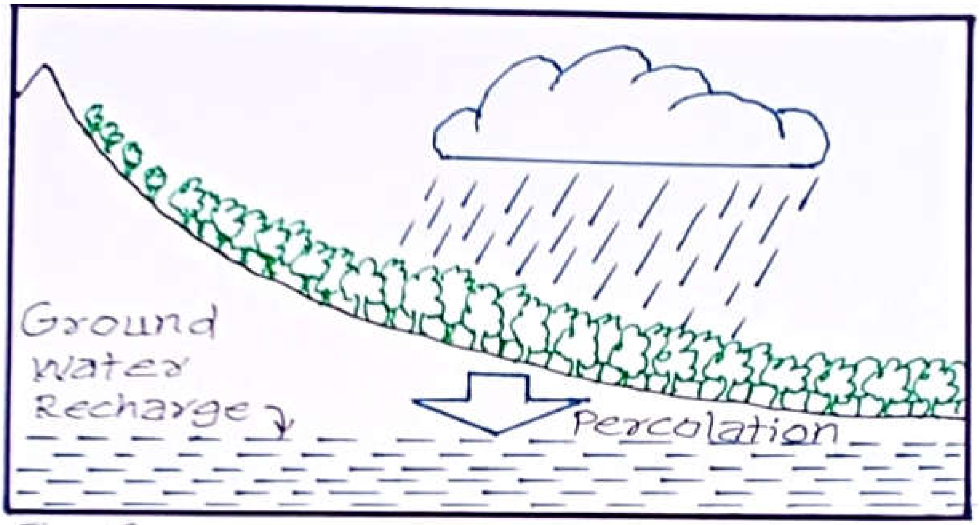
Effects of Human Activities and Land Uses on Watershed-

Watersheds areas & base flow of water are closely associated with vegetation and soil in that region. Large scale human activities like removal of forest urbanization and agriculture are responsible for change in the original land use & so it affects baseflow, watershed, vegetation and even changes in the soil properties.



Deforestation

Forests and dense vegetation which covers the soil help to obstruct and reduce the velocity of raindrops. Hence the physical impact of raindrop coming to the earth's surface with high velocity is reduced. Soil is also protected from erosion. Forests & vegetation help rainwater to percolate more and so it increases the ground water recharge and has an impact on watershed.



Removal of forest reduces percolation and increases in the surface flow of rainwater.

With the encroachment of agricultures, pastures urbanisation, constructions of road & others suburban land uses on the forest land the percolation of water in the soil decreases due to the following factors.

1) Soil compaction
2) Reduction of soil organic matter
3) Increases in impervious surface

All these factors are responsible for reduction in the base flow of underground water and has an adverse impact on watershed in the region.

Agriculture

Agriculture can have positive or negative response to the underground storage & baseflow of water depending on the management practices. If the crops are irrigated from surface water resources linked to stream network increased evapotranspiration may reduce baseflow of water. However increases in baseflow may occur if irrigation water is drawn from disconnected storage resources or front outside the drainage basin.

Varied management practices of agriculture are associated with a wide range of soil impacts. e.g. conventional tillage practices to no till and conservation tillage, differing temporal pattern to intensive cropping i.e. perennial versus seasonal cultivation and whether or not crop residue or other soil cover are used during the follow season.

Urbanization

With increase in the standard of living urban development is very rapid all over the world. Urbanization is responsible for removal of forest & vegetation in that region. It leads to.

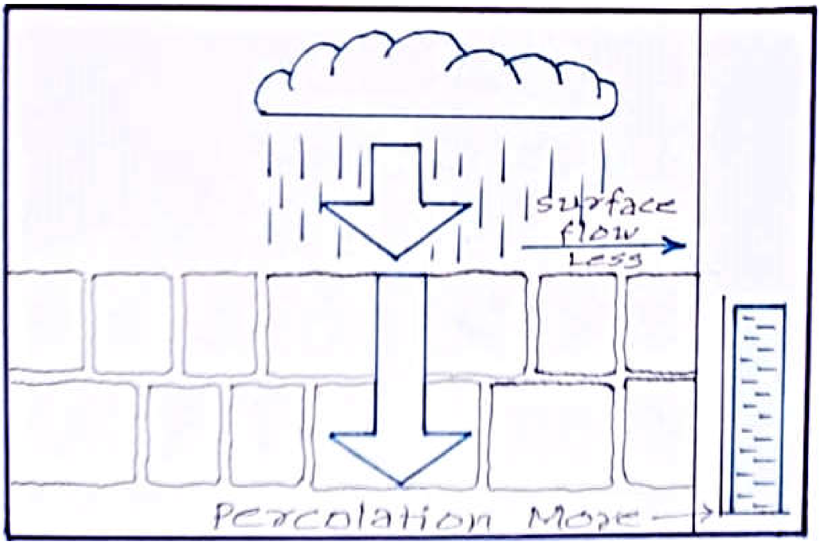
1) Development of impervious surface
2) Compaction of soil
3) Channelization of water & sub-surface storm drainage network.

Hence water from urban area is quickly flushed throughout due to reduced hydraulic resistances of land surface. Road network, rooftops, buildings and other land uses in the urban areas increase impervious surface and obstruct percolation of water.

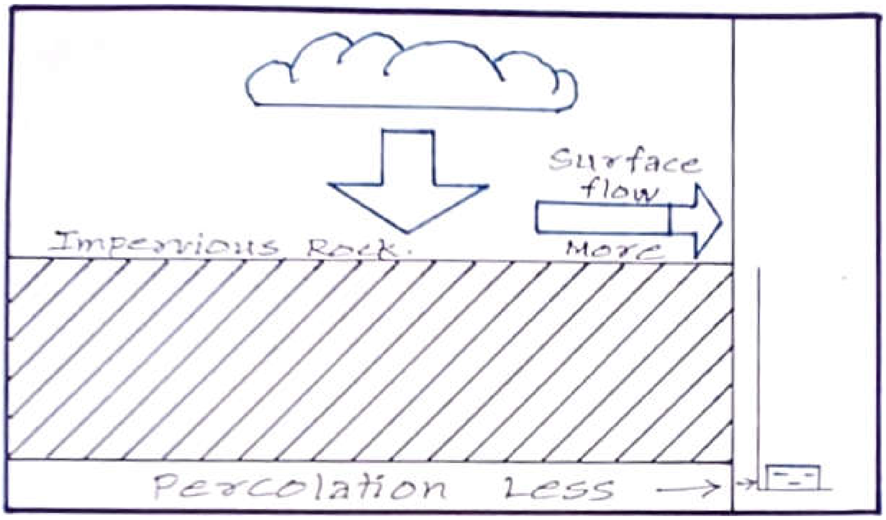
In most of the urban areas water is redistributed to accommodate human activities and prevent flood damage. Water is routed through surface and subsurface via storm drains, ditching, water mains, waste water, sewers, and other means altering the rates and paths of water transmission through urban basin.

GEOLOGY

Geology of the catchment area plays an important role in the percolation of water, storage etc. Percolation of water is more in the regions having highly fractured pervious rocks, porous rack, permeable rocks.



On the other hand, in the areas of massive crystalline rocks bedrocks, with of minor fractures the surface runoff of water is more and percolation is less.



Geological structure is also of great importance in the percolation of water & its contribution to the watershed.

a) Folding - Smith (1981) showed that low flows in shale and sandstones in

Virginia are related to the degree of bedrock folding.

In the region having more of folds.

b) Bedrock -Fractures

Fractures is the bedrock easily transmit Water in deep subsurface storage.

c) Solution cavities
In the karst topography limestone and dolomite dissolved in the weak carbonic combination of rainwater sand carbon dioxide Hence cavities formed in limestone & dolomite have high storage capacity of groundwater.

d) Porous Rocks –
Porous rocks like limestone have impact on baseflow losses.

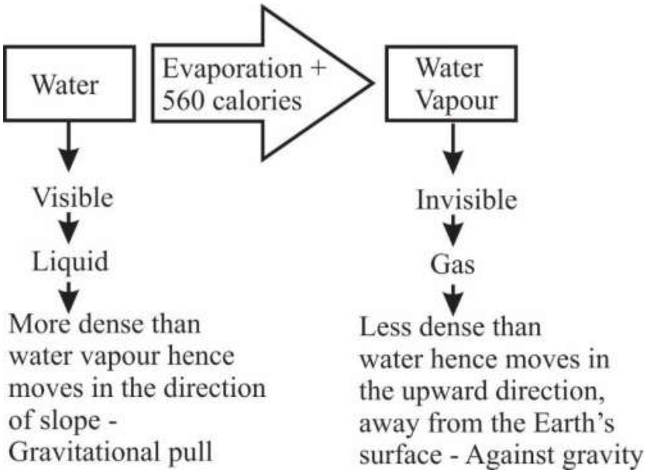
e) Easily eroded bedrock.
If the bedrock is composed of softer rock formations it is easily eroded which helps in the development of more channels and formation of soil Both of these affect the storage capacities and rates of water transmission.

f) Weathered material –
Weathered material accumulated on the surface can hold water and serve as base flow reserves

g) Lateral drainage-
Large quantities of baseflow may also originate from the near surface valley bottom storage such as alluvial depositions bank soil and wetlands.

4.4 METEOROLOGICAL FACTORS INFLUENCING EVAPORATION PHYSICAL FACTORS INVOLED IN EVAPORATION PROCESS

Evaporation is process in which water, (which is in liquid form) is converted into gaseous form i.e. water vapour.



Water is the magical liquid found on the Earth. It is available in all three stages solid (ICE / Snow) liquid (water) and Gas (water vapour)

Conversion of water from one stage to another requires Latent heat. Following diagram represents various stages of water and latent heat.

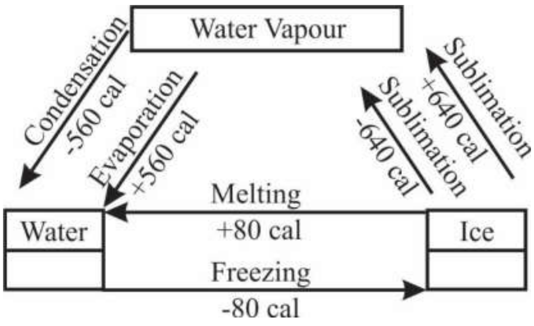


Fig : Different stages of Water

Latent heat is required for the transformation of water from one stage to another. It is not recorded on thermometer. e.g. Evaporation of water requires 560 calories of latent heat.

Which is termed as the latent heat of Evaporation or latent heat of vaporization.

Latent Heat means hidden or stored heat :

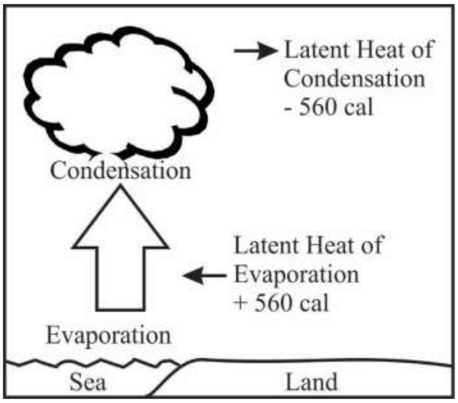


Fig. Latent Heat of Evaporation & Condensation

Evaporation as cooling process :

Evaporation helps to reduce temperature and contributes to the cooling process. when we switch on the fan, the sweat from our body / face evaporates, so we feel cool.

Doctors apply spirit as antiseptic before giving injection. Spirit is evaporated rapidly & so we feel cool. Similarly in the environment evaporation has cooling effect on the evaporating bodies.

When the rain drop comes to the Earth's surface through the dry layers of atmosphere, the air is chilled due to the process of evaporation, because most of the energy needed for evaporating water is provided by the air itself.

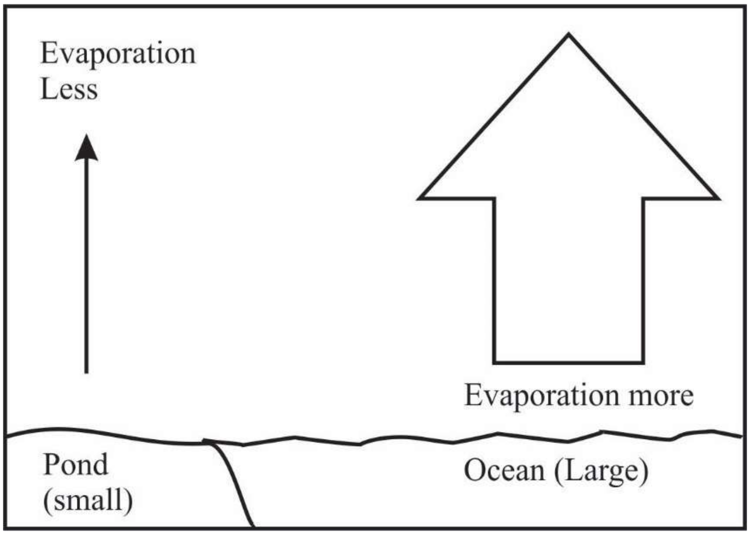
Gabler R.E. stated that 'The reservoir of energy required to maintain the Earth's surface temperature against evaporation cooling is supplied by the part of the exess of solar radiation absorbed by the ground (mainly the Oceans) over longwave radiation emitted to space.'

Factors involved in Evaporation Process :

1) The amount of water :

Evaporation is less when the amount of water is less. e.g. small pond contains less amount of water & so the amount of water evaporated is also less.

On the other hands oceans contain huge amount of water and so the amount of water evaporated from ocean is much more.



2) Temperature :

Evaporation is directly proportional to the temperature. Evaporation process becomes more rapid with increase in temperature.

$\boxed{Evaporation \ \alpha \ Temperature}$

With increase in temperature, the capacity of the air to hold moisture also increases.

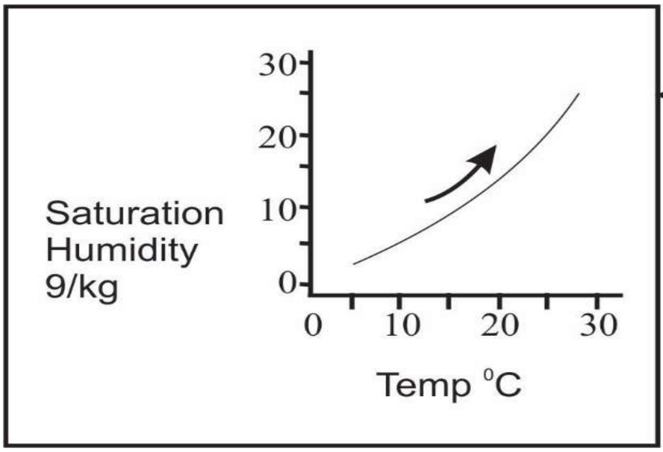


Fig
Water
Vapour
Capacity

With increase in the temperature of air, more energy molecules for escaping from liquid to a gaseous stage state. Hence warm surface has higher rate of evaporation than the cool surface.

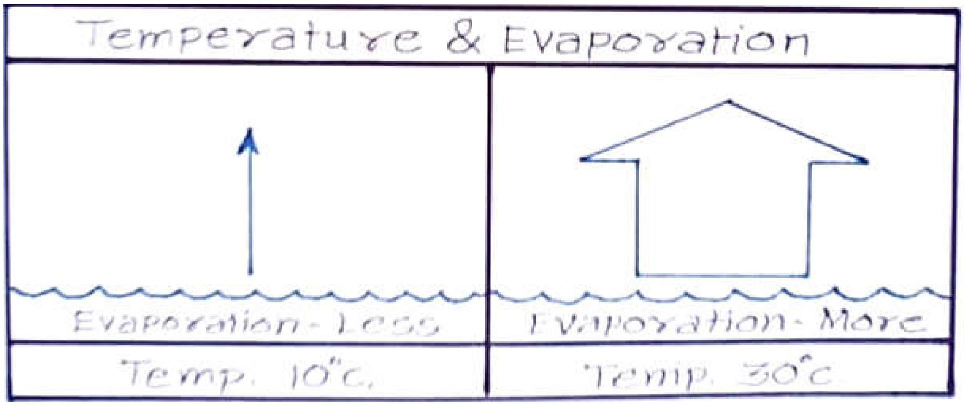


Fig. Temperature & Evaporation

3) Relative Humidity :

$$\text{Relative Humidity} = \frac{A.H.}{S.H} \times 100$$

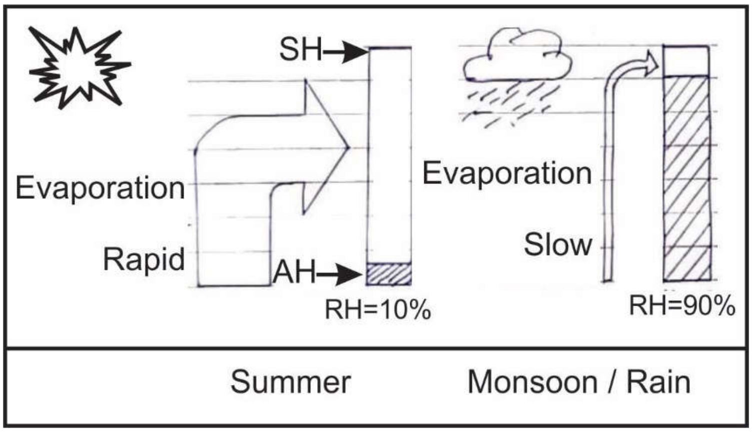
A.H. = Actual amount of water - Vapour present in the air.

S.H. = Saturation Humidity - The Amount of water vapour that the air can hold at the given temperature.

R.H. = 80% $\rightarrow$ Humid Air

R.H. = 10% $\rightarrow$ Dry Air

If the dry air has 10% Relative Humidity which means, it has only 10% of water Vapour and can accommodate 90% more water vapour & so the rate of evaporation is faster during summer when the air is dry.



On the other hand during monsoon season R.H. is about 90%. So, air can accommodate only 10% more water vapour, So the rate of evaporation is very slow during this season.

When we switch on fan in the month of May when air is dry, we get instant relief as the perspiration / sweat on our body evaporates quickly, so we feel cool.

On the other hand during rainy season air is saturated & so even we switch on fan, we do not get instant or sufficient relief. As the rate of evaporation is slow the sweat on our body is not quickly evaporated & so we feel sultry and uneasy.

Hence Evaporation is inversely proportional to the Relative Humidity.

a) When R.H. is less evaporation is more.

b) When R.H. is more evaporation is less.

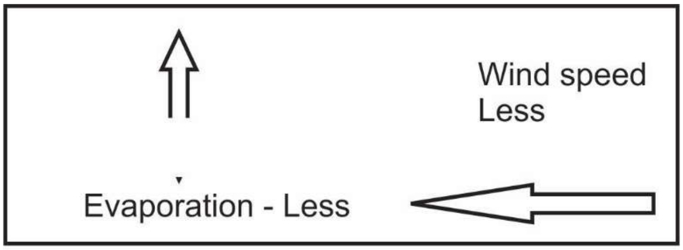
4) Wind Speed :

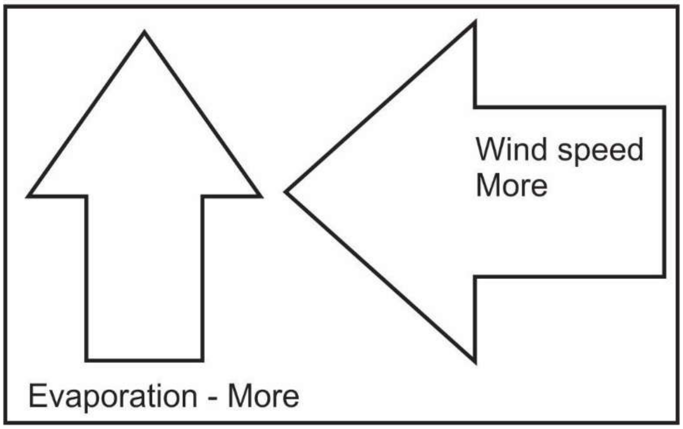
Evaporation process is directly related to wind speed.

When wind speed is less, evaporation is very slow.

When wind speed is more, evaporation is very rapid.

When wind is light a thin layer of air just above the surface gets nearly saturated in this situation the difference between the vapour pressure between ground and air is very small.

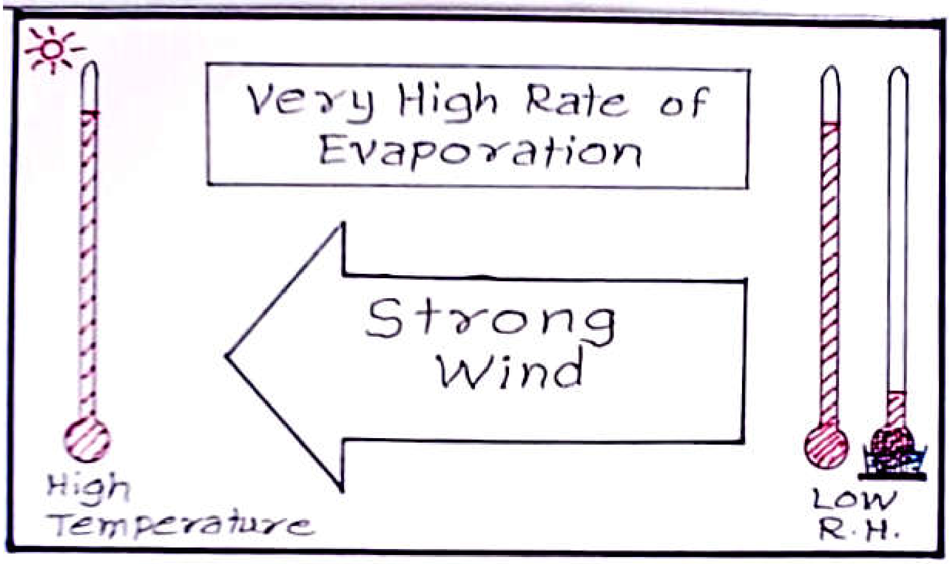




When the wind velocity is high, turbulence is set up in the air, Moisture evaporated from the ground is mixed upward and so the vapour pressure difference between the earth's surface and the atmosphere remains large. Hence the rate of evaporation is accelerated.

The rate of evaporation is exceptionally high when there is a combination of following three factors.

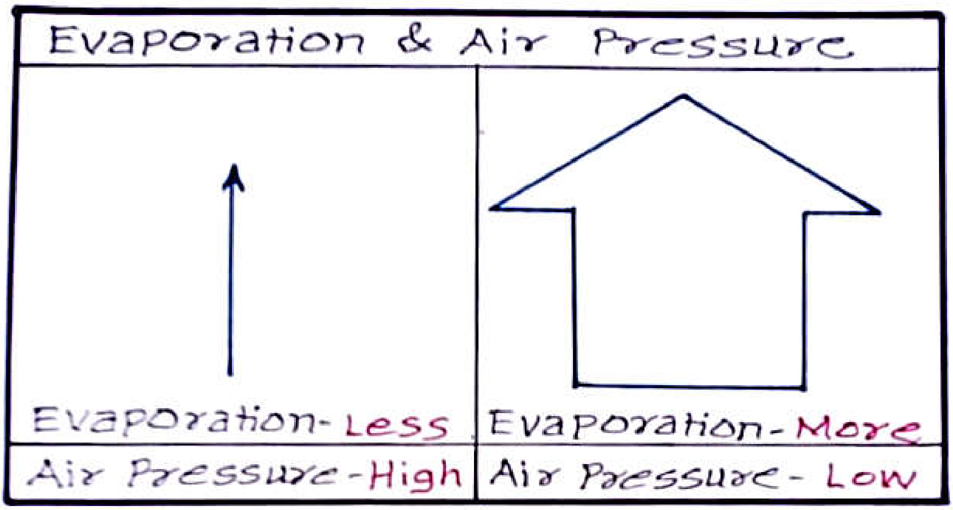
1) High Temperature
2) Very low Relative Humidity (R.H. = 10%)
3) Strong wind



5) Area of evaporating surface :

If the area of evaporating surface is less, the rate of evaporation is also less.

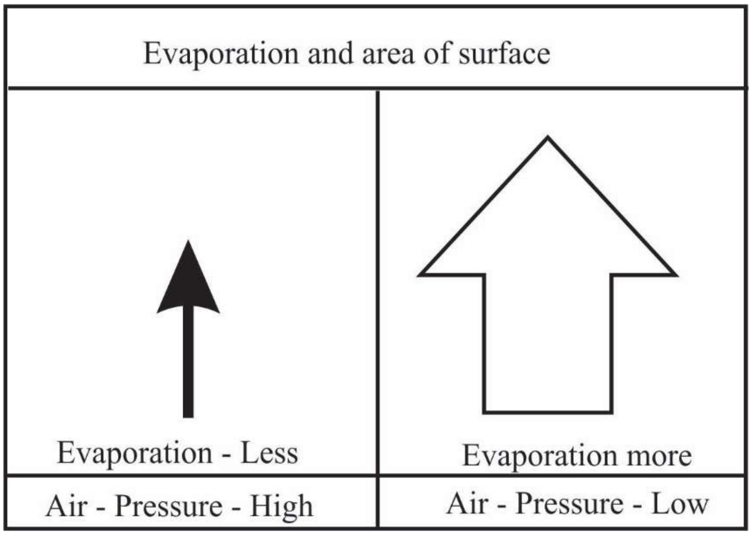
On the other hand if the area of evaporating surface is more or large then the rate of evaporation is also more evaporation and area of surface.



6) Air pressure :

Evaporation process is related to the atmospheric pressure, exerted on the evaporating surface.

Rate of evaporation is faster when the air pressure is low.



7) Composition of water :

Rate of evaporation is rapid or faster for fresh water than the saline.

Evaporation is inversely proportional to the salinity Higher salinity reduces the rate of evaporation. Hence the ocean water (which is saline) evaporates about 5% slower than the fresh water.

Potential Evapotranspiration:

Potential Evapotranspiration, this term is a combination of 3 words.

a) Potential - Maximum possible.

b) Evapo - Evaporation

c) Transpiration - from plants & biotic elements.

Potential evapotranspiration refers to the ideal conditions in which there would be enough rainfall to provide sufficient moisture for all possible evapotranspiration in an area.

Following factors are taken into consideration to determine potential evapotranspiration for any place or area.

1) Latitude

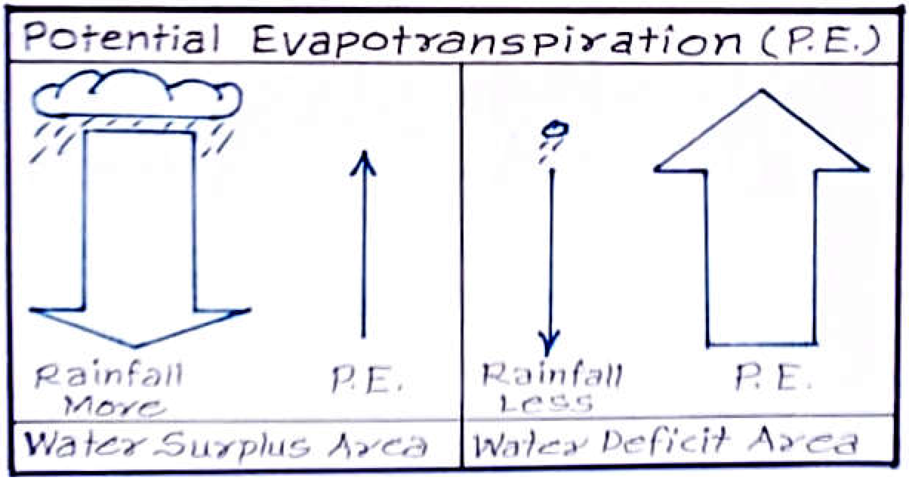
2) Temperature

3) Vegetation

4) Permeability of soil / rock

5) Water retention capacity of soil.

Surplus water is available in areas which have surplus of precipitation than the evapotranspiration.



The surplus water is stored underground and can be used for canal irrigation or other types of irrigation.

In the areas of water deficit - where evapotranspiration is in excess of precipitation no water is available for storage. Even if certain amount of water is stored during the rainy season it is quickly evaporated due to dry and warm air so the soils become dry and vegetation is adversely affected.

Farmers and irrigation engineers are interested in having a knowledge of potential evapotranspiration, so that they can make a correct assessment of their needs and the availability of water supply.

4.6 SUMMERY

We got clear idea about the concept of watershed and difference between topographical watershed and effective watershed in first fold of this topic. We studied physiographic characteristics of watershed in the second topic. In third topic we understood various factors related to soil and geology which influence functioning of watershed. Last topic deals with concept of evaporation, evapotranspiration and various factors affecting the process of evaporation understanding of the science based concept has become easy with the help of many diagrams include along with the text matter.

❖❖❖❖