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THE HYDROLOGIC CYCLE AND WATER BALANCE

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PREFACE

The present growth of production, the rise of living standards, higher culture and welfare requirements of the population are resulting in greatly increased water demands.

With developing culture and civilisation, the significance of water is dynamically growing for man and society alike; the consumption of water in industry as well as in agriculture, in households as well as in communities, grow rapidly enough to make it, in certain areas of the earth, the availability of water and the controlled and rational utilisation of the resources a decisive factor in progress. Taking the present rate of water consumption and the population growth as a basis, the needs for water may be expected to increase to one and half times or even more of what they are now, in the next twenty years. Improving living standards - a rightful claim of all people in the world - the struggle to overcome famine in certain parts of the world by irrigation and by introduction of agriculture over ever larger areas, the establishment of new industrial plants and the progress of industry throughout the world, are expected to cause a further substantial increase in water demand.

To satisfy this growing demand considerable difficulties must be overcome, as for instance the varying distribution of the available resources in the different areas, the natural fluctuations in the water regime, the variations in the requirements in space and time and also the fact that over the most densely populated and industrialized regions, the pollution of natural waters and available resources, grows simultaneously with increasing needs.

The magnitude of this task implies that we should search every where and with every available means for those sources of fresh water that will appear the least costly in satisfying the steadily growing demands.

Comprehensive water management imperatively calls for thorough knowledge on the objectives of water resources development, on the magnitude of available resources, as well as their variations in time. A survey of the resources and an investigation into the water cycle on our planet, on our continent and on our country have become questions of immense importance. In their elucidation the first problem awaiting solution is, what exactly is meant under "available water resources".

This valuable booklet has been prepared by Dr. R.S. Varshney, former Secretary General, International Commission on Irrigation & Drainage which gives answer to the basic question as to what are "available water resources" on earth, on our Asia continent and on India. Attempt has been made to include information on water naturally surrounding our planet, in the forms of ice and vapour as well as liquid water; how all the forms and distributions with their varying abundance are linked together by hydrologic cycle; especially how water as a natural resource becomes available over our planet, continent Asia and our country India and broadly cover the effect which man is having, wittingly or unwittingly on this vital heritage.

Satish Chandra

(SATISH CHANDRA)

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THE HYDROLOGIC CYLCE AND WATER BALANCE

1.0 THE HYDROLOGIC CYCLE

The hydrologic cycle is a continuous process by which water is transported from the oceans to the atmosphere, to the land and back to the sea. Many sub-cycles exist. The evaporation of inland water and its subsequent precipitation over land before returning to the ocean is one example. The driving force for the global water transport system is provided by the Sun, which furnishes the energy required for evaporation. It may be noted that the water quality also changes during passage through the cycle; for example sea water is connected to fresh water through evaporation.

The complete water cycle is global in nature. World water problems require studies on regional, national, international, continental and global scales. The practical fact is that the total supply of fresh water available to the earth is limited and is very small compared with the salt water content of the oceans:

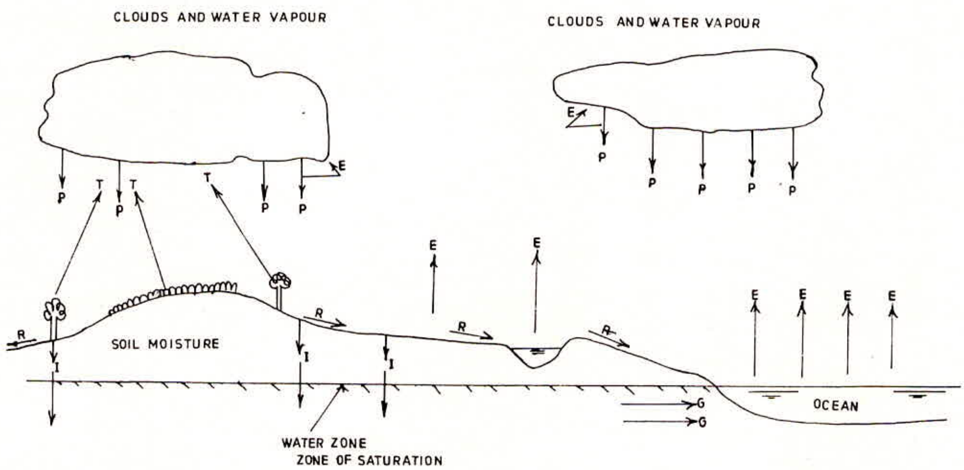

Fig.1: The hydrologic cycle.

T= Transpiration; E= Evaporation; P= Precipitation; R= Surface run-off
G= Groundwater Flow and I= Infiltration

The global water cycle is closely linked with the conversion of solar radiation, which is the only sub-stantial sources of energy for the physical processes which take place on the earth's surface.

The rays of the sun heat the surface of the earth, most of which has a temperature above the freezing point of water, which makes it possible for basins to contain water in the liquid state. In polar and high mountain regions, and over large areas of the temperate zone during cold periods of the year, low temperature on the earth's surface lead to creation of permanent and seasonal layers of water, as snow or ice.

The energy absorbed from solar radiation is largely used up in evaporation from the surfaces of water bodies, and from those of snow and ice. It is also expended in evaporation from soil whenever the soil contains sufficient moisture. Some energy is also expended for evaporating drops of water or ice forming crystals the clouds in the atmosphere.

The water vapour formed by evaporation is disposed in the atmosphere and where the relative humidity is sufficiently high, condensation takes place, forming water drops or ice crystals and giving rise to clouds and fog. During condensation a certain amount of heat is released, which, considering the earth as a whole is also expended for melting of snow and ice, while the formation of ice, when water or moisture in the soil freezes, is accompanied by a release of heat. Under natural conditions, the quantity of heat used to convert water from the solid to the liquid state and the release of heat in the opposite process of converting water to ice, are usually less obvious processes than the release of heat in the condensation of water vapour, or the expenditure of heat in evaporation.

The global water cycle on the one hand depends greatly on natural energy resources and, in turn exercises a considerable influence on the energy balance of the atmosphere and the earth's surface.

2.0 DISTRIBUTION AND ESTIMATED QUANTITIES OF WATER IN THE EARTH'S HYDROSPHERE.

It has been estimated that for each square centimetre of the earth's total surface, there are 273 litres of water, distributed as below.

Sea water	268.45	litre	98.33	percent
Fresh water	0.1	litre	0.036	percent
Continental ice	4.5	litre	1.64	percent
Water vapour	0.003	litre	0.0011	percent

Several attempts have been made in estimating the total water resources of the earth. The average estimates are given in Table 1.

Table 1: Approximate distribution of water in the Earth

Form of water	Area covered km^2	Volume km^3	Depth of m	Share of World's reserve of total water reserve	of fresh water reserve
World Ocean	361,300,000	1,338,000,000	3700	96.5	
Ground Water (gravitational and Capillary)	134,800,000	23,400,000	174	1.7	
Predominantly fresh ground water	134,800,000	10,530,000	78	0.76	30.1
Soil moisture	82,000,000	16,500	0.2	0.001	0.05
Glaciers and permanent snow cover	16,227,500	24,064,100	1463.2	1.74	68.7
Antarctica	13,980,000	21,600,000	1546	1.56	61.7
Greenland	1,802,400	2,340,000	1298	0.17	6.68
Arctic islands	226,100	83,500	369	0.006	0.24
Mountainous areas	224,000	40,600	181	0.003	0.12
Ground ice in zones of permafrost strata	21,000,000	300,000	14	0.022	0.86
Water reserves in lakes	2,058,700	176,400	85.7	0.013	
Fresh Water	1,236,400	91,000	73.6	0.007	0.26
Salt Water	822,300	85,400	103.8	0.006	
Marsh Water	2,682,600	11,470	4.28	0.0008	0.03
Water in rivers	148,800,000	2,120	0.014	0.0002	0.006
Biological Water	510,000,000	1,120	0.002	0.0001	0.003
Atmospheric Water	510,000,000	12,900	0.025	0.001	0.04
Total Water Reserves	510,000,000	1,385,984,610	27.8	100	
Fresh Water	148,000,000	35,029,210	235	2.53	100

Nearly three-fourth around 71 percent - of the 510 million square km of the earth's surface i.e. 360 million square km are covered by seas and oceans.

97.2 percent of the total resources is represented by salt-water, i.e. the amount of salt water in inland seas, oceans and salt lakes, totals 1300 million km^3.

Freshwater resources make out but 2.8 percent of the total i.e. 37 million km^3. A considerable portion of even small quantity of 37 million km^3, i.e. 28.5 million km^3 is made up by hardly accessible freshwater, accumulated partly in the polar ice caps and glaciers and partly in the moisture content of the atmosphere. This means that no more than 0.61 percent - in terms of volume 8.2 million km^3 - of the earth's entire water resources is at present under management. The distribution of this freshwater as may be seen in Table 1, shows that 1.52 percent of the total fresh water quantity on the continents viz 124,230 km^3 is above the surface while 98.48 percent of it i.e. 8,063,000 km^3 is underground water.

At any given time, the surface water resources represent a relatively small volume. But their significance and usefulness is augmented by the fact that they take part in the hydrologic cycle and are constantly renewed. The average water volume figuring in all rivers of the Earth amounts to 1230 km^3, the average annual discharge is between 31,000 and 37,000 km^3 - thus 25 to 30 times more than the volume stored.

The area of the earth's surface covered by sea water may be called the world ocean, the area of this ocean is 361.3 million km^2 and average depth is 3.7 km. These are four main oceans - the Pacific, Atlantic, Indian and Arctic Oceans. The proporational relation of the areas of the individual oceans is shown diagrammatically in figure 2. The basic morphometric characteristics of the oceans are given in Table 2 and the basic data on larger seas are given in Table 3.

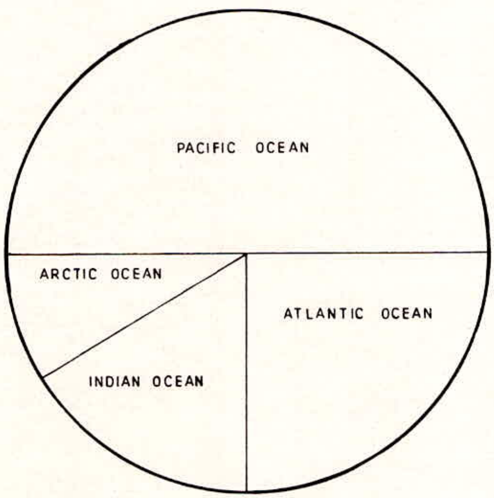

Fig.2: Proportional Relation of the Areas of Individual Oceans.

Table 2: Basic morphometric characteristics of oceans (after UNESCO)

Ocean	Overall area million km²	Area of the water surface million km²	Area of islands million km²	Volume of Water million km³	Average depth m	Max.-depth m
Pacific	182.6	178.7	3.9	707.1	3957	11,034
Atlantic	92.7	91.7	1.0	330.1	3602	9,219
Indian	77.0	76.2	0.8	284.6	3736	7,430
Arctic	18.5	14.7	3.8	16.7	1131	5,220
World ocean	370.8	261.3	9.5	1338.5	3704	11,034

Table 3: Basic morphometric characteristics of seas (after UNESCO)

Sea	Area 10^3 km²	Volume of Water km³	Average depth m	Max. depth m.
PACIFIC OCEAN				
Coral Sea	4,791	11,470	2,394	9,165
South China Sea	3,447	3,929	1,140	5,245
Bering Sea	2,344	3,796	1,640	4,191
Sea of Okhotsk	1,617	1,317	821	3,372
Sea of Japan	1,070	1,630	1,535	3,669
East China Sea	752	263	349	2,370
Banda Sea	695	2,129	3,064	7,440
Java Sea	480	22	45	89
Celebes Sea	435	1,586	3,645	5,842
Yellow Sea	417	17	40	105
Sulu Sea	348	553	1,591	5,576
Molucca Sea	291	554	1,902	4,970
Ceram Sea	187	227	1,209	5,319
Flores Sea	121	222	1,829	5,123
Bali Sea	119	49	411	1,296
Sawu Sea	105	178	1,701	3,370

Sea	Area 10^3 km^2	Volume of Water km^3	Average depth m	Max. depth m.
ATLANTIC OCEAN				
Carribean Sea	2,754	6,860	2,491	5,420
Mediterranean Sea	2,505	3,754	1,498	5,121
Gulf of Mexico	1,545	2,332	2,500	4,023
North Sea	554	52	96	809
Baltic Sea	448	20	48	459
Black Sea	431	555	1,170	2,211
Sea of Azov	40	0.4	9	14
Sea of Marmora	11	4	357	1,261
INDIAN OCEAN				
Arabian Sea	3,683	10,070	2,734	5,875
Bay of Bengal	2,172	5,616	2,585	5,258
Arafura Sea	1,037	204	197	3,680
Timor Sea	615	250	406	3,310
Andaman Sea	602	660	1,096	4,198
Red Sea	450	251	558	2,635
ARCTIC OCEAN				
Barents Sea	1,470	268	186	600
Norwegian Sea	1,547	2,408	1,742	3,860
Greenland Sea	1,205	1,740	1,444	4,846
East Siberian Sea	926	61	66	155
Kara Sea	903	101	113	620
Hudson Bay	819	92	100	274
Baffin Bay	889	593	861	2,136
Laptev Sea	678	363	540	2,980
Chuckchee Sea	590	45	77	160
Beaufort Sea	476	478	1,004	3,731
White Sea	91	4.4	49	330

Water in the Ice of Polar Regions and in the Glaciers of Mountainous Regions

The bulk of all fresh water is contained in the ice caps and glaciers of polar regions and in those of high mountainous regions. The distribution of ice cover over the earth is shown in Table 4.

Underground Ice Zones in the Permafrost Areas

Permafrost areas are distributed over an area of 21 million km^2, or 14% of the land. Most of this area is located in the Northern Hemisphere (consisting of north eastern Europe, the northern and north-eastern part of Asia, a large part of Canada, the islands of the Arctic Ocean and Green land). In the Southern Hemisphere, permafrost areas occupy about 1 million km^2 in Antarctica and in South America. In most areas permafrost does not exist at depths below 400 to 650 m, but it extends to a depth of 1500 m in the upper reaches of the Markha river in eastern Siberia.

In permafrost areas a certain amount of water is stored in areas of "Aufeis" formed by the freezing of ground water rising to the surface from beneath a layer of frozen-ground. River "Aufeis" formation have taken many years to develop and are often very large: their surface areas may extend to 100 km^2 and their volumes to 0.5 to 0.6 km^3.

Table 4: Distribution of Ice Formation by Region

Glacier region	Area of Ice covered surface (1,000 km^2)
Northern Polar regions	2,000
Temperate countries of the Northern Hemisphere	190
Tropical countries	0.1
Temperate countries of the Southern Hemisphere	26
Antarctica	14,000
Total for the earth	16,200

The water reserves in surface ice in Asia region are given in Table 5.

Table 5: Water Reserves in Surface Ice-Asia

Territory	Area of ice (km^2)	Water reserves (km^3)
Pamir Alia	11,255	1,725
Tien Shan	7,115	735
Dzungarian Alatau, Altai,Sayan Mountains	1,635	140
Eastern Siberia	400	30
Kamchatka, Koryak Range	1,510	80
Hindu Kush	6,200	930
Karakoram Range	15,670	2,180
Himalayas	33,150	4,990
Tibet	32,150	4,820
Total	109,085	15,630

Water Reserves in the Part of the Earth's Crust

It is usual to include in the natural groundwater reserves, the amount of gravity water contained in the pores and cracks of water bearing strata of the earth's crust. Calculations of the natural reserves of the ground water in the upper part of the earth's crust are broken down into continents and include depths down to 2000 m. Along this depth passes the isobath which marks approximately the limit of the continental crust of the earth. The amount of such water is shown in Table 6.

Annual Recharge of Ground Water

The volume of ground water in the total river run-off as determined by hydrograph separation is shown in Table 7.

Soil Moisture

Soil moisture is more closely related to weather conditions than is ground water. During wet seasons moisture is stored in the soil, while in dry seasons it is removed by evaporation and transpiration.

The most important changes in water storage occur in a layer of soil 1 to 1.5 m thick. Practically all soil moisture is contained within a layer 2 m thick.

Table 6: Natural amounts of groundwater in the upper part of the earth's crust by hydrogeological zones

Continent	Total area with islands 10^6 km^2	Mean attitude above sea level m	Zone classification	Thickness of zone m	Effective porosity %	Amount of ground water by zones 10^6km^3	Total amount ground water 10^6km^3
Europe	10.5	300	1st	100	15	0.2	
			2nd	200	12	0.3	
			3rd	2000	5	1.1	1.6
Asia	43.5	950	1st	200	15	1.3	
			2nd	400	12	2.1	
			3rd	2000	5	4.4	7.8
Africa	30.1	650	1st	200	15	1.0	
			2nd	400	12	1.5	
			3rd	2000	5	3.0	5.5
North America	24.2	700	1st	200	15	0.7	
			2nd	400	12	1.2	
			3rd	2000	5	2.4	4.3
South America	17.8	580	1st	100	15	0.3	
			2nd	400	12	0.9	
			3rd	2000	5	1.8	3.0
Australia and Oceania	8.9	350	1st	100	15	0.1	
			2nd	200	12	0.2	
			3rd	2000	5	0.9	1.2
Total							23.4

Zone 1 - Zone of active water exchange
Zone 2 - Zone of relatively active water exchange
Zone 3 - Zone of reduced water exchange

Table 7: Natural ground water resources renewed annually by continents

Continent	Annual volume of river run-off km^3	Ground water run-off in % of river run-off	Ground water run-off into Rivers km^3/yr.
Europe	3,210	35	1120
Asia	14,410	26	3750
Africa	45,570	35	1600
North America	7,450	29	2160
South America	11,760	35	4120
Australia	2,390	24	575
Total	43,790	30	13,320

* Excluding polar regions.

If we exclude from the total land area the 10% covered by ice and permanent snow, the 14% taken up by permafrost and the 21% accounted for by arid and semi-arid areas where free soil moisture is found only during relatively short periods (excluding irrigated areas), then the area of the soil cover containing moisture will amount to 55% of the land area, or 82 million km^2.

On the average, the 2 m layer of soil in question contains 10% of moisture, which is equivalent to a layer of water 0.2 m deep.

From the area of the soil cover (82 million km^2) and its moisture content (0.2 m of water) the calculated total storage of moisture in the soil is equivalent to 16,500 km^3 of water.

Water in Lakes and Reservoirs

Lakes of the world are one of the more important sources of water that are available for economic use.

On the average, the water storage in large lakes (area > 100 km^2) may be taken as equal to 95% of the total reserves in all lakes. The total water volumes in 145 large lakes throughout the word amounts to 168,000 km^3 i.e. the total volume of lake water amounts to 176,400 km^3. The water reserves in large lakes of the world are shown in Table 8.

Volume of water in some large lakes is given in Table 9.

The total capacity of the 10,000 man made reserviors of the world now in operation, or under construction amounts to about 5000 km^3 and the useful capacity to about 2000 km^3.

Table 8: Water reserves in large lakes of the world

Continent	Number of lakes with a water surface area > 100 km^2		Total area 10^3 km^2	Water reserve km^3	
	Total	Investigated		Fresh water	Salt water
Europe	34	30	430.4	2,027	78000
Asia	43	24	209.9	27,782	3165
Africa	21	15	196.8	30,000	
North America	30	20	392.9	25,623	19
South America	6	2	27.8	913	2
Australia and Newzealand	11	1	41.7	154	174
Total	145	92	1300	86,500	81360

Table 9: Volume of water in some large lakes of the world

Lake	Volume of water km^3
Ladoga	908
Saimaa	36
Vanern	180
Baikal	23,000
Tanganyika	18,900
Erie	545
Ontario	1,710
Winnipegosis	16

Water Storage in Swamps

Marshes include areas of land characterised by abundant, stagnant or slowly seeping moisture in the upper layers of soil and earth. The total area of marshland amounts to about 2,882,000 km^2 or about 2% of the land surface. The distribution of marshy areas throughout the continents is shown in Table 10.

Table 10: Distribution of marshlands throughout the world

Continent	Area of marshland	
	10^3 km^2	% of total area of continent
Eurasia	925	1.8
Africa	341	1.2
North America	180	0.9
South America	1,232	7.0
Australia	4	0.05

Marshes, on average, are 95% water. It can be estimated, therefore that the total amount of marsh water in the world is 11,470 km^3.

Water Storage in River Channels

Depending on changes in the climatic factors that effect run-off (precipitation and evaporation), the quantity of water in rivers changes continually from one year to another and from one season to another. As there is no flow in most rivers at their sources. it follows that the volume of river reserves is half the average long-term flow of rivers at their mouths, multiplied by their lengths. However, analysis of the normal water flow variations along the length of rivers in different parts of the world has shown that the average flow of water is generally 0.4 of the mean long term flow of water at the estuary. The river channel storage in each continent are given in Table 11.

Table 11: Water storage in river channels

Continent	Water storage in river channels km^3
Europe	80
Asia	565
Africa	195
North America	250
South America	1000
Australia and Oceania	25
Total	2115

Even though the volume of river water (2120 km^3) represents only 0.002% of the total water reserves on the earth and only 0.006% of all fresh water, it is of great importance to man as a continually renewed water supply.

Biological Water

The quantity of bioloical water-water contained in living organisms, is very small compared with that of other water resources. Neverthless it is an important link in the chain of processess making up the water cycle. Thus the greater part of the water evaporated from land areas reaches the atmosphere from the soil through transpiration by plants. About 12% of the total evaporation from the earth's surface is attributable to plants, although at any given moment plants contain only a small amount of water.

The total amount of living matter in the biosphere is 1.4 x 10^{12}t. The average water content in living matter is 80%. i.e. 1.12 x 10^{12}t or 1120 km^3. Of the total quantity of water contained in living organisms 60% circulates in the water cylce.

The quantity of bio-mass fluctuates during the year, following the death and growth of annual plants in countries with cold climate. The adjusted volume at biological water is only approximate: this is because quantitative estimates of the bio-mass vary with investigations from 366 x 10^{11} to 10^{14}t.

Water in the Atmosphere

Water is contained in the atmosphere in the form of water vapour, water drops and ice crystals. The total quantity of moisture in the atmosphere amounts to 12,900 km, equivalent to 25 mm of water spread over the whole surface of the earth. At 70^0 latitude the average water vapour content is 0.2%, at 50^0 latidue 0.9% and at the equator 2.6%. Under certain conditions the vapour content reaches 4%. The concentration of water vapour decreases very quickly with latitude; 70% of the total moisture in the atmosphere is in the first 3.5 km above the surface, while about 90% of all the vapour is in the layer from 0 to 5 km.

The amount of water vapour carried by air currents in wet and dry areas does not vary appreciably, although the annual quantity of precipitation in different areas is not the same. This is due to differences in atmosphere circulation and to differences in the relative moisture content of the air masses.

3.0 THE HYDROLOGIC - BUDGET

Because the total quantity of water available to the earth is finite and indestructible, the global hydrologic system may be looked upon as closed. However, these are many hydrologic sub-systems and these are the types analyzed by the engineering hydrologist. For any system a water budget can be developed to account for the hydrologic components.

To illustrate, assume the simple and highly restricted system of Fig.3. Consider a completely impervious inclined plane surface (water can not be transmitted through the surface), confined on all four sides with an outlet at corner A. Since this surface is assumed to be a perfect plane, there are no depressions in which water can be stored.

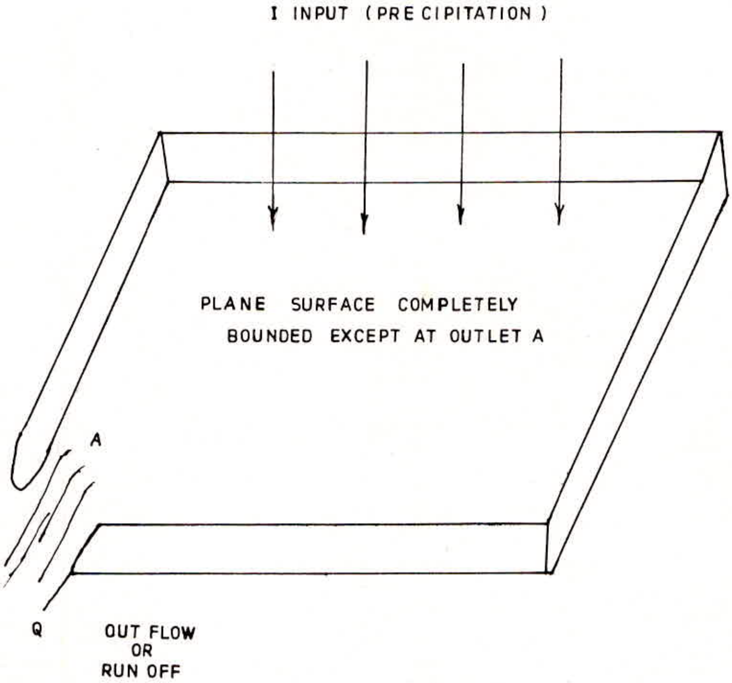

Fig.3: Simple Hydrologic System Model

If a rain storm input is applied, an output or outflow, designated as surface run-off, will be developed at A. The hydrologic water budget for this system can be represented by the following differential equation.

$$I = Q = \frac{ds}{dt} \qquad \text{...... (1)}$$

Where,

I	=	Inflow per unit time.
Q	=	Outflow per unit time.
ds/dt	=	the change in storage within the system per unit time.

Until a minimal depth is accumulated on the surface, outflow can not occur, but, as a storm intensifies, the depth retained on the surface (surface detention) increases. At the cessation of input, water held on the surface becomes the outflow, neglecting the small quantity electrically bound to the surface and any evaporation during the period of input (a reasonable assumption for the system depicted). This elementary illustration suggests that any hydrologic system can be described by a hydrologic budget which accounts for the disposition of inputs to the system and changes in storage.

A more generalized version of the hydrologic budget will explain the various components of a hydrologic cycle and provide an insight to problem-solving techniques for composite hydrologic regions. Such regions may be topographically defined area drained by a river/stream or system of connecting rivers streams such that all outflow is discharged through a single outlet.

To demonstrate the nature of a generalized hydrologic budget, figures 1,4 and 5 may be seen. A general hydrologic equation can be developed based on the concepts illustrated in figures 1 and 4. Figure 5, a more abstract version of figure 1, represents schematically the hydrologic cycle of a region and it serves a useful purpose, since it is readily translated into mathematical terms. Hydrologic varables P,E,T,R,G and I are defined in Figure 1. Susbcribes 's' and 'g' denote sectors originating above and below the earth's surface respectively. For example:-

Rg signifies groundwater flow that is effluent to a surface stream and Eg signifies groundwater flow that is effluent to a surface stream and Es represents evaporation from surface water bodies or other surface storage areas. Letter 'S' stands for storage. The region under consideration specified as 'A' has a lower boundary below which water will not be found. The upper boundary is the earth's surface. Vertical bounds are arbitrarily set as projections of the periphery of the region. For water budget, Fig.5 can be translated into the following mathematical statements, where all values are in units of volume per unit time.

1. Hydrologic budget above the surface.

$$P + R_1 - R_2 + Rg - Es - I - Ts = \Delta S_3 \qquad \text{.....} (2)$$

2. Hydrologic budget below the surface.

$$I + G_1 - G_2 - Rg - Eg - Tg = \Delta Sg \qquad \text{......}(3)$$

3. Hydrologic budget for the earth (sum of eqns. 2 and 3)

$$P - (R_2-R_1) - (Es+Eg) - (Ts+Tg) - (G_2-G_1) = \Delta (S_3 + Sg) \qquad \text{......} (4)$$

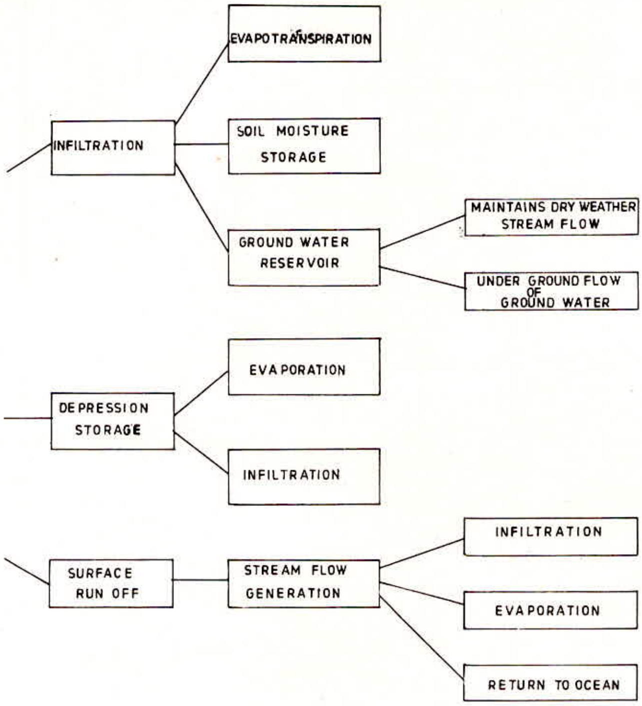

Fig.4: Flow Diagram Indicating Disposition of Infiltration, Depression Storage and Surface Run-off.

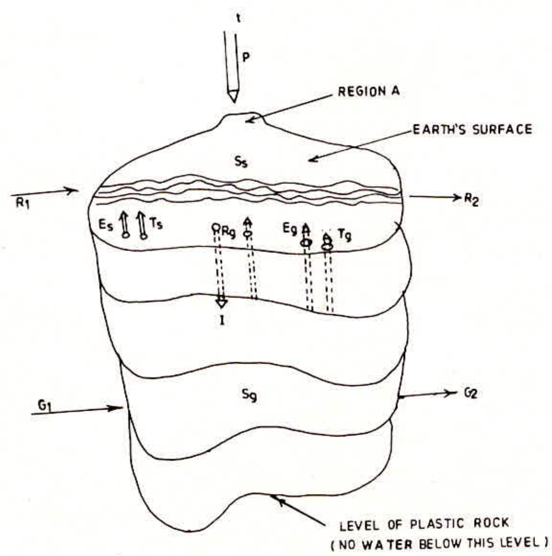

Fig.5: Schematic Diagram of Hydrologic Cycle for a Region

If the subcripts are dropped from equation 4, so that letters without subcripts refer to total precipitation and net volumes of surface flow, underground flow, evaporation, transpiration and storage, the hydrologic budget for a region can be written simply as:-

$$P - R - G - E - T = \Delta S \qquad \text{...... (5)}$$

This is the basic equation of hydrology

For the simplified hydrologic system of Fig.1, terms G,E and T do not apply and equation 5 reduces to:-

$$P - R = \Delta S \qquad \text{...... (6)}$$

which is basically the same as differential equation 1. The general equation 5 is applicable to exercises of any degree of complexity and therefore basic to the solution of all hydrologic problems.

The difficulty in solving practical problems lies mainly in the inability to properly measure or estimate the various hydrologic equation forms. For local studies reliable estimates are often made, but on a global scale quantification is usually crude. Precipitation is measured by rain or snow gauges located throughout the area. Surface flows can be measured using various devices such as weirs, flumes, velocity meters and depth guages located in rivers and streams of the area. Under good conditions these measurements are frequently 95% or more accurate, but large floods can not be directly measured by current methods and data on such events are sorely needed Soil moisture can be measured using neutron probes and gravimetric methods: infiltration determined locally by infiltrometers or estimated through the use of precipitation run-off data. Areal estimates of soil moisture and infiltration are generally very crude, however, the extent and rate of movement of groundwater are usually exceedingly difficult to determine, and adequate data on quantities of groundwater are not always available. Knowledge of the geology of a region is essential for groundwater estimates if they are to be more than just rough guides. The determination of the quantities of water evaporated and transpired is also extremely difficult under the present state of development of the science. Most estimates of evapotranspiration are obtained by using evaporation pans, energy budgets, mass transfer methods, or empirical relationships. A predicament inherent in the analysis of large drainage basins is the fact that rates of evaporation, transpiration, and groundwater movement are often highly heterogeneous.

Nevertheless the hydrologic equation is a useful tool and it can be employed in various ways to estimate the magnitude and time distribution of hydrologic varaibles.

Special Features of the Water Balance Equation for Different Time Intervals

The water balance may be computed for any time interval, but distinction may be made between mean water balances and balances for specific periods (such as a year, season, month or number of days) sometimes called current or operational water balances. Water balance computations for mean values and specific periods each have distinctive characteristics. Mean water balances are usually computed for an annual cycle (calendar year or hydrological year), although they may be computed for any season or month.

The computation of the mean annual water balance is the most simple water balance problem, for over a long period, positive and negative water storage variations tend to balance and their net value at the end of a long period may be assumed to be zero.

The reverse situation occurs when computing the water balance for short time intervals, for which $\Delta S = O$. The shorter the time interval, the more precise are the requirements for measurement or computation of the water balance components, and the more sub-divided should be the values of ΔS and other elements. This results in a complex water balance equation which is difficult to close with acceptable errors. The term ΔS must also be considered in the computation of mean water balances for seasons or months.

Special Features of the Water Balance Equation for Water Bodies of Different Dimensions

The water balance may be computed for water bodies of any size, but the complexity of computation depends greatly on the extent of the area under study.

A river basin is the only natural area for which large scale water balance computations can be simplified, since the accuracy of computation increases with an increase in the river basin's area. On the other hand the complexity of the computation of the water balance of lakes, reservoirs, swamps, groundwater basins and mountain - glacier basins tends to increase with increase in area, mainly because of difficulty in accurate measurements.

Closing of the Water Balance Equation

The discrepancy of water balance is given as a residual term of the water balance equation and includes the errors in the determination of the components, and the values of the components not taken into account by the particular form of the equation being used.

4.0 WATER CYCLE AND WATER BALANCE IN THE ATMOSPHERE

The term "World Water Balance" can be taken to mean determination of the relation between different forms of water, within the process of their specific cycling on the earth. Within this balance, separate water balances may be examined. For the ocean that between evaporation, precipitation and run-off from rivers and groundwater; for the land, that between precipitation, evaporation, infiltration and run-off; and for the atmosphere that between evaporation, precipitation and moisture transfer.

4.1 Atmospheric Circulation

Air currents, caused by atmospheric circulation, transfer water vapour over long distances, create vertical movements of considerable magnitude, lift moisture into the upper part of troposphere, lead to the formation of precipitation and also cause inequalities in its distribution in time and space. Thus atmosphere circulation is closely related to both the water cycle and the water balance. The energy basis of the overall atmospheric circulation is uneven heating of the earth's surface caused by the different influxes of solar radiation of various latitudes and different conditions of its absorption and conversion into heat through different forms of active surface. The greatest differences occur between land and ocean; they vary according to seasons and latitude, and also between surfaces covered with ice and snow and bare surface. The contrasts of energy inflows of different latitudes and the consequent temperature differences can be compared generally with differences between the ocean, the land, and the polar ice covers. These contrasts occurring on the rotating earth, finally determine the field of atmosphere pressure and cause the transfers of air masses, heat and moisture condensationof water vapour during the process of atmospheric circulation (especially at the fronts of cyclones and within the tropical zone of conveyance, and also when passing over orographic obstacles), is a source of energy approximately 5 times as great as straight forward turbulent heat flows. Atmospheric circulation processes are instable over areas equal to or smaller than a hemisphere. Transfers along parallels of latitude alternate with meridional dispersals and circulation zones are displayed in the process of vortex formation as well as by changing seasons and by changing conditions on the active surface. In this connection, general circulation and precipitation processes under go particularly great changes in time and space, forming unpredictable weather during short intervals of time (specially in temperate and high latitudes) and climatic fluctuations over larger periods.

4.2 Water Cycle and Water Balance in the Atmosphere

The water balances of the earth's surface and of the atmosphere are closely inter related. Exchange of moisture between continents and oceans occurs in the atmosphere by phase changes of the water as well as by the transfer of water vapour in transit over land.

The equation for the water balance of the atmosphere over any region (related to a unit of area) may be expressed in the form

$$Q' = P - E + \triangle W \qquad \text{...... (7)}$$

Where,

$\triangle Q'$	=	change of the total flow of moisture in the atmosphere
P	=	average precipitation
E	=	average evaporation
$\triangle W$	=	change in moisture content (precipitable water) of the atmosphere

Equation (7) gives the relation between the main elements of the water balance in the system of interactive media-the atmosphere and the active surface. It makes it possible to evaluate the "climate" flux (P-E) from moisture changes in the atmosphere.

Exchange of moisture between continents and oceans and within continents occurs in two ways. For small areas, advection of moisture in any direction is followed by discharge beyond its boundaries of the water vapour formed over the given area. At the same time the directions of moisture transfers of different heights may differ. The value of the water vapour dispersion for small territories is insignificant.

When the area under investigation is large and the separate moisture transfers are small, random outflows of water vapour cease to be of importance in the exchange of moisture over the region concerned and over adjoining regions. As a result, the effective moisture transfer velocity is nearly equal to the resultant velocity of the wind at each level of free atmosphere.

Table 12 presents data on the water content of the atmosphere over the continents and oceans of the globe throughout the year. The total water content of the atmosphere of our planet, including the polar regions amounts to 12,900 km^3. The moisture content in the atmosphere above the oceans makes up about two-thirds of the total atmosphere content. The largest transfers of water vapour are also over the oceans (up to 98,000 km^3 over the Pacific Ocean).

Table 12: Annual Water Resources of the atmosphere over continents and ocean

Continents/Oceans	Area excluding islands	W=Moisture continent in the atmosphere column km^3	Total Annual transfer of moisture km^3
Continents			
Europe	9.8	144	10,000
Asia	40.8	864	20,100
Eurasia	50.6	1008	22,000
Africa	29.5	848	24,600
North America	20.1	329	12,300
South America	17.7	522	20,700
Australia	7.6	183	12,800
Antarctica	14.0	21	860
Islands		200	
Sub Total		3100	
Oceans			
Arctic	14.7	97	4,150
Atlantic	91.7	2400	58,100
Indian	76.2	2100	58,700
Pacific	178.7	5200	96,750
Sub Total		9800	
Total moisture content of the atmosphere		12900	

5.0 HYDROLOGICAL CYCLE ON THE EARTH

5.1 Basic Information

Water is in continual movement. It is used and recycled throughout the water cycle process.

Every year 577,000 km^3 of water evaporates from the surface of the globe. Most of this (505,000 km^3) is from the World Ocean and a smaller part (72,000 km^3) is from land areas. Evaporation moisture condenses and falls as precipitation.

Total annual precipitation on the ocean amounts to 458,000 km^3 which is less than the evaporation. The surplus of the evaporated moisture, a total of 47,00 km is transfered by air currents to continents and islands where it forms rivers, lakes, glaciers and ground water, thus creating conditions favourable for development of the natural environment and for the economic activities of man. The same amount of water returns to the ocean during the year in the form of river run-off (approximately 45,000 km^3) and direct discharge of ground water not drained by rivers (approximately 2,000 km^3).

Precipitation on land (exlcuding islands) derived from moisture brought in from the ocean amounts to 66,000 km^3. Thus there is an excess of precipitation of oceanic origin amounting to 19,000 km^3, which falls on land, is evaporated again, and is carried away to the ocean.

The humidity of different areas of the earth varies as a result of the general circulation of the atmosphere. This circulation is caused by uneven heating of the oceans and continent and by the differing conditions for evaporation and condensation of moisture. Consequently, some regions have a permanent excess of humidity and others a shortage.

The maximum amounts of evaporation from the ocean, which are related to very dry air flows, take place in the trade wind zones of both hemispheres, between 10^0 and 20^0 latitude.

Maximum precipitation over the world ocean is in the equatorial zone, in the 10^0 to 0^0 N. latitude belt (2,280 mm per year on the average).

The greatest precipitation, more than 4,000 mm per year falls in the Indian ocean near the coasts of Indonesia and Myanmar (Burma), and the least is observed in the tropical trade wind zones of the Northern and Southern hemispheres, between 20⁰ and 30⁰ N. latitude (690 mm) and between 20⁰ and 30⁰ S.latitude (1170 mm). Minimum precipitation (less than 50 mm per year) falls in the eastern parts of the oceans adjoining deserts for example the Sahara Desert and the Arabian Peninsula. On the whole the amount of precipitation on the oceans is related to peculiarities of atmospheric circulation (trade winds and monsoons) and to the distribution of warm and cold sea currents.

The moisture balance for the water exchange between ocean and land is given in Table 13.

5.2 Duration of Discharge and Renewal of Different Kinds of Water

The basic mechanism of the water cycle process in nature is water exchange between the ocean and the land, which can be balanced for a yearly cycle. It also provides the starting point for other links of the complete cycle.

The different forms of water are interrelated during their displacement. The velocity of transfer of different forms of water is not the same, so the time required for their discharge and renewal is also different. It fluctuates between very wide limits: from a few hours (biological water) to several thousands of years (glaciers) and even tens of thousands of years (ground water).

Table 13: The moisture balance of continent

Continent	Area 10^3 km^3	Total annual transfer of moisture km^3	Moisture in transit over continent km^3	Advective precipitation (mainly of oceanic origin) km^3	River run-off km^3	Atmospheric run-off due to evaporation from land km
Europe	9,800	10,100	4,800	5,310	2,730	2,500
Asia	40,775	20,100	4,200	15,860	10,790	5,300
Africa	29,530	24,600	9,500	15,080	4,185	9,200
North America	20,060	12,300	2,500	9,790	6,630	2,800
South America	17,800	20,700	3,800	16,900	11,760	3,700
Australia	7,615	12,800	9,700	3,040	301	2,560
Total	125,580	100,600	34,500	66,000	36,400	26,100

The periods of renewal for reserves of different forms of water, calculated from data on their annual rate of discharge, are given in Table 14.

Table 14: Periods of renewal (average) for resources of water on the earth

Form of Water	Period of renewal	Form of Water	Period of renewal
World Ocean	2500 yrs.	Under ground ice in permafrost areas	10,000 yrs.
Ground water	1400 yrs	Water in lakes	17 yrs
Soil moisture	1 yr.	Water in marshes	5 yrs
Polar glaciers and permanent snow cover	9700 yrs.	Water in river Channels	16 days
Glaciers of mountain ranges	1600 yrs.	Biological water	a few hours
		Atmospheric moisture	8 days

5.3 Ground Water Run-off into the World Ocean

Ground water flows into the world ocean in three distinct ways:

1. By degasification of the mantle (juvenile water);
2. As the underground component of river run-off;
3. By underground run-off originating on land, by passing rivers, and emptying directly into the sea.

From the studies undertaken on the subject the following conclusions may be drawn.

1. A rough estimate of underground discharge directly into the world ocean, obtained independently by a hydrodynamic method is approximately 2,200 km^3/yr, or 70,000 m^3s^{-1}. This is very small in comparison with other elements of the world water balance.

2. In spite of the small part played by underground discharge in the water balance of seas and oceans, its role in the formation of their salt balance and also in their temperature and hydrobiological regimes may be quite important.

6.0 WATER BALANCE AND WATER RESOURCES OF ASIA

6.1 General

Asia (area inlcuding islands 43,475,000 km^2) is a part of the Eurasian continent. Europe is separated from Asia by the Ural mountains. The Asian continent is washed by the waters of four oceans; a considerable part of it is composed of internal run-off areas (12.3 million km^2), the largest of which is the central region (area 9.5 million km^2).

With respect to the oceanic slopes the surface of Asia (including island) is distributed (fig 6) as follows (including internal run-off areas of the slopes).

Arctic Ocean	11672,000	km^2	or	26.9%
Pacific Ocean	11905,000	km^2	or	27.4%
Indian Ocean	9656,000	km^2	or	22.2%
Atlantic Ocean	742,000	km^2	or	1.7%
Total	33975,000	km^2	or	78.2%

There are some very large lakes in Asia (Lake Baikal, the Aral Sea, etc). Many of its rivers are among the largest in the world. The water content of the Ganga-Brahmaputra river system is the third largest in the World (after the Amazon and the Congo rivers), and the Yangtze (5,520 km) is the fourth. The Yangtze is the longest river in Asia; only the Nile, Amazon and the Mississippi are longer than it.

Total solar radiation varies approximately from 7 kcal cm^{-2} yr^{-1} in the far north to 160 to 200 kcal cm^{-2} yr^{-1} in the subtropical and near-equatorial latitudes. Differences in the radiation balance, which characterize the energy aspect of the water balance, are even greater: from about 10 kcal cm^{-2} yr^{-1} in the Arctic to 80 to 90 kcal cm^{-2} yr^{-1} in the tropical and equatorial areas.

Moisture transfer from the Atlantic Ocean is of great importance to humidification in the northern half of Asia and its southwestern areas whereas the south eastern and eastern area depend on moisture transfer from the Pacific and Indian Oceans.

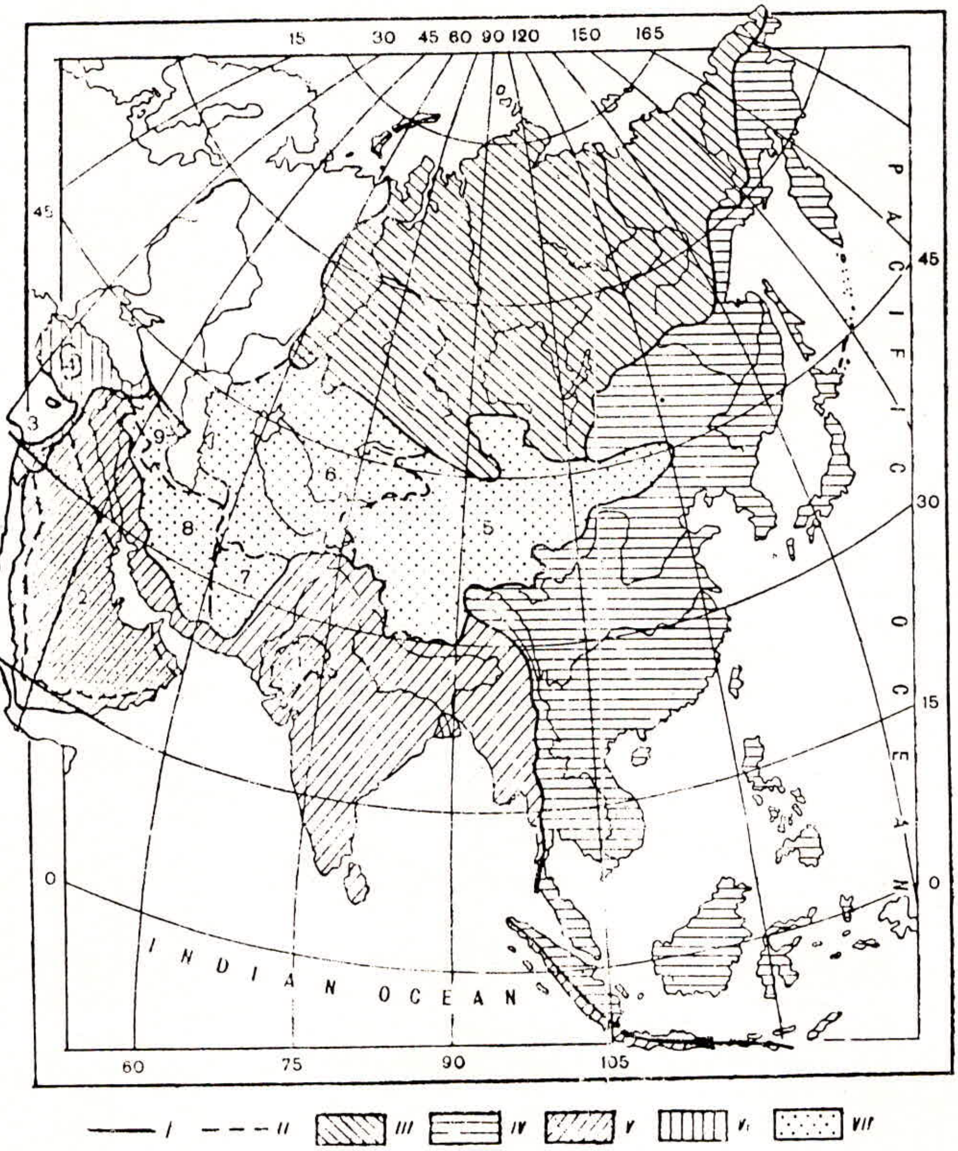

Fig. 6: Ocean drainage basins of Asia.

I- Boundaries of drainage basins, II- Boundaries of internal run-off regions:
Ocean basins: III-Arctic Ocean; IV-Pacific Ocean; V- Indian Ocean; VI- Atlantic Ocean;
VII- Internal run-off regions;
1. Thar Desert, 2- Arabian Peninsula, 3- Dead Sea basin, 4- Inland Anatolia, 5- Central Asia,
6- Kazakhstan and Middle Asia, 7- Seistan depression and adjacent regions, 8- Iranian highlands,
9- Precasplan area.

The moisture content of the atmosphere above Asia (in the layer between 0 and 7 km) amounts to 21.2 mm/yr (864 km^3). Of the whole amount of moisture mainly oceanic-that reaches the continent (about 20,100 km^3), precipitation represents 79%. The remaining 21% is carried away in the atmosphere. Loss of water vapour from the continent, including moisture that evaporates from the land surface, amounts to approximately 47% of the moisture carried in from the oceans.

The moisture that comes from the Indian Ocean and the south-western part of the pacific is of particular significance with regard to the general water balance of Asia, especially during the summer monsoon. The northern boundary of the south western (summer) monsoon can be represented approximately by a line joining the cities of Magadan and Damascus. However, the main mass of the moisture it carries remains in south-eastern Asia (Indian subcontinent with the adjacent mountain complexes, Indochina, Southern China, the islands in the subtropical and near equatorial latitudes, as well as a strip of the eastern coast of the continent in the temperate zone).

The areas subject to the influence of the Indian and Pacific oceans get more than 70% of the total volume of the continental precipitation, in spite of the seasonal character of their precipitation (almost exclusively in summer).

Orography has a marked influence on the water balance of Asia, which is felt mainly in the distribution over the continent of the moisture that comes from the oceans.

Asia can be divided into seven latitudinal zones (fig. 7). In over 70% of the surface of the tropical zone, variation in natural conditions corresponds to vertical belts (of different types). This is also the case in other zones, but to a lesser degree.

6.2 Precipitation

Climatic contrasts between the different parts of Asia are in no respect so clearly marked as in the extremely uneven distribution of precipitation. Precipitation is exceptionally abundant on the southern slopes of the Himalayas,

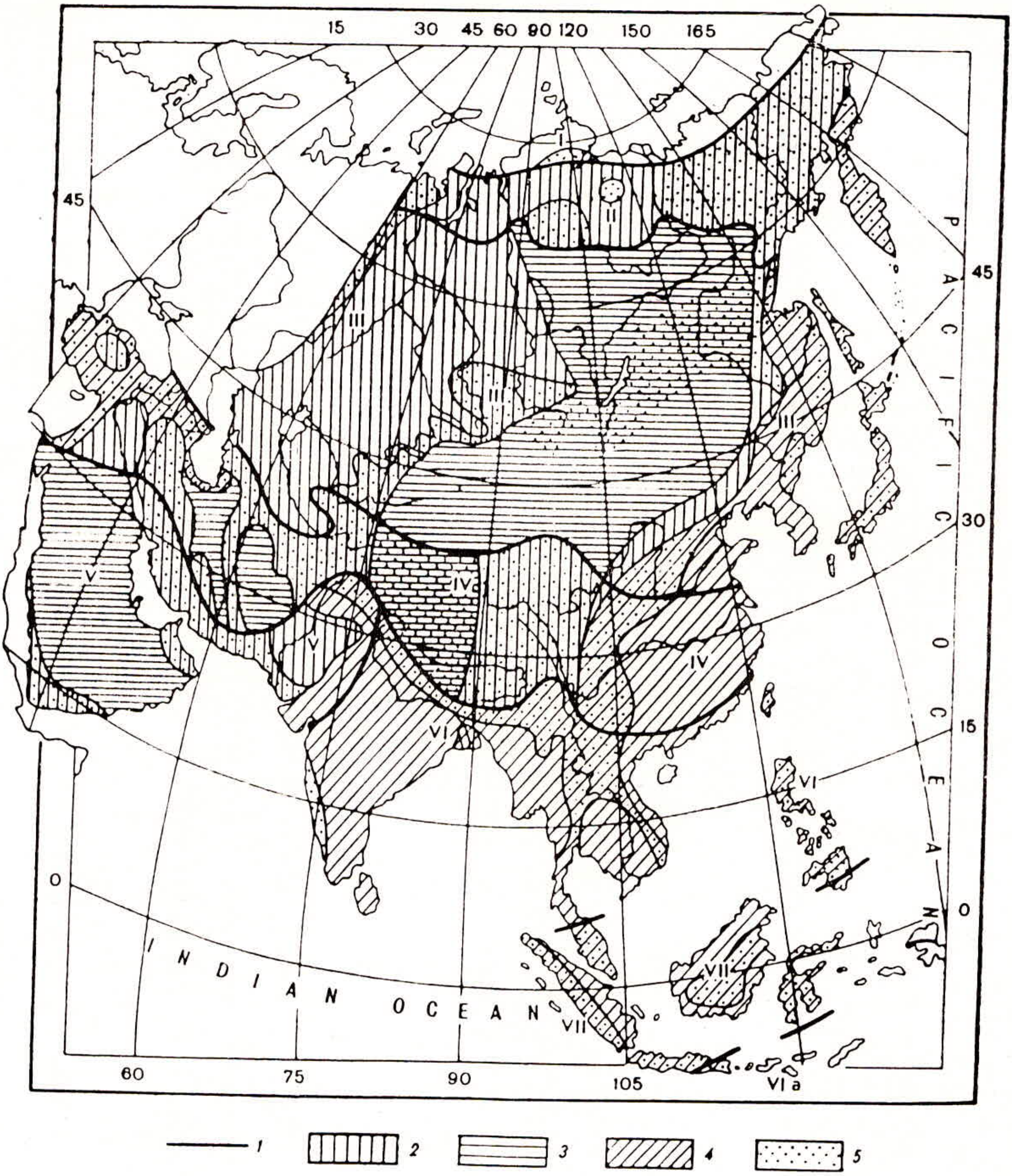

Fig. 7: Geographical belts in Asia (according to [185], pages 75, 116)

I-arctic, II- subarctic. III- temperate, IV-subtropical, V- tropical, VI- sub-equatorial (VIa- of the Southern Hemisphere), VII- equatorial.

I- boundaries of the belts. 2- areas with a continental or moderately continental climate, 3- areas with a markedly continental climate, 4- near-oceanic areas or areas subject to marked (permanent or seasonal) influence of the ocean on the climate, 5- mountainous territory, characterized by vertical climatic and natural vegetation zones.

on the western slopes of the mountains of Hindustan and Indochina, and on all the islands of Indonesia, which receive yearly 1500 to 3000 mm of rain and in some places considerably more. It includes one of the most humid regions in the world-Cherrapunji, which has an average annual precipitation amounting to 11,270 mm. On the other hand, almost all of the south-western part of the continent the huge expanses of inner Asia are extremely dry; in many regions, precipitation amounts to less than 200mm/yr. The average precipitation in Asia is shown in Table 15.

Annual variation in precipitation is shown in figures 8 & 9.

6.3 Potential and Actual Evaporation

The mean values of potential and actual evaporation in Asia as a whole are given in Table 16.

6.4 Average Annual run-off and its Areal Distribution

The range of run-off variation within Asia is very wide-from 4000-5000 mm or more to almost zero values. The region which has the most run-off is the Asian islands (Malay Archipelago, the Philippines, etc) and on the continent the mountain ranges and uplands of Indochina, southern China and the eastern parts of India (Himalayas), where most of the very large rivers of southern Asia (Indus, Ganga, Brahmaputra, Irravaddy, Mekong, Hsi Chiang) have their source. In respect of the specific water content, the Brahmaputra and Irravady are the first of the large rivers of Asia (mean depth of run-off: 1,100 to 1,200 mm). In the basin of Brahmaputra (Shillong plateau) the flow appears to be more than 5,000 to 6,000 mm (precipitation at Cherrapunji reaches 11,000 mm). A high run-off (3,000 to 4,000 mm) is observed on the southern slopes of the eastern Himalayas, in the western coastal areas of Indochina (windward slopes of the Arakan and Tenasserim ranges), and in the mountainous ranges of the Indonesian islands. Run-off of 3,360 mm has been recorded in the Western Ghats (Ghatprabha river: surface of the drainage basic as for as the gauge station, 347 km^2: period of observation, 24 years).

Table 15: Average annual amount of precipitation (mm) in Asia (including islands)

Latitude degrees	Longitude east (degree) 20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120-130	130-140	140-150	150-160	160-170	170-180	Longitude west degrees 180-170	average
0-80 N								290										290
80-70	-	-	-	-	395	402	433	543	425	367	358	292	276	276	-	233	236	398
70-60	-	-	-	-	625	590	630	764	524	388	374	342	415	434	526	602	584	518
60-50	-	-	-	-	450	454	682	546	475	540	541	658	700	996	1060	-	-	571
50-40	760	-	-	200	205	414	310	197	178	330	646	756	1660	-	-	-	-	370
40-30	777	424	344	241	272	706	299	412	644	806	1142	2300	1870	-	-	-	-	537
30-20		61	78	100	140	675	1440	2110	1420	1740	2100	-	-	-	-	-	-	995
20-10		-	176	66	-	1270	1190	2450	1820	1950	2710	-	-	-	-	-	-	1350
10-0 N		-	-	-	-	1410	1700	2750	2470	3180	2340	-	-	-	-	-	-	2650
0-10 S		-	-	-	-	-	-	-	3200	2520	2160	-	-	-	-	-	-	2595

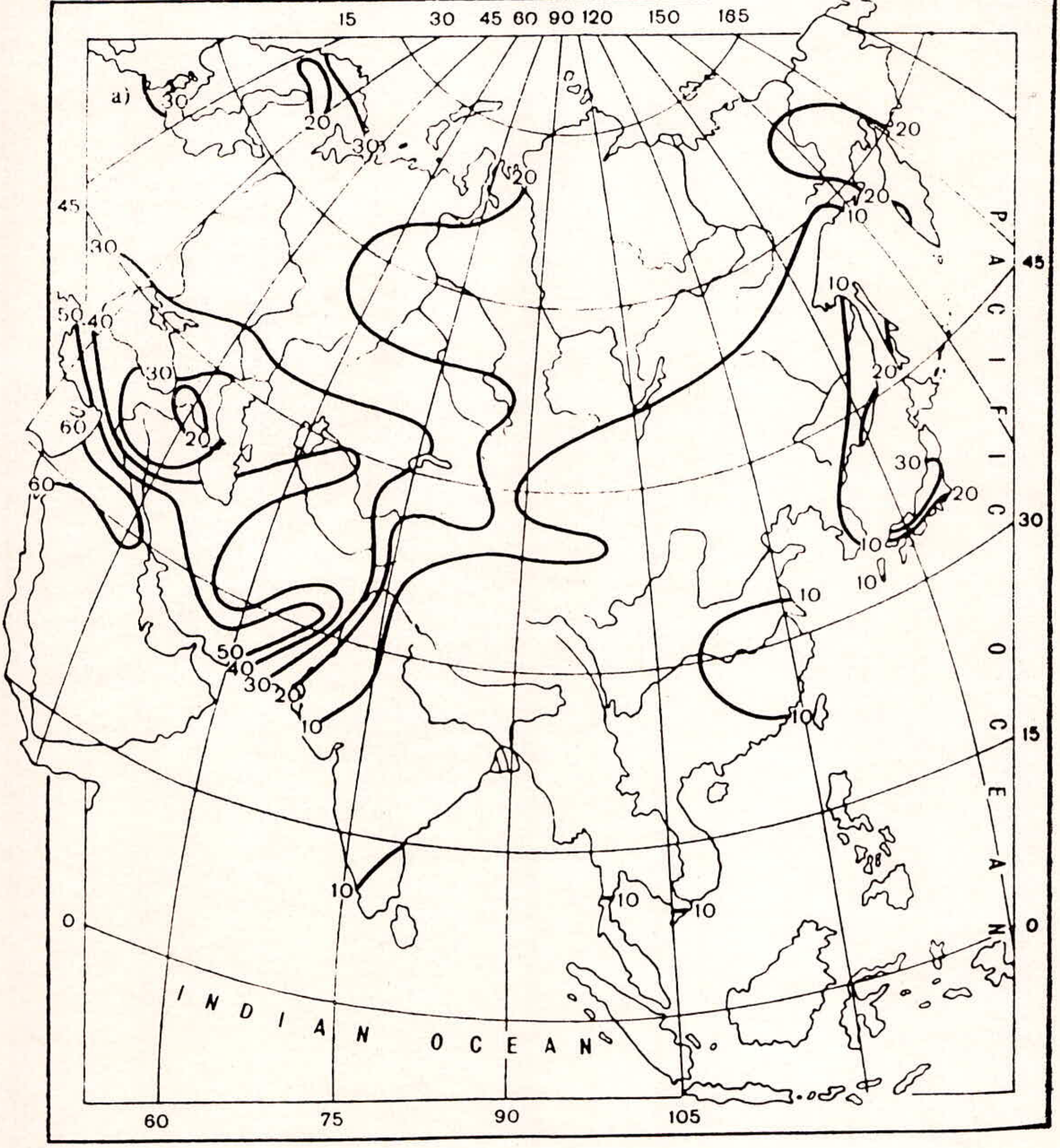

Fig 8a: Distribution of precipitation over the seasons (in percentages of the annual total)
Winter (December to February)

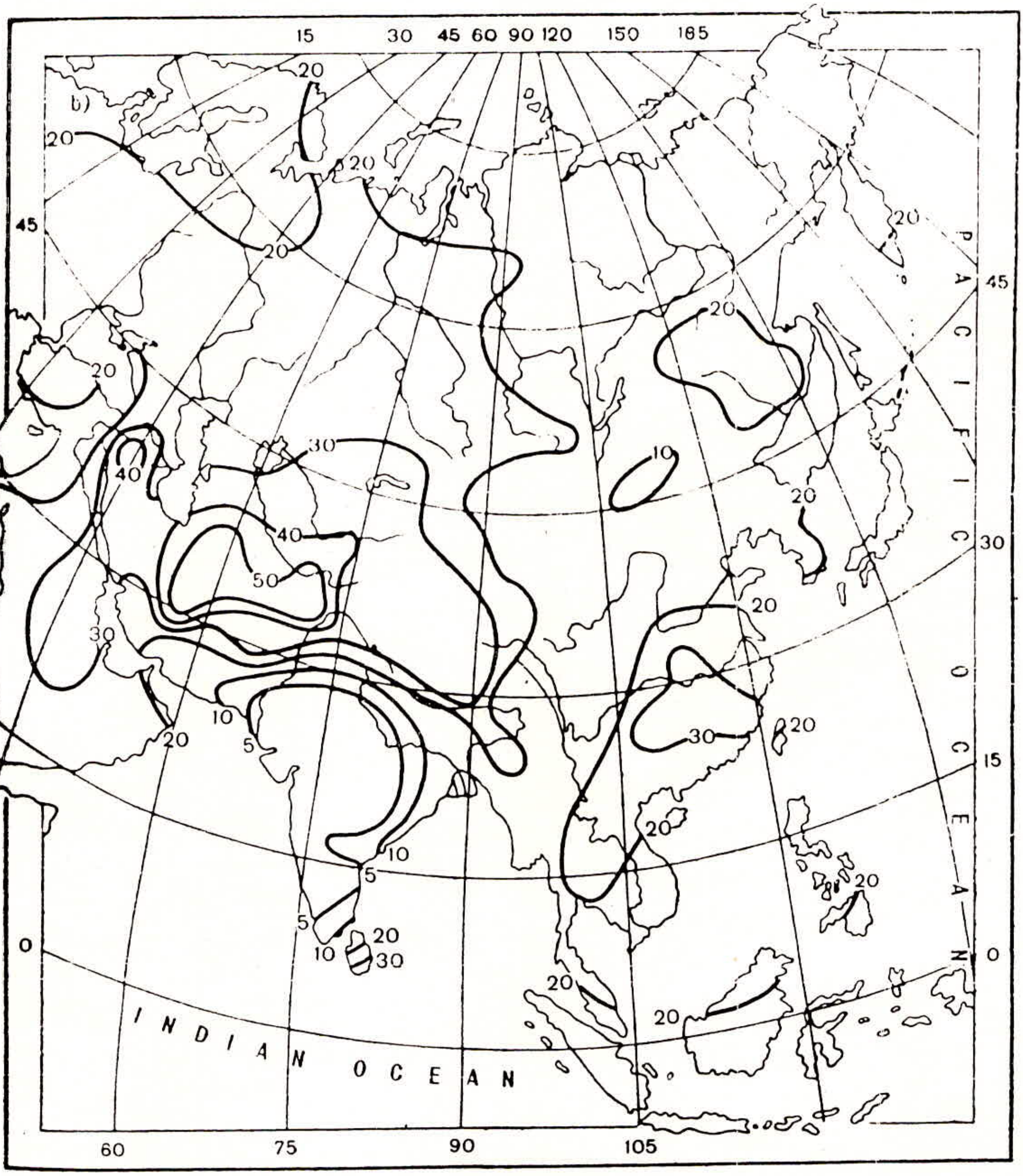

Fig 8b: Distribution of precipitation over the seasons (in percentages of the annual total)
Spring (March to May)

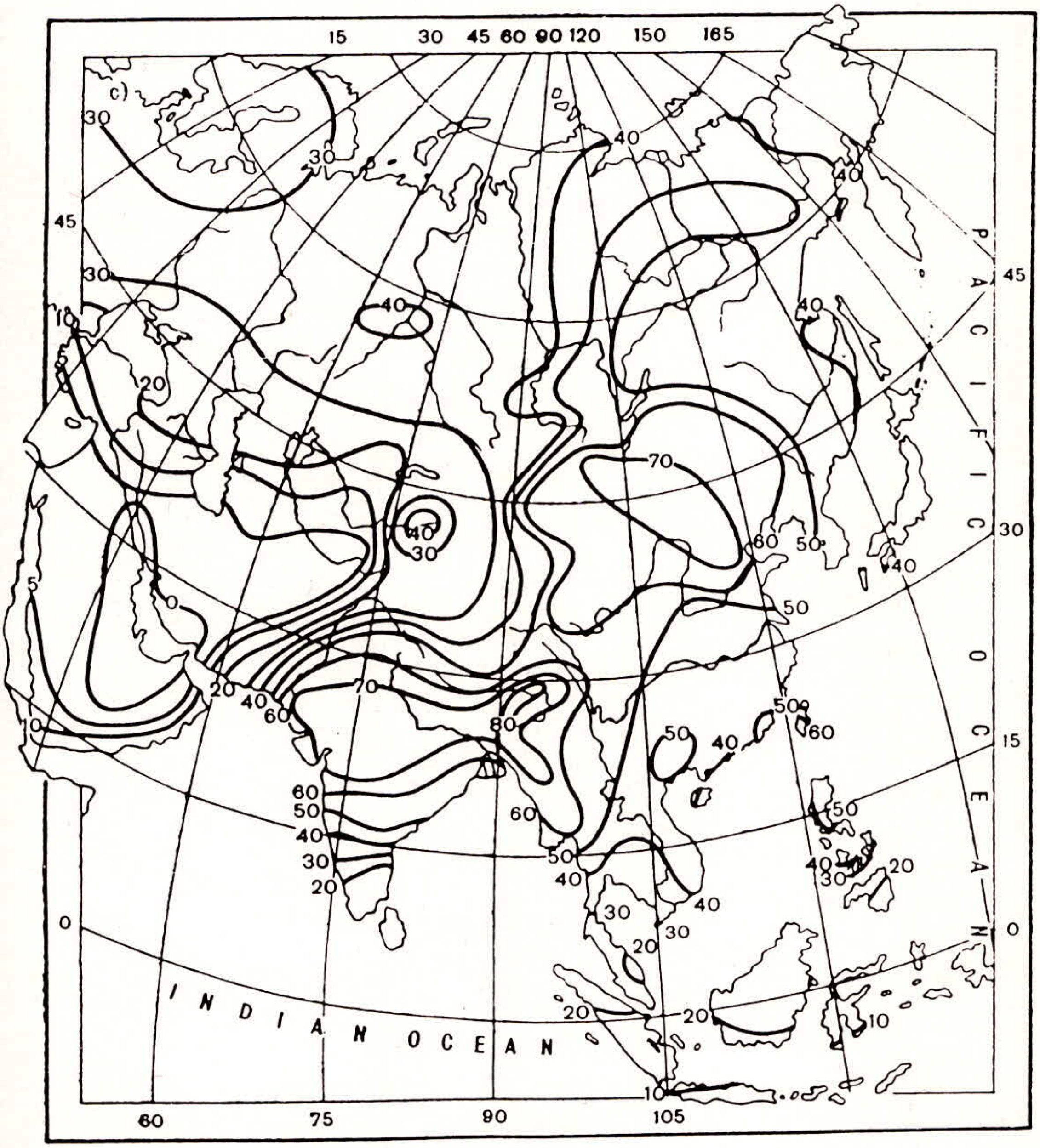

Fig 9a: Distribution of precipitation over the seasons (in percentages of the annual total)
Summer (June to August);

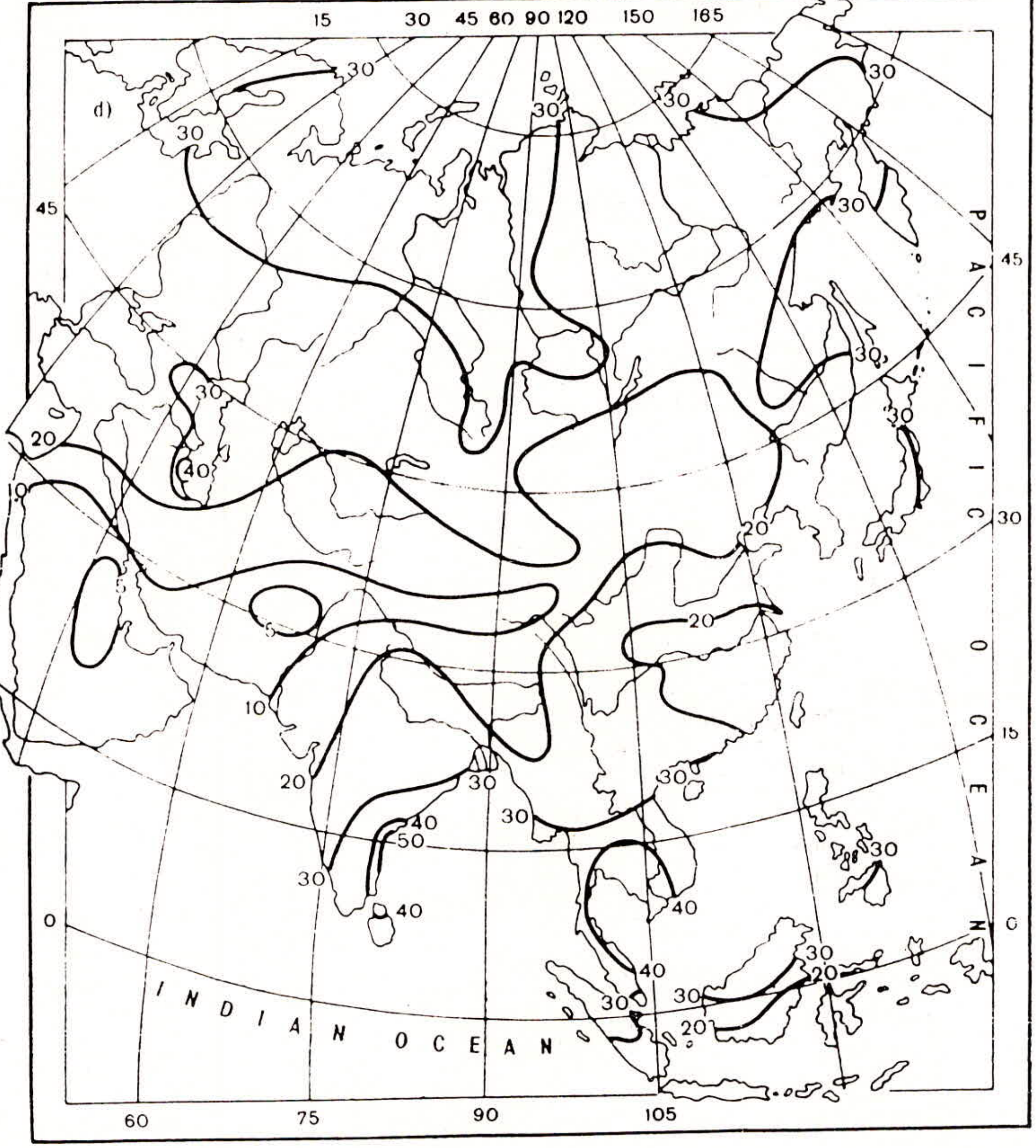

Fig 9b: Distribution of precipitation over the seasons (in percentages of the annual total)
Autumn (September to November)

Table 16: Mean values of potential evaporation in Asia (including islands)

Latitude in degrees	82-70	70-60	60-50	50-40	40-30	30-20	20-10	10-0N	0-10S
Potential evaporation mm/yr	210	360	510	910	1220	1650	1740	1340	1510
For the whole continent	1050								
Actual Evaporation mm/yr	160	260	350	260	320	470	660	1160	1170
For the whole continent	450								

Asia is characterised not only by an extremely uneven river run-off distribution over its expanses and considerable annual variations but also by a quite wide variability within the year (Fig. 10).

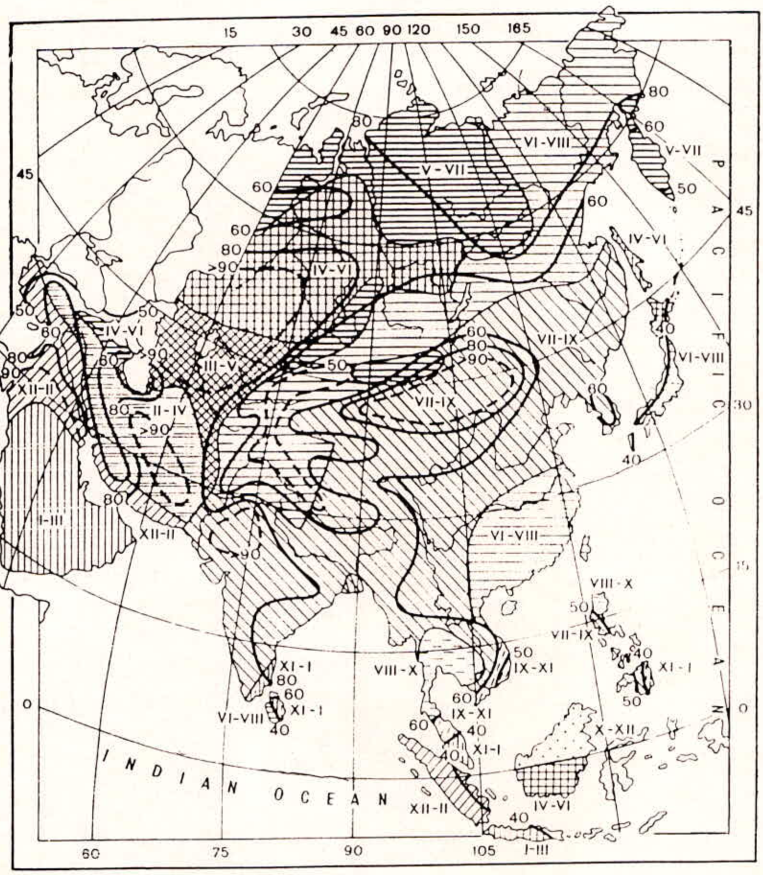

Fig. 10 Run-off for the three-month phase of highest water, in percentages of the annual run-off (rivers with watersheds ranging from 5,000 to 20,000 km²

I-XII-months

Most rivers in the south eastern part of Asia have their highest stages from July to September. In these months the run-off, which in the rivers on India, reaches 80 to 90% of its annual values, decreases to 60 to 55% east of the monsoon area, because of the prolonged activity of the south-western monsoon in this area.

6.5 Water Balance

6.5.1 Water Balance of Continent

Table 17 gives the water balance of Asia. One remarkable feature of the water balance in Asia is the notable difference between the quantities of river run-off originating within the boundaries and the flow actually reaching the ocean. This is due to vast areas of internal run-off as well as to water losses from rivers travelling to the ocean across arid regions. Underground flow towards the ocean is approximately 570 km^3 or 1.8% of the precipitation. A part from deep infiltration of precipitation, it seems that groundwater is formed to a certrain extent by river water that soaks into alluvial plains composed of loose, thick sediments.

6.5.2 Water Balance of the Ocean Slopes and Areas of Internal Run-off

The largest quantity of precipitation falls on the slope of the Pacific Basin (about 1000 mm on an average) and the smallest quantity on the slope of the Arctic Basin (approximately 500 mm). The entire run-off generated in these areas (435 and 202 mm respectively) reaches the ocean, since the losses of river water are very low (they do not exceed 1% of precipitation).

A characteristic feature of the water balance of the central area of internal run-off is the sharp contrast between the degree of moistening of the mountains and the vast plains adjoining them. Due to arid conditions prevailing in the plains, the flow generated in the mountains, is spent entirely by evaporation. As they flow from the mountains, most rivers disappear. The largest rivers carry their water through deserts, ending in no-outflow reservoirs (Aral Sea, Balkhash etc). The value of the local run-off relative to the whole surface of the area considered (9.5 million km^2) is not more than 47 mm, that is, about seven times less than for the peripheral part of the continent. The respective contribution of the peripheral part of the continent (separate pre-oceanic slopes) and of the central areas of internal run-off to the general balance of moisture of the continent are shown in figure 11.

Table 17: Water balance of Asia

Precipitation (P)		River run-off: Total value (Qt)		River run-off: Inflow to ocean (Q)		Evaporation losses through evap. & infil.		Potential Eo	Total E		Discrepancies of balance P-Q-E		Coefficient of run-off (Q/P)
mm	km³	mm	km³	mm	km³	mm	km³	mm	mm	km³	mm	km³	
Continent and islands - Area 43 475000 km²													
742	32240	332	14410	312	13560	19**	845**	1050	414	17980	16	700	0.42
Continent - Area 40,775,000 km³													
631	25740	265	10790	244	9940	21**	845**	1020	375	15,220	14	580	0.39
Area of external run-off area 28,500,000 km²													
800	22810	362	10330	349	9940	14**	390**	880	435	12420	16	450	0.44
Area of internal run-off-area 12275000 km²													
239	2930	37	458	0	0	37	458	1350	228	2800	11	130	0
Islands Area 2,700,000 km²													
2410	6500	1340	3620	1340	3620	3-5%*		1320	1020	2760	45	120	0.56

*Including losses of river run-off.

**About 100 km³ of river water infiltrates below the zone of river drainage.

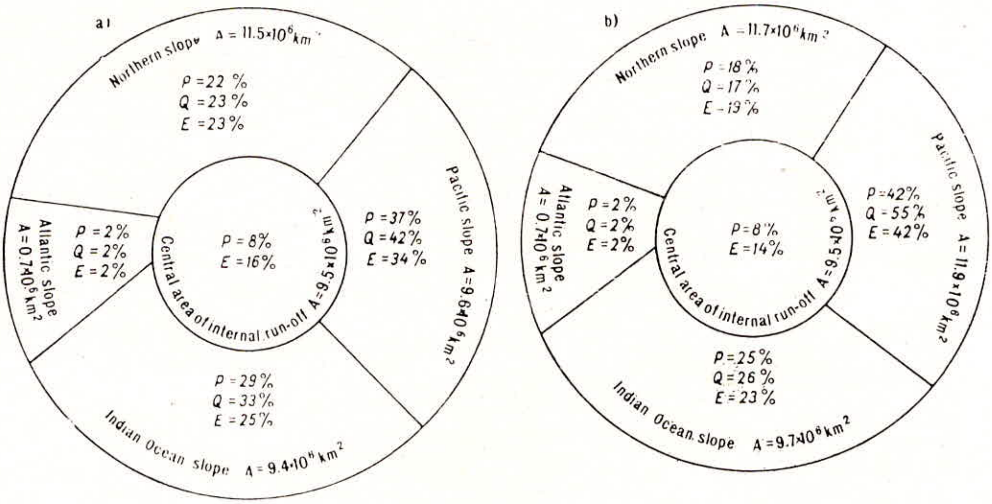

Fig. 11: Distribution of the components of the water balance in Asia between the ocean slopes and the central area of internal run-off.
a- the continent without the islands, b- the continent with the islands

It would be seen that the Pacific and the Indian Ocean slopes prevail in the water balance of the continent (nearly 47% of the continents surface), since they get 66% of the precipitation while their river run-off constitutes 75%, and their evaporation amounts to 60% of the total values. The data on these two slopes viz Pacific and Indian oceans is given in Table 18.

6.5.3 Water Balance of River Basins.

Water balance of large rivers, (slope of the Indian Ocean Rasin) is given in Table 19.

In the basins of Ganga, Brahmaputra and Meghna 170 km^3 of water do not reach their common mouth annually. About 80 km^3 can reasonably be attributed to evaporation losses, together with the yearly expenditure of about 150 km^3 of Ganga water for irrigation. The remaining 90 km^3 per year is apparently due to infiltration.

Table 18: Water balance of the Ocean slopes (with adjacent islands) and areas of internal run-off in Asia (after UNESCO)

Territory	Surface Area $10^3 km^2$	Precipitation (P)		River run-off Total (Q/T)		River run-off flow towards ocean (Q)		River run-off losses through evaporation & infiltration(Qt-Q)		Total Evaporation E		Discrepencies of balance P-Q-E		Co-efficeint of run-off Q/P
		mm	km^3	mm	km^3	mm	km^3	mm	km^3	mm	km^3	mm	% of P	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Slope of the Pacific Ocean basin														
Continental part	9570	983	9410	435	4160	435	4160			542	5190	6	1	0.44
Islands	2335	2500	5840	1410	3290	1410	3290		3-5%	1050	2450	40	2	0.56
Continental part and islands	11905	1280	15250	626	7450	626	7450			642	7640	12	1	0.49
Slope of the Indian Ocean basin														
Continental part	9440	792	7480	388	3660	345	3260	42	395	408	3850	39	5	0.44
Area of extenal run-off	6780	1060	7190	538	3650	481	3260	57	387	525	3560	54	5	0.45
Area of internal run-off (Arabian Peninsula, Thar desert)	2660	109	290	3	8	0	0	3	8	110	293	-1	-1	0
Islands	216	2840	613	1400	302	1400	302		3-5%	1350	292	90	3	0.49
Continental parts and islands	9656	838	8090	410	3960	369	3560	41	395	429	4140	40	5	0.44

Note: Data on slopes of the arctic ocean, Atlantic ocean and central area of internal run-off not reproduced

Table 19: Water balance of the river basins of Asia (after UNESCO)

River	Area of basin $10^3 km^2$	Precipitation (P)		Total in basin (Q/T)		River run-off: At mouth between brackets: issuing out of the mountains or at indicated point) (Q)		River run-off: losses through evap. & infilt. (Qt-Q)		Total Evaporation in E		Discrepencies of balance P-Q-E		Co-efficeint of run-off Q/P
		mm	km^3	mm	km^3	mm	km^3	mm	km^3	mm	km^3	mm	% of P	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Slope of the Indian Ocean Basin														
Salween	325	1220	396	650	211	650	211		-	533	173	37	3	0.53
Irrawaddy	410	1970	810	1185	486	1185	486		10-20	761	312	29	1	0.60
Ganga, Brahmputra and Meghna complex	1730	1465	2530	810	1400	710	1230	100	170	651	1125	104	7	0.48
Brahmputra upto its confluence with the Ganga at Goalundo	580	1700	985	1110	644	1110	644		30-60	518	300	72	4	0.65
Ganga upto the top of the delta (Farakka Station)	952	1200	1140	500	475	415	395	85	80	695	660	90	8	0.35
Godawari	314	1110	348	390	122	350	110	40	12	688	216	72	6.5	0.32
Narmada	102	1170	114	380	39	380	39		1-3	582	60	158	14	0.34
Indus	960	568	538	230	220	98	94	132	126	425	408	45	8	0.17
Indus (mountainous part of the drainage basin)	414	900	372	503	208	503	208		2-5	375	155	22	2	0.56
Shatt-al-Arab (Tigris, Euphrates, Karun)	750	382	286	147	110	61	46	86	64	318	238	3	1	0.16
Euphrates upto the Hit station	264	410	108	110	29	110	29		1-3	280	74	20	5	.27
Tigris upto the Salman Pak Station below Baghdad)	166	650	108	292	48.5	256	42.5	36	6	379	66	15	2.5	0.39

Note: Data on slope of the Arctic Ocean basin, slope of the Pacific ocean basin, slope of the Atlantic ocean basin and central area of internal run-off not reproduced

Run-off in the Indus at its mouth is less than half of the flow generate in the basin. The river is fed principally in the mountain regions of the Himalayas and the Hindu Kush. With average precipitation amounting to 900 mm, total run-off composed of the discharges from the Indus itself as it issues from the mountains (Kalabagh) and of its Hamalayan tributaries amounts to 503 mm, that is, 208 km^3. The general volume of the flow in the basin equals 220 km^3, of which only 94 km^3, reach the ocean. The main reason for such huge losses of flow is intense use of river water for irrigation.

6.5.4 Water Resources

Asia's overall fresh water reserves are as high as 3.5 x 10^6 km^3 (Table 20). More than 98% is contained within the earth's crust and 1.5% in glaciers of the mountainous regions and of the Arctic islands, in large lakes (Baikal, Balkhash and others). These reserves are categorized as secular water; their renewal takes place extremely slowly. Thus for example, nearly 400 years would be necessary for the natural renewal of the entire volume of water of excellent quality contained in Lake Baikal (23,000 km^3).

The continent's water resources that have the greatest practical importance are represented mainly by quickly replaced river water, whose simultaneous reserves amount to only 565 km^3 within the river channel network and to 1060 km^3 together with the water storage basins, taking their net volume into account (about 860 km^3 of water are contained in the "dead" space of water storage projects). The renewal time of river water reserves is 27 days.

Table 20: Fresh water reserves of Asia (islands included)

Type of water	Volume in 10^3 km^3	Quantity in % of overall resources on the continent	Quantity in % of world reserves
Underground water	3400	98.4	32.3
Glaciers inside polar circle and in high mountainous areas	24.9	0.72	0.10
Lakes	27.8	0.80	30.5
Storage basins (1972 fig.)	1.35	0.04	27.0
Water reserves in the river bed network	0.56	0.02	
Total	3455	100	

According to water balance computations the river water resources in Asia and adjacent islands represent 14,400 km^3/yr or 332 mm and within the continental part alone, 10800 km^3 (265 mm).

Asia occupies first place among the continents as far as its total volume of river run-off is concerned, which is in fact due largely to its large dimensions. The resources, in surface flow, are distributed most unevenly over the territory. An average of 332,000 $m^3/yr/km^2$ at river water are present. The Pacific slope with its adjacent islands is best provided with water (6.3×10^6 m^3/yr km^2) next is the central area of internal run-off (47,000 $m^3/yr/km^2$); the arid plains have the least water dispersed over more than 70% of its total surface (5000 m^3).

7.0 WATER RESOURCES OF INDIA

7.1 General

The annual precipitation of India is estimated as 4000 km^3 including snow fall. The seasonal rainfall is of the order of 3000 km^3. After allowing for evaporation losses etc, the country's estimated water potential is 1800 km^3. Most of the surface flows of rivers in India occur during the monsoon season of 4 to 5 months and particularly as flood flows. Further the availability of water also varies from place to place and is not spread uniformly over the country creating pockets of scarcity. Due to paucity of surface water, particularly in the lean period, tapping of ground water becomes imperative. The annual replenishable resources of ground water are assessed to be about 600 km^3 of which the annual utilisable resources are estimated as 420 km^3.

7.2 Climate, Rainfall

The presence of the great mountain mass formed by the Himalayas and its spurs on the north and of the ocean on the south, are the two major influences operating on the climate of India. The first poses an impenetrable barrier to the influence of cold winds from central Asia, and gives the sub-continent the elements of tropical type of climate. The second, which is the source of cool moistureladen winds reaching India, gives it the elements of the oceanic type of climate.

India has a very great diversity and variety at climate, and an even greater variety of weather conditions. The climate ranges from continental to Oceanic, from extremes of heat to extremes of cold, from extreme aridity and negligible rainfall to excessive humidity and torrential rainfall. Rainfall in India is dependent in differing degrees on the south-west and north-east monsoons, 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 annual and seasonal rainfall in different meteorological sub-divisions of the country are given n Table 21.

7.3 River Systems

The river systems of India can be classified into four groups viz (i) Himalayan rivers (ii) Deccan rivers (iii) coastal rivers and (iv) rivers of the inland drainage basin. The Himalayan rivers are formed by melting of snows and glaciers and therefore have continuous flow throughout the year. During the monsoon months, Himalayas receive very heavy rainfall and rivers swell, causing frequent floods. The Deccan rivers on the other hand are rainfed and therefore fluctuate in volume. Many of these rivers are non-perennial. The coastal streams, specially on the west coast, are short in length and have limited catchment areas. Most of them are non-perennial. The streams of inland drainage basin of western Rajasthan are few and far between. Most of them are of ephemeral character.

The main Himalayan river systems are those of the Indus, Ganga-Brahmaputra-Meghna system. Indus rises near Mansarovar in Tibet and flows through Kashmir and there after through Pakistan and finally falls in the Arabian sea near Karachi. Its important tributaties originating in Indian territory are the Sutlej (originating in Tibet) the Beas, the Ravi, the Chenab and the Jhelum. The Ganga has two main head waters in Garhwal Himalayas, the Bhagirathi and the Alakhnanda which join at Dev Prayag to form Ganga. It traverses through Uttar Pradesh, Bihar and West Bengal in India and there after enters Bangladesh. Its important tributatries are the Yamuna, the Ramaganga, the Ghaghra, the Gandak, the Kosi, the Mahananda and the Sone. River Chambal and Betwa are the important sub-tributaries which join Yamuna, before it meets Ganga. The Brahmputra rises in Tibet and enters India in Arunachal Pradesh and after traversing through Assam and Bangladesh joins Ganga at Goalundo in Bangladesh. Its important tributaries are Dihang, Luhit, Subansiri, Manas and Tista. The Barak river, the head stream of Meghna, rises in the hills in Manipur at an elevation of about 2900 m. The important tributaries of the river are Makku, Trang, Truvai, Jiri, Sonai, Rukni, Kabakhal, Indeshwari, Lanjachini, Maduva and Jatinga. The Meghna is the part of the Ganga-Brahmputra-Meghna system. The contained Ganga Brahmputra river meets Meghna in Bangladesh and this combined system flows as one river for some distance before falling into the Bay of Bengal.

Table 21: Annual and Seasonal Rainfall in different meteorological sub-division of the country

Sl. No.	Sub-division	Annual rainfall mm	Seasonal (June to Sept.) rainfall mm
1.	Arunachal Pradesh	2997	2085
2.	Assam and Meghalaya	2497	1624
3.	Nagaland, Manipur, Mizoram and Tripura	2314	2092
4.	Sub-Himalayan West Bengal and Sikkim	2779	2172
5.	Gangetic West Bengal	1429	1079
6.	Orissa	1484	1143
7.	Bihar Plateau	1371	1125
8.	Bihar Plains	1204	1023
9.	Uttar Pradesh West	836	726
10.	Uttar Pradesh East	1014	893
11.	Hills of West Uttar Pradesh	1750	1409
12.	Haryana	556	463
13.	Punjab	611	467
14.	Himachal Pradesh	1518	993
15.	Jammu & Kashmir	997	458
16.	Rajasthan West	310	275
17.	Rajasthan East	700	647
18.	Madhya Pradesh West	1043	945
19.	Madhya Pradesh East	1398	1227
20.	Gujarat Region	967	920
21.	Saurashtra & Kutch	515	479
22.	Konkan	2881	2705
23.	Madhya Maharashtra	940	788
24.	Marathwada	794	660
25.	Vidarbha	1102	960
26.	Coastal Andhra Pradesh	1008	572
27.	Telangana	931	759
28.	Rayalseema	676	367
29.	Tamil Nadu	1007	301
30.	Coastal Karnataka	3292	2886
31.	Interior Karnataka North	1685	447
32.	Interior Karnataka South	1271	868
33.	Kerala	2978	1998

The important river systems in Deccan are the Narmada and Tapi which flow west-wards into Arabian sea and the east flowing rivers the Mahanadi, the Godavari, the Krishna, the Kaveri, which fall into Bay of Bengal.

There are numerous coastal rivers which are comparatively small streams. While only handful of such rivers drain into the sea near the deltas of east coast there are as many as 600 such rivers on the west coast. The west coast rivers are of great importance as they contain as much as 14 percent of the country's water resources while draining only 3 percent of the land.

A few rivers in Rajasthan do not drain into the sea. They drain into salt lakes like the Samnhar or get lost in sands with no outlet to the sea.

The major river systems are shown in Table 22.

Table 22: Major River Basins

Sl.No.		Name of river	Catchment Area km^2
1.		Indus	(468,068) 321,289
2.	(a)	Ganga	(1,050,000) 861,404
	(b)	Brahmaputra	(580,000) 187,113
	(c)	Barak and other rivers flowing in to Meghna	70,895
3.		Sabarmati	21,674
4.		Mahi	34,842
5.		Narmada	98,796
6.		Tapi	65,145
7.		Brahmani	39,033
8.		Mahanadi	141,589
9.		Godavari	312,812
10.		Krishna	258,948
11.		Pennar	55,213
12.		Cauvery	81,155
		Total	2,549,908

Note: The figures within brackets indicate the total figures for the river basin in India and neighbouring countries.

Principal Glacier-fed River Systems

Snow and ice has vast potential for water resources in India. The principal glacier fed river systems of Himalayas are given in Table 23.

7.4 Surface Water Resources

The revised estimate made by Central Water Commission puts the country's surface water resources at 1800 km^3.

Table 23: Principal glacier fed river systems of Himalayas (after Jagdish Bahadur. Snow and Glaciers and their contirbution to India's water Resources: NIH. Water Science Educational Series No. 1 February 1992)

Sl. No.	Name of river	Major river system	Mountain area km^2	Glacier area km^2	Percentage of glaciation
1.	Indus		268,842	8790	3.3
2.	Jhelum		33,670	170	5.0
3.	Chenab	Indus	27,195	2944	10.0
4.	Ravi		8,029	206	2.5
5.	Sutlej		47,915	1295	2.7
6.	Beas		14,504	638	4.4
7.	Yamuna		11,655	125	1.1
8.	Ganga		23,051	2312	10.0
9.	Ramganga	Ganga	6,734	3	0.04
10.	Kali		16,317	997	6.01
11.	Karnali		53,354	1543	2.9
12.	Gandak		37,814	1845	4.9
13.	Kosi		61,901	1318	2.1
14.	Tista		12,432	495	4.0
15.	Raidak		26,418	195	0.7
16.	Manas	Brahmaputra	31,080	528	1.7
17.	Subansiri		18,130	725	4.0
18.	Brahmaputra		256,928	1080	0.4
19.	Dibang		12,950	90	0.7
20.	Luhit		20,720	425	2.01
	Total		1,001,294	25724	2.6

The basin wise water availability is given in Table 24. While the land area of India is about 2.11% of the entire World, India possesses about 4.9% of the annual run-off from the rivers and occupies 5th position after Canada, China

Table 24: Average annual flow in the river systems

Sl. No.		Basin	Average Annual flow km^3	Utilisable flow km^3
1.		Indus (upto border)	73.31	46.00
2.	(a)	Ganga upto border	501.64	250.00
	(b)	Brahmaputra upto border	499.91	24.00
	(c)	Barak etc	90.80	
3.		Godavari	118.98	76.30
4.		Krishna	67.79	58.00
5.		Kaveri	20.70	19.00
6.		Pennar	6.86	6.86
7.		East flowing rivers between Krishna and Pennar and between Mahanadi and Godavari	16.95	13.11
8.		East flowing rivers between Pennar and Kanyakumari	17.73	16.73
9.		Mahanadi	66.88	49.99
10.		Brahmani & Baitarani	36.23	18.30
11.		Subarnarekha	10.76	6.81
12.		Sabarmati	2.88	1.93
13.		Mahi	11.83	3.10
14.		West flowing rivers of kutch Kathiawar including Luni	15.10	14.98
15.		Narmada	42.97	34.50
16.		Tapi	16.97	14.50
17.		West flowing rivers from Tapi to Tadri	110.88	15.07
18.		West flowing rivers from Tadri to Kanyakumari	71.98	14.93
		Total	1,801.15	684.11

(mainland) Russia and Brazil, U.S.A. with about 2.5 times the area of India has an annual average run-off- of about 1700 km^3. The yields of some of the rivers are given in Table 25 and flows in larger tributaries of Ganga are given in Table 26.

Table 25: Annual yield of some major rivers (after CWC)

Sl. No.	River	Location	Yield km^3 Dependability		
			50%	75%	90%
1.	Narmada	Jamtara	10.76	8.24	5.07
		Mortakka	33.90	21.1	20.09
		Garudeshwar	40.94	33.58	24.35
2.	Krishna	Vijayawada	67.72	58.33	
3.	Godavari	Dowalaishwaram	117.80	71.30	
4.	Kaveri	Krishnaraja-Sagar	6.21	5.32	4.75
		Mettur	14.38	12.28	11.73
5.	Ganga	Allahabad	121.20	96.00	72.40
		Patna	273.10	244.10	166.40
		Farakka	428.10	383.30	303.20

Table 26: Mean Annual Flow in the Tributaries of Ganga

Sl. No.	River	Site	Mean Annual Natural Flows km^3
1.	Ramaganga	Zirarahimpur	13.84
2.	Yamuna (including Chambal)	Pratappur	89.80
3.	Chambal	Udi	32.55
4.	Ghagra (including Sharda)	Turtipar	98.44
5.	Sone	Koelwar	30.28
6.	Gandak	Lalganj	51.69
7.	Burhi Gandak	Rusera	7.06
8.	Kosi	Raltara	68.28
9.	Mahananda	Labha	13.57
10.	Tributaries down stream of Farakka (Mayurakshi+Damodar+Kangsabati+Ajay+Rupnarayan etc)		47.08

7.5 Groundwater Resources

The groundwater resources of India (utilisable) have been assessed by Central Ground Water Board as 422.86 km³ per year. The details are given in Table 27.

Table 27: Ground water resources potential in different states of India

Sl. No.	State/Union Territory	Utilisable resources km³/yr	Draft Km³/yr	Potential available for future development km³/hr	Stage of ground water development %
1.	Andhra Pradesh	36.60	7.40	29.20	20
2.	Arunachal Pradesh	1.13	N.A.	1.13	1
3.	Assam	16.50	0.20	16.30	1
4.	Bihar	28.60	5.90	22.70	21
5.	Gujarat	20.30	6.90	13.40	34
6.	Haryana	8.80	6.10	2.70	70
7.	Himachal Pradesh	0.67	0.16	0.51	24
8.	Jammu & Kashmir	1.89	0.10	1.79	5
9.	Karnataka	13.00	1.80	11.20	15
10.	Kerala	6.90	0.90	6.00	13
11.	Madhya Pradesh	59.50	4.90	54.60	8
12.	Maharashtra	34.50	6.60	27.90	12
13.	Manipur	0.08	N.A.	0.08	1
14.	Meghalaya	0.28	0.01	0.27	3
15.	Mizoram	N.A.	N.A.	N.A.	N.A.
16.	Nagaland	0.03	N.A.	0.03	1
17.	Orissa	21.50	0.90	20.60	4
18.	Punjab	13.10	9.50	3.60	73
19.	Rajasthan	18.30	4.60	13.70	25
20.	Tamil Nadu	26.90	9.90	17.00	37
21.	Tripura	0.59	0.01	0.58	1
22.	Uttar Pradesh	92.70	26.80	65.90	29

23.	West Bengal	10.40	4.90	11.50	30
24.	Sikkim	N.A.	N.A.	N.A.	N.A.
	Sub Total I	418.27	97.58	320.69	23.3
1.	Andaman & Nicobar	N.A.	N.A.	N.A.	N.A.
2.	Chandigarh	0.03	0.035	N.A.	116
3.	Dadra, Nagar Haveli	0.03	0.01	0.12	33
4.	Delhi	2.68	2.37	0.31	88
5.	Goa	1.85	0.17	1.68	9
6.	Lakshdweep	N.A.	N.A.	N.A.	N.A.
7.	Pondicherry	N.A.	N.A.	N.A.	N.A.
	Sub Total II	4.59	2.585	2.01	56.8
	Grand Total	422.86	100.165	322.70	23.7

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AUTHOR'S BIOGRAPHICAL SKETCH

Born on 01 May 1930 and a graduate of Agra University, Dr. R.S. Varshney obtained his B.E. (Civil) with honours in 1952, M.E. (W.R.D.) in 1962 and Ph.D. in 1972, all from the University of Roorkee. He is a recipient (1965) of the Diploma of the French Government in "Design and Construction of Arch Dams". His academic career has been exceptionally bright.

Dr. Varshney joined the U.P. Irrigation Department in 1953 against guaranteed posts and rose to the top post of Engineer-in-Chief and Head of that Department in which capacity he served up to April 1988. From February 1980 to December 1984, he worked on deputation with the Government of Mauritius as Advisor/Projects Co-ordinator in charge of planning, design and construction of all water resources projects in Mauritius.

In recognition of his valuable contributions to irrigation and drainage engineering, he was elected in October 1988 as the Secretary-General of the International Commission on Irrigation and Drainage and worked upto 1992.

Dr. Varshney is Chairman of Board of Consultants, Multipurpose and Hydroelectric Projects, Uttar Pradesh (India). He is also member of Panel of Experts of Shrinagar Hydroelectric Project, Dam Safety Review Panel, Orissa, Chairman, Dam Safety Review Panel, West Bengal and Consultant to Small Hydro-Corporation U.P. and to other Organisations.

Dr. Varshney has rich and varied experience of over 30 years of planning, design and construction of major river valley projects and hydroelectric schemes, notably Rihand, Yamuna Hydroelectric Scheme Stage II Part I (Chibro underground power house), Lakhwar Vyasi Project, Gandak Canal Project, Maneri Bhali Stages I and II, Tehri, Shrinagar, Vishnu Prayag etc. He has extensive experience of Irrigation systems and flood management.

Dr. Varshney has several research and design innovations to his credit and has contributed many formulae, design principles in the domain of hydraulics, alluvial channels, hydrology, and water resources engineering.

Dr. Varshney has to his credit over 110 papers published in India and abroad. Many of his papers have won prizes and awards including the Khosla Research Prize and three CBIP gold medals and three certificates of merit. He was presented the Roll of Honour of Multipurpose and Hydroelectric Projects Organisation of U.P. Irrigation Department and U.P. State Electricity Board (1986). He got Hydrosem award of Institution of Engineers, U.P. Centre, 1987 and Jawahar Lal Nehru Research Award 1988. He was given Roll of Honour (December 1990) by Systems Society of India. He got Bharat Singh Award (1989) for his valuable contribution to Hydrology.

Dr. Varshney is author of nine books in English and one book in Hindi on irrigation engineering, hydrology, water resources economics, hydropower, Earth and Rockfill Dams and concrete technology. His books have been acclaimed as valuable reference books in India and abroad.

Dr. Varshney is Fellow, National Academy of Engineering; Fellow, Institution of Engineers (India); Fellow, Indian Association of Hydrologists; and member of various other technical organisations.