WORKSHOP

ON

MODELLING OF HYDROLOGIC SYSTEMS

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Basic Hydrology

by
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Organised by

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1.0 Definition of Hydrology

The term Hydrology refers to the `Science of water'. In a broad sense, The Hydrology can be defined as an Applied Science which links Atmosphere, Hydrosphere, Lithosphere and Biosphere. The Science of Hydrology includes the scientific examination and appraisal of the whole continuum of a hydrologic, or water cycle. To define hydrology as a science as distinguished from the application of Science-in-general to problems of water resources assessment and management, Ad Hoc panel on Hydrology of the Federal Council for Science and Technology (established by the President of the United States in 1959) recommended the following definition: "Hydrology is the Science that treats of the waters of the Earth, their occurrence, circulation, and distribution, their physical and chemical properties, and their reaction with their environment, including their relation to living things. The domain of Hydrology embraces the full life history of water on the Earth".

1.1 Hydrological Cycle

The hydrologic cycle has no beginning or end, as water evaporates from the oceans and the land and becomes a part of the atmosphere. The evaporated moisture is lifted and carried in the atmosphere until it finally precipitates to the earth,, either on land or in the oceans. The precipitated water may be intercepted or transpired by plants, may run over the ground surface and into streams or may infiltrate into the ground. Much of the intercepted and transpired water and the surface runoff returns to the air through evaporation. The infiltrated water may percolate to deeper zones to be stored as groundwater which may later flow out as springs or seep into streams as runoff and finally evaporate into the atmosphere to complete the hydrologic cycle. Thus,. the hydrologic cycle undergoes various complicated processes of evaporation , precipitation, interception, transpiration, infiltration, percolation, storage, and runoff. Many diagrams have been designed to illustrate the hydrologic cycle (Fig.1 to Fig 3).

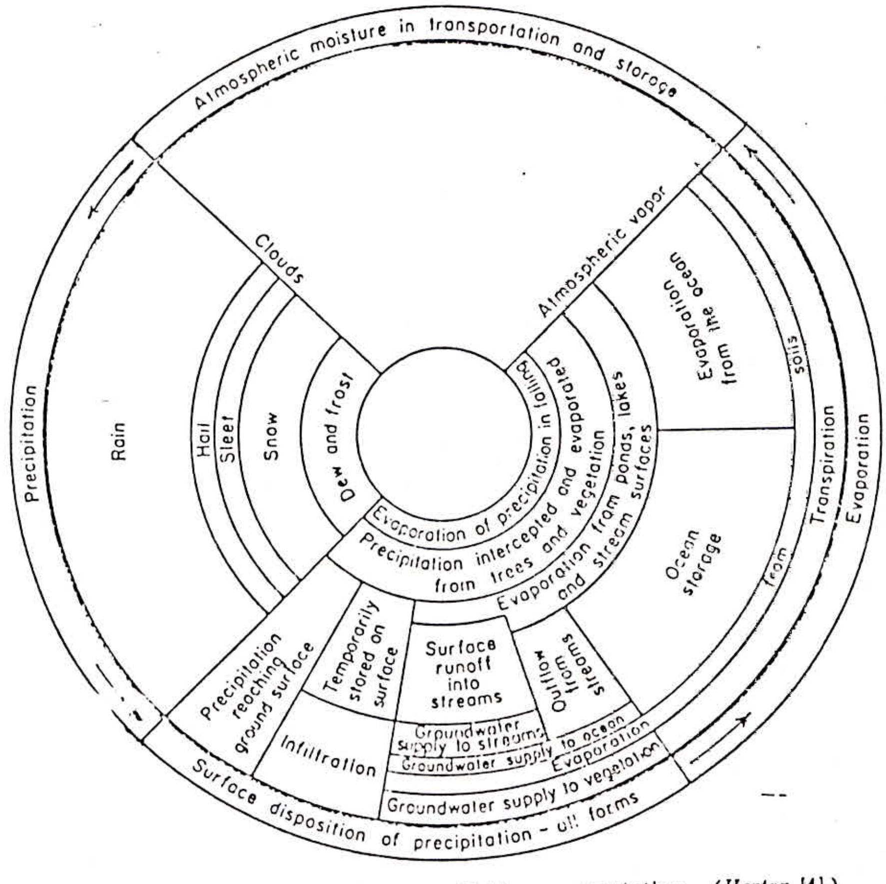

FIG. 1. . The hydrologic cycle—a qualitative representation. (*Horton* [4].)

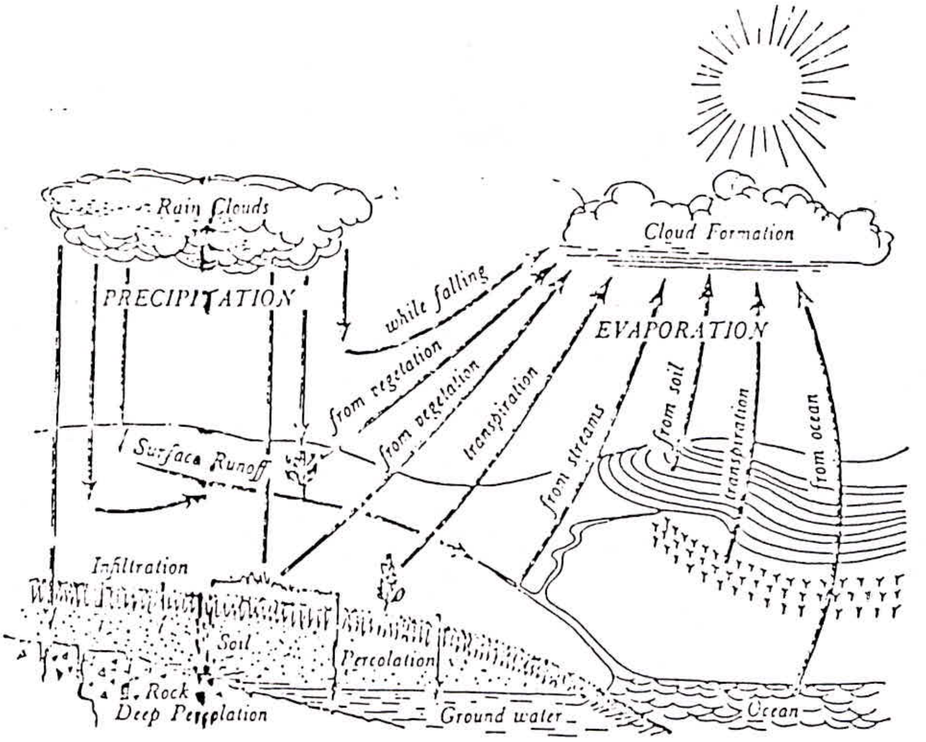

Fig. -2. The hydrologic cycle—a descriptive representation. (*Ackermann, Colman, and Ogrosky* [5].)

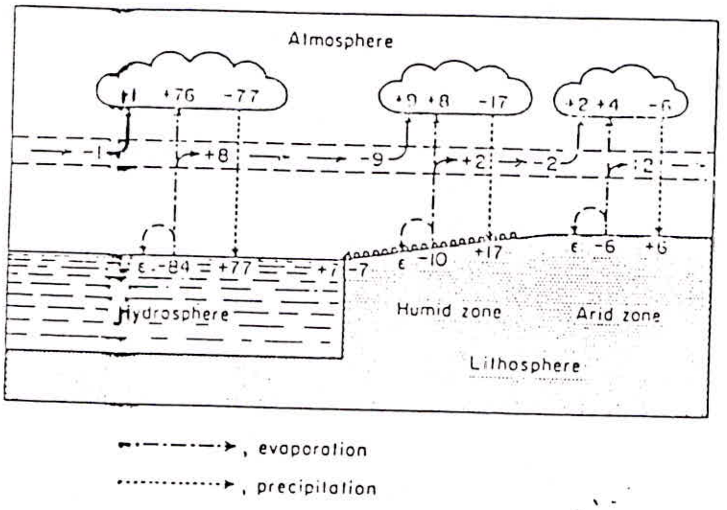

Fig. -3. The hydrologic cycle—a quantitative representation. 100 relative units = 85.7 g/cm²/year or 857 mm (33.8 in.) global annual mean of precipitation. (*Lettau* [6].)

According to the estimates made by various authors, wrote that 97 per cent of all the water in the world, or one quadrillion (10^{15}) acre feet is contained in the oceans. If the world were a uniform sphere, this quantity would be sufficient to cover it to a depth of 800 ft. The total amount of fresh water is estimated at about 33 trillion acre-feet. It is distributed roughly as follows. 75 per cent in polar ice and glaciers; 14 per cent in ground water between depths of 2,500 and 12,500 ft; 11 per cent in ground water at depths less than 2,500 ft; 0.3 per cent in lakes; 0.06 per cent as soil moisture; 0.035 per cent in atmosphere; and 0.03 per cent in rivers. These are, however, stationary estimates of distribution. While the water content of the atmosphere is relatively small at any given moment, immense quantities of water pass through it annually. The annual precipitation on land surfaces alone is 7.7 times as great as the moisture contained in the entire atmosphere at any one time, that is, about 30 times as great as the moisture in the air over the land. The mean annual precipitation for the entire earth is about 86 cm / year(34 in. / year) which under stationary conditions is balanced by an equally large evaporation amount. Thus, the average evaporation for the whole earth amount to 2.37mm (about 0.1 in.) of water per day. The availability of global water resources and water resources of India is briefly described here under. The relative quantities of the earth's water contained in each of the phases of the hydrologic cycle are presented in Table 1.

Table 1: Quantities of Water in the Phases of the Hydrologic Cycle

Sl. No.	Item	Area 10 6 sq. km	Volume cu. Km	Percent of total water	Percent of fresh water
1.	Oceans	361.3	1,338,000,000	96.5	
2.	Groundwater Fresh Saline	 134.8 134.8	 10,530,000 12,870,000	 0.76 0.93	 30.1 -
3.	Soil moisture	82.0	16,500	0.0012	0.005
4.	Polar ice	16.0	24,023,500	1.7	68.6
5.	Other ice and snow	0.3	340,600	0.025	1.0
6.	Lakes Fresh Saline	 1.2 0.8	 91,000 85,400	 0.007 0.006	 0.26 -
7.	Marshes	2.7	11,470	0.0008	0.03
8.	Rivers	148.8	2,120	0.0002	0.006
9.	Biological water	510.0	1,120	0.0001	0.003
10.	Atmosphere water	510.0	12,900	0.001	0.04
11.	Total water	510.0	1,385,984,610	100	-
12.	Fresh water	148.8	35,029,210	2.5	100

(Table adapted from World Water Balance and Water Resources of the Earth, UNESCO,1978).

1.2 Water Resources of India

(a) Surface water resources

India with a geographical area of 3.29 million square kilometers receives the annual precipitation of about 4000 cubic kilometers, including snowfall. Out of this seasonal rainfall is of the order of 3000 cubic kilometers. Rainfall in India is dependent in differing degrees on south-west and northeast monsoon, on shallow cyclonic depressions and disturbances and on violent local storms which form in regions where cool humid winds from the sea meet hot dry winds from the land and occasionally reach cyclonic dimension. Most of the rainfall in India takes place under the influence of south-west monsoon between June to September except in Tamil Nadu where it is under the influence of North-East monsoon during October and November. The rainfall in India shows great variations unequal seasonal distribution, still more unequal geographical distribution and the frequent departures from the normal.

As per the estimate made by Dr. A.N.Khosla, the founder Chairman of Central Water and Power Commission, the total average annual flow of all the river systems of India is found to be 1673 cubic kilometers. In this approach runoff was considered as a function of rainfall and temperature.

Central Water and Power Commission during 1952 to 1956 estimated the surface water resources of the country as 1881 cubic kilometers. These estimates are based on the statistical analysis of the available flows of rivers and suitable rainfall runoff relationships in case of meagre observed data.

Dr. K.L.Rao in his book "India's Water Wealth"(1973) has stated the country's available annual surface runoff as 1645 cubic kilometers. Thus, the estimates of surface water resources of the country vary from 1645 to 1881 cubic kilometers. Most of surface flow of the rivers occurs during the monsoon season of 4 to 5 months and particularly as flood flows.

The amounts of evaporation, precipitation, runoff, and other hydrologic quantities are not evenly distributed on the earth, either geographically or momentary. About 70 to 75 per cent of the precipitation is returned to the atmosphere by evapotranspiration and direct evaporation, while the remaining 30 per cent becomes runoff. About one-fourth of the runoff is diverted. About two-thirds of that diverted is fed back into the stream and eventually goes to oceans for storage and evaporation, and the remaining one-third is consumed and returns to the atmosphere directly.

The quantities of water going through any arc or arcs of the hydrologic cycle can be evaluated usually by the so-called hydrologic equation, which simply states as

$I - O = \Delta S$ --(1)

Where I is the inflow during a given period to a problem area including, for instance, the total inflow of the channel and overland runoff to the area above the ground surface and of the groundwater across the boundaries of the area plus the total precipitation over the area during the period; O is the outflow during the given period to the area including, for instance, total evaporation, transpiration, and outflow of surface runoff in channel and on overland from the area above the surface plus the overflow of groundwater across the boundaries of the area; and ΔS is the change in storage in various forms of retention depression, and interception. Equation (1) is essentially a form of continuity equation.

1.3 Space - Time Scale in Hydrology

The scope of hydrology is best defined by the hydrologic cycle. Depending on the hydrologic problem under consideration, the hydrologic cycle or its components can be treated at different scales of time and space. As a consequence, different hydrologic problems may have different space-time scales. The global scale is the largest spatial scale and the watershed, or drainage basin, the smallest spatial scale. A drainage basin, or watershed, is the area that diverts all runoff to the same drainage outlet. In between these two scales lie such scales as continental, regional and other space scales convenient for hydrologic analysis. Clearly, the watershed, or drainage-basin, scale is the most basic of all; and all other scales can be constructed by building on the drainage-basin scale. Most hydrologic problems deal with a drainage basin. It should be clearly understood that the watershed scale does not usually or necessarily coincide with territorial or jurisdictional boundaries that might be determined by political or economic considerations. A drainage basin can be of almost any size. It might be as small as small parking lot or as large as Ganga River basin. Large watersheds are usually broken down into smaller drainage basins to suit the requirements of a particular problem and to assist in orderly quantitative analysis.

Time scales used in hydrologic studies range from a fraction of an hour to a year or perhaps many years. The time scale used in a hydrologic study depends on the purpose of the study and the problem involved. Hourly, daily, weekly, ten daily, monthly, seasonal and annual time scales are common. Sometimes the time interval for the collection of data determines the time scale for hydrologic analysis. Hydrologic time scales often do not coincide with those used in fluid mechanics or hydraulics and likewise do not coincide with political, environmental or economic time scales.

1.4 Hydrologic Budget

The hydrologic budget of a drainage basin is mathematical statement of its hydrologic cycle. It is expressed by equating the difference between inflow, I and outflow, Q, of a drainage basin to the rate of change of storage with in the basin, ΔS, for a specified period of time, Δt and its hydrologic budget can be expressed as :

$$\frac{\Delta S}{\Delta t} = I - Q \quad \text{---}(2a)$$

$$\frac{S2-S1}{\Delta t}=\frac{I1+I2}{2}-\frac{Q1+Q2}{2} \text{------------------------------}(2b)$$

where, I and Q are, respectively, average inflow and average outflow for time interval Δt, which is assumed to be small to justify averaging of inflow and outflow. Subscript 1 and 2 correspond to values of variables at start and at the end of time interval $\Delta t = t_2 - t_1$. If I and Q vary continuously with time t, the equation (2) can be written as:

$$\frac{ds}{dt}=I(t)-Q(t)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

In equation(2) or equation (3) it is implied that I, Q and S do not vary in space. It means these are spatially lumped. Equation(3) is also referred to as the spatially lumped continuity equation, or sometimes as the water budget. Equation(2) or Equation(3) form the basis of the system approach in hydrology.

All hydrologic analyses of drainage basins must satisfy equation (3) or else the analysis is incomplete and is, therefore, not reasonable. The appearance of this equation is in its simplicity. For most of the hydrologic problems, more than one variable is unknown, therefore, eq. 3 cannot be solved without additional information. For example, both Q(t) and S(t) are unknown when a rainfall-runoff relation is desired. Without an extra relation between S(t)) and Q(t)) with or without i(t),Q(t) cannot be evaluated. Furthermore, I and Q are not known as continuous explicit functions of time.

In eq(3), I and Q are expressed as rates having the dimensions of L^3/T. This budget equation can also be written in volumetric unit by integrating eq.(3). i.e.

$S(t)-S(0)=V_I(t)-V_Q(t)$.........(4)

where, S(0) is the initial storage or storage at t=0, $V_I(t)$ and $V_Q(t)$ are volumes of inflow and outflow at time t having the dimensions of L3. Eq(3) or its variant in equation (2b) or (4) is the fundamental governing equation for hydrologic analysis.

For a drainage basin, the inflow may be comprised of rainfall, snowfall, hail and other forms of precipitation. Surface runoff, subsurface runoff, deep percolation, evaporation, transpiration and infiltration may constitute the outflow.

The components of storage may include surface storage (over the ground, including storage in channels and reservoirs, depression and detention storage), sub-surface storage (within the root zone), ground water storage (within the aquifers) and interception (over vegetation, buildings etc.). All these components may be included in eq.(4) and the resulting water budget equation is known as the hydrologic water balance equation.

1.5 Utilisable Surface Water Resources

Within the limitations of physiographic conditions and socio-political environment, legal and constitutional constraints and the technology of development available at present, Utilisable quantities of water from the surface flow have been assessed by different authorities differently. These are indicated below:

I) Irrigation Commission of India , 1972, places the country's Utilisable quantity at 666 cubic kilometers or 38 per cent of the surface water resources of the country

(ii) Dr. K.L.Rao put the Utilisable quantity much more and has suggested that the quantum should be about 50 % of the country's available annual surface water resources.

(iii) The National Commission on Agriculture, 1976 have estimated the Utilisable quantity as 700 cubic kilometers. This amount constitutes about 38 % of the annual average flow of the river, the estimate being almost the same as that by the Irrigation Commission of India 1972.

(iv) Indian Council of Agricultural Research estimates the Usable annual surface flow at 920 cubic kilometers.

(v) In the sixth Five Year Plan document, the total availability of water including the ground water has been assessed as 1050 cubic kilometers ;out of which 700 cubic kilometers consist of surface flow and 350 cubic kilometers as ground water.

(vi) As per the recent estimates made by the Central Water Commission the Utilisable annual surface runoff is bout 684 cubic kilometers.

The availability of water shows a great deal of variability from place to place. Due to the topographic hydrological and other constraints, it is assessed that only about 700 cubic kilometers of surface water may be beneficially utilized by the conventional methods of development.

1.6 Application Of Hydrology

Hydrology touches every human life in some manner. Modern applications of hydrology are often concerned with floods and flooding along with flood plain management. Changing land use patterns such as urbanization, deforestation etc. have aggravated flooding, and as a result, flooding is higher and more spread in some areas than before. Drought is other extreme of the hydrologic cycle. To those people who depend on water for crops and livestock, the role of hydrology is most important. Increasing population and the accompanying increase in industry have provided tremendous sources of pollution for our water resources. Hydrologists are deeply involved in attempting to alleviate this serious problem.

There are many other applications than those mentioned previously. Industry throughout the world has an important concern with hydrology. Agriculture is dependent on irrigation for the production of food and fibre. The irrigated food production is so important that the present world could not be fed without this hydrologic application of water. Highways, rail roads and other commercial entities require bridges to span streams and rivers. Navigation of streams, harbors and seas have always been a basis for commerce. Water sports are an important part of life of many people. Fortunately, other hydrologic applications such as dams for power and irrigation provide added opportunity for the recreational use of water. The fishing industry and recreational fisherman have a vital interest in providing water compatible with fishing. More and more, modern society demands that the appearance of water development and use be maintained in a manner that is pleasing to view. These and other demands by people, government and industry provide unlimited opportunities for application of hydrology. In this section some specific applications of hydrology are discussed.

1.6.1 Flood Control

The problem of flooding is defined by its areal extension, duration, intensity and damage. The projects designed to mitigate flooding and flood damage may be structural (e.g. dams, levees,dykes diversions, flood walls and channels), non structural (e.g. flood forecasting, flood plain zoning, flood plain management and relocation) or a combination of both. The hydrologic input needed to design such projects includes : (i) peak discharge and its frequency of occurrence, (ii) duration and volume of flood hydrograph and their probabilities of occurrence and (iii) the arrival of the next flooding.

1.6.2 Drought Mitigation

A drought occurs when there is a shortage of water by comparison with the demand for it. There may not be enough water in lakes, reservoirs or streams or precipitation may be deficient. Agricultural, hydrological and meteorological droughts are usually distinguished. These three types are significantly interrelated, although in the extreme, these may be independent of one another. Analogous to flooding, the problem of drought is defined by its areal extent, duration, severity and the onset of the next drought. From a hydrological perspective, low discharge (defined over a period) and its frequency of occurrence, duration of this low discharge and volume of low flow, as well as their frequencies, and the probability of occurrence of the next drought are useful to design drought mitigation projects. A similar type of information is needed for rainfall in case of meteorological drought and for soil moisture in case of agricultural drought. Construction of water impoundment's, groundwater pumpage, interbasin transfer, water conservation and even augmentation of atmospheric precipitation through cloud seeding are some of the ways to mitigate droughts.

1.6.3 Water Supply

A water supply scheme must provide sufficient water of acceptable quality to serve its intended purpose, be it urban, agricultural or industrial. The disruption in water supply should be minimum. Hydrology determines the volume of water to be stored to achieve the desired objective and the probability with which this volume of water will not be available. Hydrology also specifies the arrival of the next shortage of water and the frequency of its occurrence. In coastal area, ground water aquifers are threatened by salt water intrusion. This problem is further exacerbated by an excessive pumping of ground water. Hydrological techniques are used to determine a safe yield without encroachment of salt water.

1.6.4 Pollution Control

Water is an efficient and economical carrier of undesirable materials. It dilutes the waste and to a certain extent, by natural processes, disposes of that waste. However, there is a limit to the amount of waste that can be absorbed by any water course, including rivers, lakes, reservoirs and seas. This limitation is too often forgotten in the rush of disposing of waste resulting from growing population and expanding industry. Our polluted water bodies are an ample evidence to attest to this attitude. This however, is not to suggest prohibition of all water products from water courses, but to plea for wise water management, economically and socially viable. Hydrology is a key to achieve an acceptable, economic balance that takes into account the many and various services rendered by water bodies. Specially, it provides information for disposition of water in time and space, both in terms of quantity and quality, in water bodies.

1.6.5 Urban Development

Urban planning and development involve construction of houses or ;sub-divisions, schools, sports and recreation facilities, shopping centres, roads, culverts, bridges, drainage systems, parks, water supply schemes, waste disposal facilities etc. Hydrology gives the design discharge and its probability of occurrence needed for design of hydraulic works. It specifies the extent and severity of flooding needed to ensure building of houses on safe ground, out of flood plains. It also quantifies, on the other hand, hydrologic consequences upstream and downstream of urban development. For example, hydrology determines if flooding will increase or decrease as a result of urban development.

1.6.6 Industrial Development

For industrial development to take place, two basic problems have to be resolved: (i) water supply and (ii) disposition of waste. Hydrology assists with addressing these problems. However, industrial development also involves roads, land use change etc. and hydrology determines consequences of these changes.

1.6.7 Design of Hydraulic Works

Dams, culverts, spillways, bridge crossing, dikes, levees, diversions, channel improvement works, drainage works etc. are typical hydraulic works required for water resources development and management. Design of these works requires an estimate of peak discharge of given frequency. Hydrology produces this estimate. The environmental consequences of these works are also estimated using hydrology.

1.6.8 Agricultural Production

Crop production involves moisture forecasting, supply of water to farms, management of irrigation water, application of chemical and fertilizers, drainage of excess water, soil conservation etc. Hydrology is used to determine the time history of soil moisture needed of irrigation scheduling and to dispose of excess waters during flooding. It is also needed to determine soil erosion and sediment transport, migration of chemicals and fertilizers and their impacts on water quality. Hydrology may be used to design a network of wells for farming , or plan a system of dams, canals and ditches based on soil properties, land slope, location of the water table, climate and other factors. Hydrology also assists for identifying the areas prone to water logging and salinity problems so that the remedial measures could be planned in those areas.

1.6.9 Energy Resource Development

Thermal, nuclear and hydropower plants constitute the principal sources of electrical power generation. Hydrology is applied to design these plants safely to avoid flooding and minimize consequent risk of failure. Thermal and nuclear power plants generate waste that needs to be disposed of. Hydrology is applied to determine the water supply needed for cooling purposes and for safe disposition of plant generated waste. Geothermal energy appears as steam from deep beneath the earth's surface. Knowledge of Hydrology is used to help to locate areas where use of geothermal energy may be feasible and also to design the well fields to extract the heated water. Hydrology plays a crucial role in mining and oil exploration. The landscape disturbed, as a result of these activities, should be restored to its original form. Hydrology is applied to design such a landscape.

1.6.10 Land Conservation

Careless farming methods can speed up the runoff of rainfall, resulting in erosion of soil. This increases the danger of flooding downstream and causes streams to become more turbid because of increased concentration of sediments in the stream. Loss of fertile lands due to erosion and of coastal areas has been of growing concern. Not only does hydrology determine the space-time history of erosion, but also, is used to develop scenarios for prevention of erosion through, for example, soil conservation, appropriate farm practices, vegetation management, water diversion, afforestation, reduced flooding and controlled land use.

1.6.11 Environmental Impact Assessment

Sediment transport, fertilizers, pesticides and feedlot wastes, disposal of urban and industrial waste chemical spills etc. have major impact on the quality of environment and ecology. With increasing industrialization and urbanization, larger and larger amounts of waste are generated and their disposition, without detrimental effects , is of growing concern. Sediment from eroded fields may choke streams and silt reservoirs. Fertilizers, pesticides and feedlot waste and disposal hazardous waste through land fill may leach into ground water or wash into streams, poisoning plants, fish and wild life. Hydrology determine migration of these wastes and their effect on water quality, thereby developing standards for safe and economic disposal of waste through water bodies.

1.6.12 Land Use Change

Land use change can be point or non-point. Agriculture practices, afforestation and deforestation, urbanization, high way development, channel improvement and so on are examples of non-point change. Dams, culverts, bridges, industrial plants, land fill sites etc. represent point changes. Hydrologic consequences of these changes are to be determined before a land use change can be justified. These changes can have significant effect on environment, the quality of life, fish and wild life, plants and vegetation. etc.

1.6.13 Forest and Wildlife Management

Application of pesticides and chemicals, forest clearing cutting, forest fires, plantation, logging, road construction, etc. are typical forest management practices. Preservation of wild life, animal grazing , animal husbandry etc. are within the purview of wild life management. Hydrology determines the consequences of these activities on water quantity and quality. Forest and vegetation cover certainly slow down the rate at which surface water flows to the main channels and spreads runoff over a larger period and reduces peak flow at the same time. This effect is significant in the case of small streams and small floods and may not be so for large watersheds and large floods. Great floods overcome the retarding effects of vegetation and the nature of the land surface becomes of little importance in slowing runoff.

1.6.14 Military Operations

Hydrology plays a crucial role in the planning and conduct of military operations. Military camps are to be located on safe grounds. When the ground is trafficable is of vital importance for movement of military vehicles. A knowledge of river flow ahead of time is required to determine if river crossing would be safe. Dam breaching and the resulting damage are important in planning tactical offenses against enemies as well as adequate defense. Downstream flooding can be an effective combat multiplier. In addition to damaging structures, the resulting flood wave may create a significant barrier in troop and vehicular movement. Military camping is done at awkward places and locating water supply quickly is crucial. Hydrology is used to address all of these problems of military action environment.

1.6.14 Navigation

In order to maintain navigability, a minimum depth of flow has to be maintained in the river. A system of locks and dams is built on the river, which monitors the river traffic.. Hydrology is employed to provide peak discharge and its probability of occurrence for designing these dams. The volume of water that will be available for river flow is estimated using hydrology. Because of siltation, navigable rivers may have to be dredged. The bulk of the sediment to the river are determined using hydrology. The study of sedimentation processes is needed to determine the location of jetties and levees so as to minimize future silting problems.

1.6.15 Recreation

Nowadays, recreational requirements are an important consideration in the development of water use projects. Design and operation of these facilities require adequate availability of water, which is estimated using hydrology. Moreover, measures for protection of facilities from vagaries of weather and other extremes depend on hydrologic analysis. Many rivers and lakes close to urban population centres are highly polluted to the extent of being useless for recreational purposes.

1.6.16 Fisheries

Commercial and sport fishing are receiving important consideration in the preliminary planning and design of water use projects. Hydrology is used to determine how much, and of what quality, water will be available in streams, ponds, reservoirs etc. for a specific time period. Thus hydrology, plays a critical role in development of fisheries resources.

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