EXPLORATION AND ASSESSMENT OF UNDERGROUND WATER RESOURCES IN WESTERN RAJASTHAN

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By

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Certified that this dissertation entitled "Exploration and Assessment of Ground water Resources in Western Rajasthan" is a record of bonafide work done by Sri Mahesh Kumar, Post Graduate student in the course of Master of Engineering (Water Resources Development) in academic years 1965-66 and 1966-67. Sri Mahesh Kumar has worked under our guidance on this dissertation during the academic year 1966-67.

To the best of our knowledge this dissertation has neither been published any where nor submitted for the award of any other degree.

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SUMMARY

The area considered in the dissertation comprises of the arid and semi arid tracts lying on the Western side of the Aravalli ranges in Rajasthan. The rainfall in the area is low and the only source of surface water is Luni river system. North and west of Luni river there is practically no surface drainage in the region. As such the development of ground water sources to supply water for irrigation and domestic use is very essential.

Most of the area comprises of alluvium and wind blown sand. Rock outcrops occupy only about 7% of the total area. Most of the ground water is contained in the alluvial formations. The wind blown sands generally lie above the regional water table and the body of most of the older rock formations is devoid of water. In rocks the water is contained mostly along the various openings. However certain rock formations e.g. Lathi series in Jaisalmer and Malani volcanites of Jalore are good water yielding rocks.

The only source of recharge of ground water in the region is by the precipitation over the area itself. The region is cut off from the Indus and Gangetic basins of ground water.

Another artifical source of recharge in the region is from the water seeping from the perennial canals viz. Rajasthan Canal, Gang Canal and Bhakra Canal systems. However, since the canals have started irrigation only recently, their exact effect can not be ascertained at this stage.

No systematic geo-hydrological studies of the region as a whole have so far been made to assess its ground water

potential. The investigations so far have been limited to location of mineral resources and production tube wells.

The methods employed generally for ground water exploration are Geophysical, Photogrammetic and Geological. The methods employed for calculating the various hydrological properties of aquifers, e.g. co-efficient of permeability, co-efficient of transmissibility, specific yield, storage co-efficient etc, are based on the non-equilibrium hydraulics of the wells. The important methods are the Type curve method, Jacobs modified straight line method and the Double slope method. The determination of storage co-efficient needs the data on some observation wells around the main pumped well. Such data has not been collected so far in the region.

For ground water resources the annual recharge is more important than the total capacity of the reservoir. The annual recharge of ground water of the region, calculated by Khosla's emperical formula, comes to 0.52 M acre ft.

The quality of water and the depth to water table are the limiting factors for the utilisation of ground water resources in the region. Considering these factors, the probable potential water bearing zones in the region are the Lathi formation in Jaisalmer, Sandstone formation in Barmer, Older alluvium and Malani volcanites in Jaisalmer and the Alluvium formation around Sikar.

For optimum utilisation of the ground water resources of the region, it is necessary that geophysical surveys should be taken up for the entire region, followed by detailed geological investigations in the more promising zones. The seasonal and annual changes in quality of water and the depth of water table should also be studied. Finally a ground water inventery should be prepared for the region to correctly asses the ground water resources.

CHAPTER - I

WESTERN RAJASTHAN AREA, ITS LOCATION, TOPOGRAPHY AND CLIMATE

1.1 LOCATION

The state of Rajasthan (formerly called the Rajputana and Ajmer Merwara) lies between the latitudes 23° - 03' and 30° - 12' and longitudes 69° - 30' and 78° - 17'. The total area of the State is 3,42,261 sq.km (1,32,147 sq. miles). It is roughly rhombic in shape. The East-West diagonal is about 854 km (540 miles) and the North-South diagonal about 816 km.(510 miles).

The Aravalli range running roughly from South - West to North-East divides the State in two distinct zones. The area on the north western side comprises of the arid and semi-arid districts of Barmer, Jaisalmer, Jodhpur, Bikaner, Nagaur, Churu and Sikar etc., while the area on its South West has regions where the rainfall is better and the lands comparatively fertile and productive.

The area discussed in this dissertation is the first referred arid and semi-arid zone which has a area of about 1,94,250 sq.km.(75,000 sq.miles). The area is bounded on the East by the Aravalli mountain ranges; on the South by the Rann of Kutch; on the West by Pakistan and in the North by the Punjab and Haryana States. The area has been shown on plate 1.1.

1.2. TOPOGRAPHY

Most of the Western Rajasthan is a gently undulating plateau having elevation ranging from 150 to 460 metres (500 and 1500 ft) above the sea level, with intermediate scattered buttes and clusters of hills close to Aravalli which reach elevation of 610 to 915 metres (2000 to 3000 ft.). Westwards from the Aravallies there are also some detached hills which can be traced into the first well marked peak of Aravalli range south-west of Didwana. Further west the hills become more prominent.

South-West of Bikaner the area generally consists of flat topped hills and lone scattered buttes; around Jaisalmer there are also flat lying ridges of elevation about 275 metres (990 ft.) . In Barmer there are also some pronounced erosional ridges; the highest peak west of Barmer town attaining an elevation of 422.5 metres(1386 ft.)

However, the greater part of Western Rajasthan is covered by alluvium and wind blown sands and rock out-crops occupy only about 7% of the total area.

The alluvium lies mainly along the flood plain of the Luni and its tributaries which is the only important river system of the region. The river has its orgin in Aravalli ranges about 7 miles North-East of Ajmer. The main river has an overall length of nearly 500 miles(800 Km) with an average ground slope 1 in 15,000, depth while running full 8' and width 3600 ft. It has an approximate catchment area of 13,000 sq. miles (33,670 Sq.km.).

Luni river and its tributaries are ephemeral and they all carry water in direct response to run-off from monsoon rains and are dry during most of the year.

North and West of Luni river, there is no integrated system stream net work owing to the low rainfall and high evaporation and due to occurrence of extensive tracts of active sand dunes which impede surface drainage . Local run off is evaporated in shallow closed depressions or by infilteration into the ground.

1.3 RAINFALL

Western Rajasthan lies in a region of low rainfall, which decreases from about 25" on the slope of Aravalli on the South-East side, to about 5" in the Thar Desert on the North - West. The gradient of isohyets is approximately 2 1" decrease for every 11 miles of ground travel. Plate 4.3 shows the isohyets of Western Rajasthan prepared by the Indian Meteriological Department as based on observations for the past 50 years. The annual rainfalls for some of the towns are given in Table 1.1. Table 1.2 gives the monthly distribution of rainfall for some of these stations and shows that the region receives seasonal yet erratically distributed rains from the South-West monsoon in the month of July, August and September with light showers during the rest of the year. Approximately 90% of the annual precipitation results from the South-West monsoon associated with atmospheric depressions in the Bay of Bengal or land depressions approaching Rajasthan from the East. About 5% of the annual rainfall occurs in the cold weather period of December to February and this is associated with atmospheric disturbances entering Rajasthan from the West. The Aravalli range cuts off a considerable part of the moisture from the monsoon currents entering from the east and relatively little moisture is received from the currents which approach from South and South-West.

Another characteristic features of the rainfall in this region is its extreme variation from year to year; the amount of rainfall received by any particular station may vary as much as 200 to 300 percent or more from that in the previous or following year. This fact will be evident from plate-14 on which the rainfall data for some of the principal towns of the region

TABLE - 1.1

MEAN ANNUAL RAINFALL

Station	Mean Annual Rainfall In Inches	Mean Annual Rainfall In Millimeters
Jaisalmer	7.05	179.1
Barmer	10.37	263.4
Pachpadra	11.89	302.0
Jalore	14.00	355.3
Pali	15.35	389.9
Marwar Junction.	15.00	381.0
Bilara	17.60	446.5
Sojat	18.20	462.0
Jodhpur	14.25	362.0
Parbatsar	14.89	378.0
Nagaur	12.58	319.5
Ganganagar	8.50	216.0
Bikaner.	11.47	291.0
Suratgarh	10.10	257.0
Sadar	10.76	273.0
Sujangarh	12.42	316.0
Rajgarh	14.38	365.0
Churu	7.05	179.1
Sikar	17.80	450.5

SOURCE:- (1) Introductory report on Ground water resources of Western Rajasthan by J.B.Auden (8)

(2) Report of the Water utilisation assessment and utilisation committee appointed by the Govt. of Rajasthan.(43)

TABLE - 1.2

MEAN MONTHLY AND ANNUAL RAINFALLS

Station	Unit	Jan.	Feb.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.	Year
Ganganagar	Inches	0.25	0.44	0.21	0.20	0.24	1.22	2.69	2.78	0.27	0.06	-	0.21	8.50
	Millimeters.	6.60	11.10	5.34	5.08	6.10	30.99	68.33	70.61	6.05	1.52	-	5.33	217.93
Bikaner.	Inches	0.27	0.27	0.23	0.19	0.59	1.21	3.34	3.60	1.21	0.21	0.05	0.20	11.41
	Millimeters	6.85	6.86	5.84	4.83	14.99	30.73	84.83	91.44	30.73	5.33	1.27	5.08	291.34
Jodhpur.	Inches	0.15	0.24	0.11	0.13	0.41	1.42	3.97	4.88	2.40	0.32	0.11	0.11	14.25
	Millimeters	3.81	6.09	2.79	3.30	10.41	36.07	100.84	123.95	60.96	1.13	2.79	2.79	361.93
Bilara	Inches	0.70	0.18	0.19	0.12	0.40	0.81	4.93	6.20	2.55	0.30	0.12	0.10	17.60
	Millimeters.	17.78	4.57	4.82	3.04	10.16	45.97	125.22	157.48	64.77	7.62	3.04	2.54	447.04
Marwar Jn.	Inches	0.12	0.03	0.01	0.02	0.37	1.44	4.21	6.33	2.10	0.27	0.04	0.01	15.00
	Millimeters.	3.04	2.03	0.25	0.51	9.39	36.57	106.93	160.78	53.34	6.85	1.00	0.25	381.00
Pali	Inches	0.11	0.15	0.11	0.07	0.32	0.77	4.13	6.11	2.20	0.19	0.10	0.09	15.35
	Millimeters.	2.79	3.80	2.79	1.77	8.12	44.95	104.90	155.19	55.90	4.82	2.54	2.25	389.89
Sojat	Inches	0.13	0.25	0.13	0.12	0.45	1.59	5.93	6.45	2.03	0.20	0.06	0.10	18.20
	Millimeters.	3.30	5.04	3.29	3.04	10.03	40.38	150.62	163.73	70.88	5.08	1.52	2.54	462.28
Barmer	Inches	0.10	0.14	0.13	0.05	0.37	0.97	3.52	3.41	1. 46	0.10	0.05	0.07	10.37
	Millimeters	2.54	3.55	3.04	1.52	9.39	24.63	89.41	86.61	37.64	2.54	1.23	1.77	263.39
Sikar Jn.	Inches	0.35	0.33	0.30	0.11	0.64	1.84	4.99	5.80	1.93	0.24	0.14	0.27	16.90
	Millimeters	9.14	8.39	7.62	2.80	16.25	46.74	12.69	14.73	4.91	6.09	3.56	6.81	42.93

from years 1900 onwards is plotted. The mean annual rainfall is also shown on this plate.

The cycles of precipitation in the region shows that the lean years are generally more frequent than the years of excess precipitation. The Rajputana Gazetteer had quoted the local proverb " One lean year in three; one famine year in eight." This proverb has been borne by experience also.

Auden (2) and others have analysed the variation of yearly rainfall in the region. The average, maximum and minimum rainfall with their "co-efficients of variation" based on 30 year data, as worked out by him are shown in table 1.3.

TABLE 1.3

Locality	Average	Maximum	Minimum	Coefficient of variation.	Average frequency of years with rainfall less than half the mean.
Sheo	8.46	31.59	0.02	71.9	1:7.5 (30 yrs.)
	8.30	31.59	0.14		1:3.9 (54 yrs)
Phalodi	9.10	20.05	2.46	60.3	1:4.3 (30 ")
Nagaur	12.96	34.71	3.61	46.0	1:10 (30 ")
Jodhpur	13.62	44.62	4.00	57.2	1:7.5 (30 ")
	14.02	44.62	0.99	50.6	1:9.0 (54 ")
Merta	16.14	51.92	8.98	36.4	1:7.5 (30 ")
Ajmer	19.00	44.10	5.90	49.4	1:7.4 (30 ")
Pali	23.52	79.55	7.96	61.1	1:7.5 (30 ")

In 12 out of the 21 stations in the former Jodhpur state the co-efficient of variation exceeds 50 percent, which postulates the great variability of the rainfall. There is no direct corelation between the cofficient of variation and the magnitude of rainfall, but in general the coefficient is greater for areas with a low average precipitation.

The rainfall records of Jodhpur and Sheo for the period 1891-1944 are plotted in figures 1.2 and 1.3. The range in five-year means lies between 9.1 and 18.5 inches for Jodhpur and between 4.2 and 12.7 inches for Sheo (See table 1.4). It should be pointed out, however, that the 5-year means are naturally influenced by the end years adopted, and that the real range, as displayed by choosing the lowest and highest five consecutive year means, is somewhat greater, since the minima in these instances are lower.

TABLE 1.4

	5 year Means, Starting at 1891: (In inches.)			Maximum and Minimum 5 Consecutive year means (In inches)		In Inches.
	Maximum :	Minimum :	Range :	Maximum :	Minimum :	Range
Jodhpur	18.5	9.1	9.4	18.5	7.7	10.8
Sheo	12.7	4.2	8.5	12.7	3.9	8.8

Figure 1.2 shows the cumulative per cent deviation from mean precipitation at Jodhpur between 1891 and 1944. It demonstrates the cyclical nature of the rainfall, with peaks at 11, 8, 10, 7, and 10-year intervals, and also shows the great decline in precipitation between 1897 and 1907, which was from + 97 per cent to − 221 per cent, a total change of 318 per cent.

The curves in figure 1.3 illustrate the lowest and highest mean precipitation for consecutive years, and show that for 3½ consecutive years at Jodhpur, and 4½ consecutive years at Sheo, the precipitation is less than 50 per cent of the mean. Actual records indicate periods respectively of 4 and 3 years, but the curves are smoothed out between the slightly scattered data points.

Another characteristic feature of the rainfall in the area is that the rains at a given locality are very uncertain in intensity. This condition is very important for determining the surface run off and the recharge of Ground Water. If the rain comes in very light showers most of the moisture is either evaporated or is retained in soil layers near the surface without reaching the water table. This retained moisture is then gradually evaporated from the soil. Again if the rain comes in intense heavy showers, much of the excess precipitation leaves the area in the form of surface run off without replenishing the ground water.

1.4 <u>TEMPERATURE</u>

The region of Western Rajasthan is characterised by great extremes in temperature. The winter period from the end of November to February is very cold; very frequently the temperature at many places falls below the freezing point. The mean maximum temperature during January varies from 20° C (68° F) at Sri-Ganganagar to 24.4°C (76° F) at Jodhpur. The mean minimum temperature during this month varies from 9.3°C(47° F) at Jodhpur. Temperature as low as - 2.2° C has been recorded at Sri Ganganagar.

The hot season prevails in this region from April to June when the heat is oppressive and day temperatures exceeding 43.3°C (110° F) are not uncommon. Owing to the dryness of atmosphere, the nature of soil and want of vegetation, the diurnal variation of temperature is markedly great in this region. The mean maximum temperature during May varies from 40.6° C(105°F) at Jodhpur to 42.8°C (109° F) at Jaisalmer. Occasionally the maximum day temperature at Jodhpur, Bikaner and Barmer shoots upto 48.9°C (120° F). Table 1.5 shows the mean maximum and minimum temperatures for several stations in Western Rajasthan.

1.5 HUMIDITY

In Western Rajasthan, relative humidity is minimum during summer months - March, April and May and maximum during monsoon months of July, August and September. It is lowest in April & highest in August, but the moisture content of the air is lowest during the cold season. The mean maximum and minimum relative humidity figures of a few stations of this region are given in Table 1.6.

1.6 WINDS

Taking the year as a whole, winds from South-West or West are most frequent in Rajasthan. They are strongest in June and lightest in November. Winds are generally light and variable in winter when North-Westerly or Northerly winds are more frequent. Hot and dust raising winds sweep the whole region during summer in their worst and voilent from in the desert area. Data for mean surface wind directions for few stations, and the mean wind velocity for Jodhpur are given in Table 1.7.

1.7. DUST STORMS

The dust storms are very frequent in the arid west and their frequency decreases progressively as we go towards the semi-arid regions on the eastern side. On an average Sri Ganganagar has 27 days of dust-storm in a year, Bikaner 10 and Jodhpur 8. June is the month of maximum number of dust storms.

T A B L E 1.5

MEAN MAXIMUM AND MINIMUM TEMPERATURES(F)

Station.		Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Sri-Ganga-nagar.	X	67.8	73.6	82.9	95.4	107.7	106.9	102.1	99.9	100.0	95.1	84.5	73.6	90.08
	M	38.1	45.7	52.2	62.0	75.0	81.3	82.5	80.4	74.1	59.7	47.8	40.0	61.6
Bikaner	X	71.7	76.9	88.7	99.6	107.0	107.0	101.2	97.5	98.0	95.7	85.6	75.3	92.0
	M	46.9	50.6	62.4	73.3	81.0	85.0	82.7	80.4	70.1	70.5	57.8	48.8	68.3
Jaisalmer	X	74.8	77.7	89.1	101.3	109.1	104.7	99.9	94.2	99.9	96.1	86.8	76.7	92.6
	M	48.1	48.1	62.5	70.6	80.3	80.3	80.5	76.9	77.1	67.1	62.4	49.1	65.6
Jodhpur.	X	76.3	80.6	90.5	99.4	105.4	103.6	96.9	91.8	94.2	95.5	87.6	79.0	91.7
	M	49.6	52.6	61.5	70.8	79.4	82.3	80.2	77.0	74.8	65.4	55.4	50.5	66.6
Phalodi.	X	72.6	79.5	91.1	101.6	103.2	106.1	99.1	94.4	96.7	97.0	87.8	76.5	92.5
	M	48.9	49.9	60.6	72.6	80.3	82.3	80.6	78.0	75.6	67.7	54.5	44.5	65.7
Barmer	X	76.4	81.3	90.2	100.3	106.4	103.4	98.5	92.5	95.2	97.1	89.4	80.1	92.4
	M	50.0	55.6	64.2	74.3	80.0	80.3	78.9	76.9	75.7	70.3	60.9	53.5	68.4
Sikar.	X	72.9	76.6	87.8	99.7	107.9	105.0	97.1	92.3	93.5	93.5	84.5	75.1	90.5
	M	44.4	45.5	57.6	68.6	80.0	83.5	79.6	76.3	73.5	63.7	48.1	41.5.	63.5

X - Maximum temperature. M- Minimum temperature.

TABLE 1.6

MEAN RELATIVE HUMIDITY (%) AT 8 HRS. AND 17 HRS. I.S.T.

Station		Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean
Sri Ganganagar	I	78	68	61	45	34	49	63	66	63	63	53	68	60
	II	42	41	31	23	20	31	43	45	47	23	32	39	34
Bikaner	I	58	55	45	40	44	53	67	73	68	52	49	53	55
	II	37	27	15	11	12	29	39	44	34	20	23	31	26
Jaisalmer.	I	64	47	60	57	75	63	89	93	83	51	37	49	66
	II	45	36	35	37	32	44	65	73	64	20	23	21	41
Jodhpur	I	50	50	30	36	45	63	73	82	76	54	45	53	55
	II	22	21	17	11	15	34	43	50	40	16	18	22	27
Phalodi	I	72	60	55	52	57	66	80	84	79	55	56	63	65
	II	43	37	32	29	27	32	52	60	43	23	32	41	30
Sikar	I	74	60	47	[illegible]	38	51	73	80	76	63	59	73	60
	II	44	24	21	16	20	25	74	60	80	23	30	30	35
Barmer	I	64	61	53	56	64	73	79	82	74	60	52	56	65
	II	28	23	30	25	31	40	51	51	44	20	26	28	34

I = 8 hrs. I.S.T. II = 17 Hrs. I.S.T.

TABLE 1.7

MEAN WIND DIRECTION AT 8 HRS AND 17 HRS. I.S.T

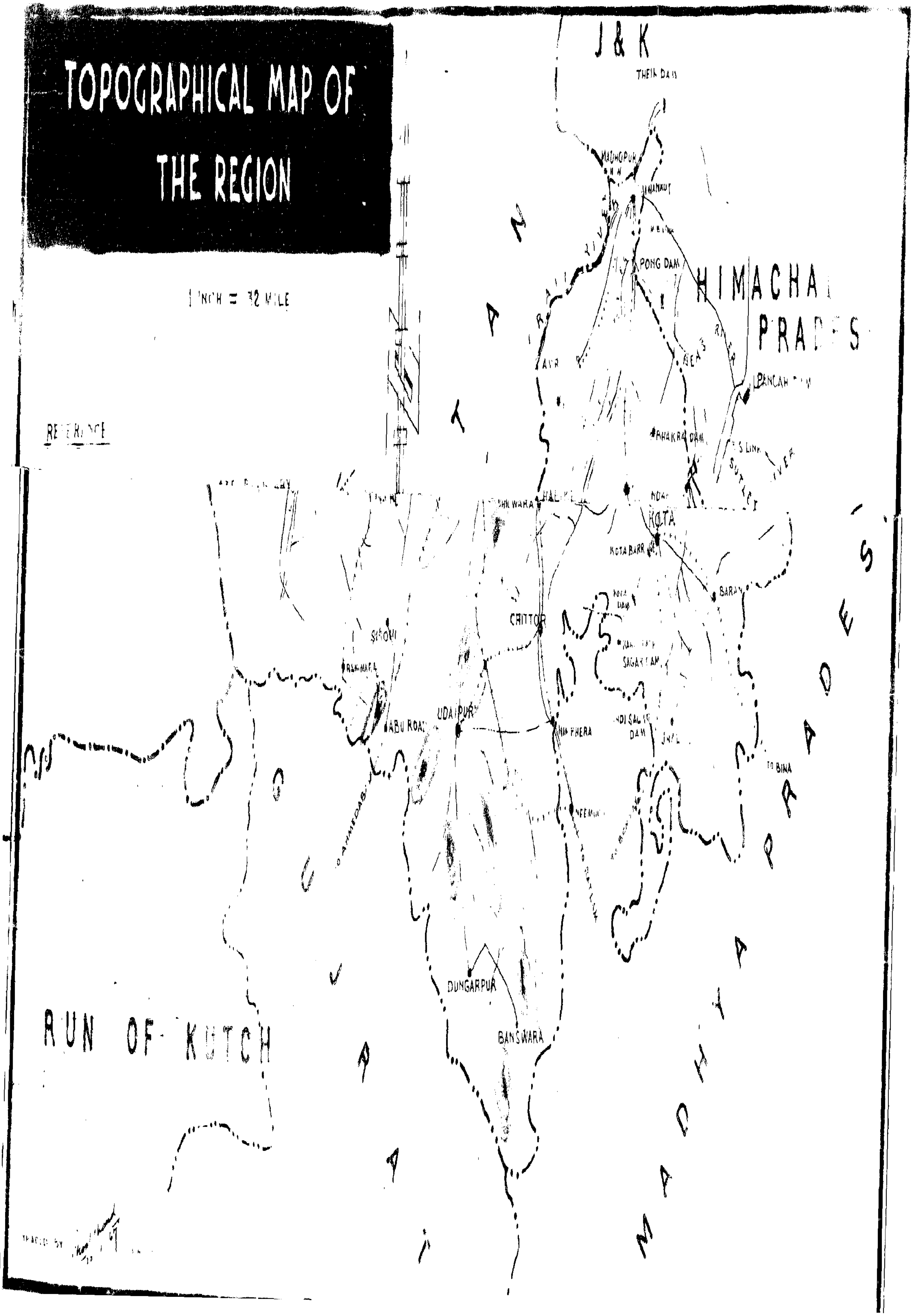
Station 1.		Jan 2	Feb. 3.	March 4.	April 5.	May 6.	June 7.	July 8
Sri Ganganagar.	I	N01W	N82E	N86E	S69E	S34W	S21W	S20W
	II	N22W	N21W	N44W	N61W	N70W	S68W	S03W
Bikaner	I	S68E	S36E	S28E	S20W	S46W	S52W	S43W
	II	N07W	N45W	N73W	N76W	N74W	S55W	S36W
Jodhpur	I	N37E	N34E	N36E	S41W	S43W	S47W	S47W
	II	N12E	N64W	N82W	S82W	S62W	S50W	S46W
Mean wind velocity (mph)		6.Ø9	6.8	6.0	6.8	10.7	12.6	12.1
Barmer	I	N36W	N37W	N35W	N54W	S38W	F.49W	S46W
	II	N01E	N43W	N64W	S80W	S68W	S33W	S41W

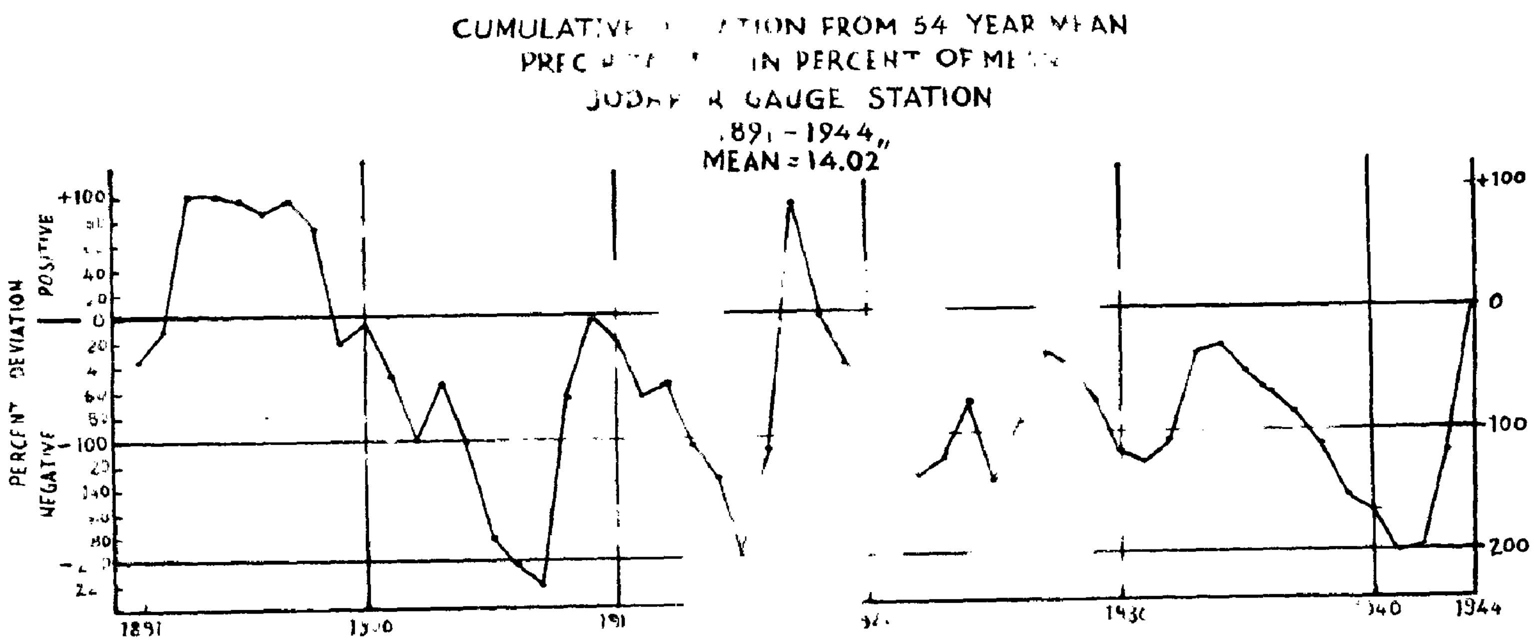
TABLE 1.7 Contd.

Station 1		August 9.	September 10	October 11	November 12.	December 13.	Year. 14.
Sri Ganganagar.	I	S32W	S38W	S04E	S41E	S54E	S03W
	II	S28W	N80W	N42W	N36W	N31W	N50W
Bikaner.	I	S45W	S65W	S39W	S10W	S66E	S29W
	II	S38W	S60W	N77W	N31[illegible]	N02E	N87W
Jodhpur.	I	S47W	S58W	N80W	N42E	N38E	S68W
	II	S40W	S44W	N87W	N08E	N21E	S73W
Mean wind velocity (mph)		9.1	7.3	4.8	4.6	6.1	7.9
Barmer.	I	S45W	S65W	N79W	S30W	N36W	N85W
	II	S34W	S39W	S62W	N06E	N27E	S68W

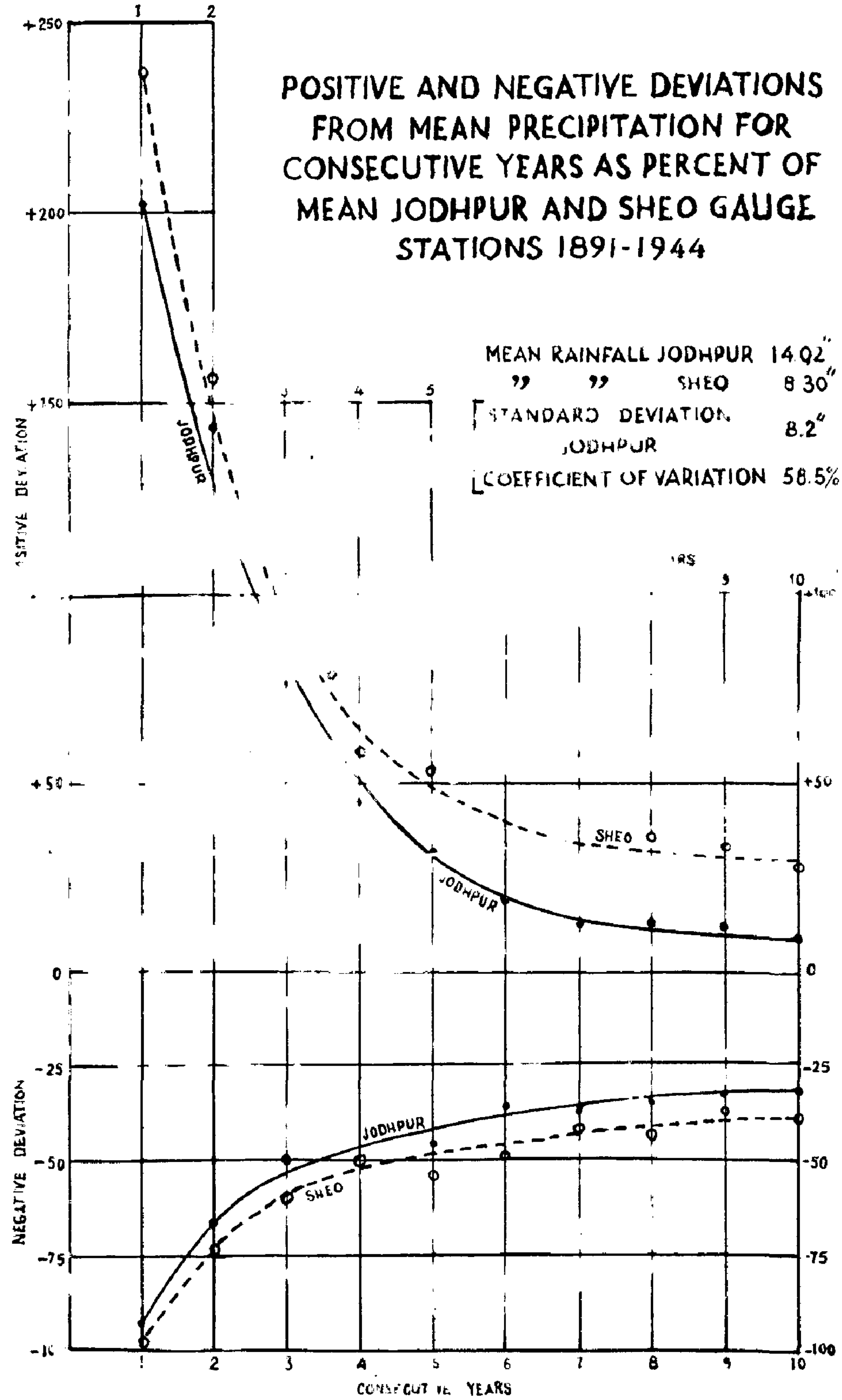
I = 8 Hrs. I.S.T.

II = 17 Hrs. I.S.T.


TOPOGRAPHICAL MAP OF THE REGION
J & K
THEIN DAM
MADHOPUR
POND DAM
HIMACHAL PRADESH
BHAKRA DAM
KOTA
KOTA BARR
BARAN
CHITTOR
UDAIPUR
ABU ROAD
DUNGARPUR
BANSWARA
TO BINA
RUN OF KUTCH
MADHYA PRADESH

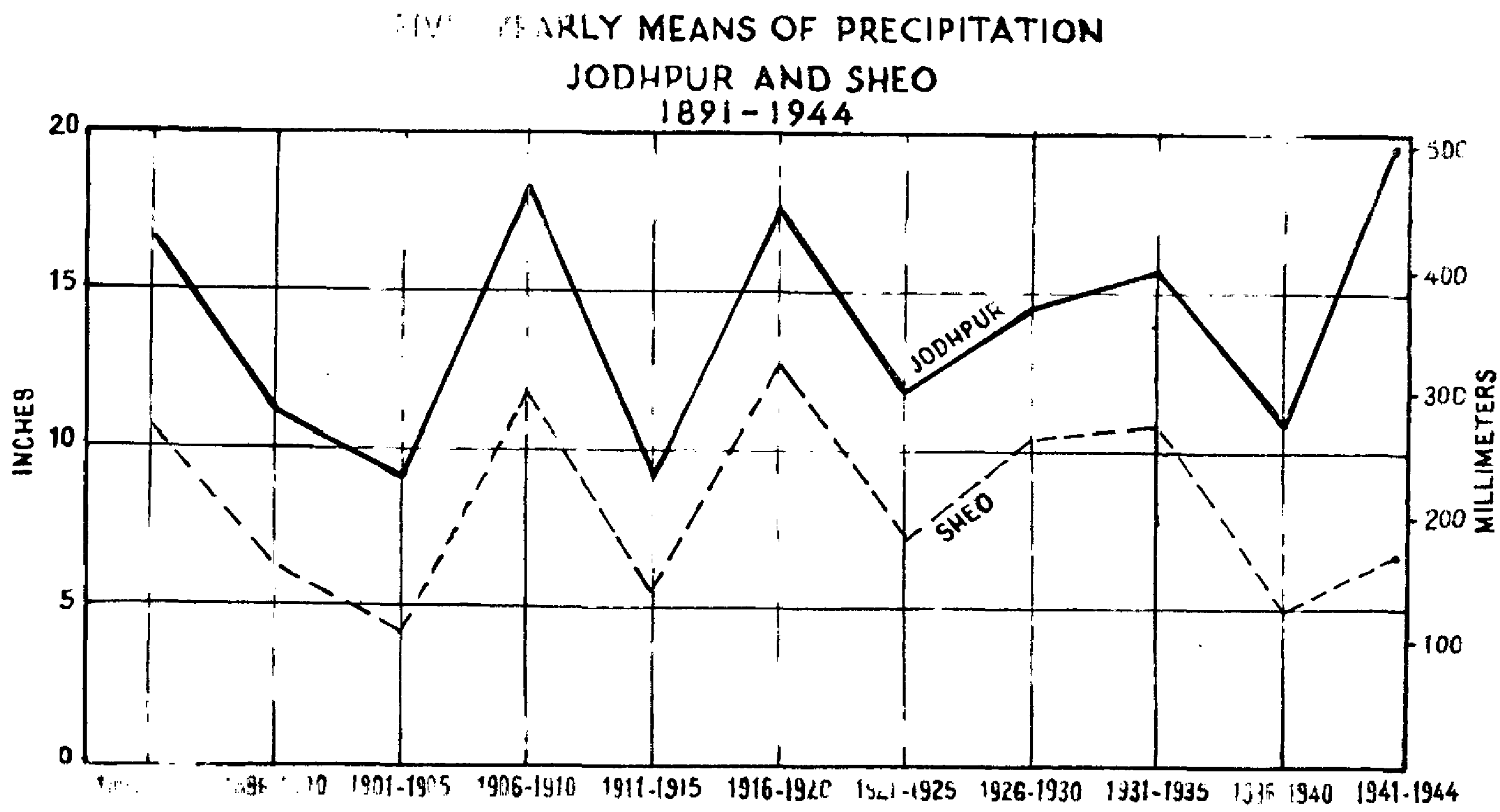

MEAN = 14.02"
STATION
PERCENT DEVIATION
POSITIVE
NEGATIVE
+100
0
100
200
1891
1930
1944

1·2



POSITIVE AND NEGATIVE DEVIATIONS FROM MEAN PRECIPITATION FOR CONSECUTIVE YEARS AS PERCENT OF MEAN JODHPUR AND SHEO GAUGE STATIONS 1891-1944
MEAN RAINFALL JODHPUR 14.02"
" " SHEO 8.30"
STANDARD DEVIATION JODHPUR 8.2"
COEFFICIENT OF VARIATION 58.5%
JODHPUR
SHEO
NEGATIVE DEVIATION
+250
+200
+150
+50
0
-25
-50
-75
-100
1
2
3
4
5
6
7
8
9
10
YEARS

FIG. 1·3



...ARLY MEANS OF PRECIPITATION
JODHPUR AND SHEO
1891 - 1944
INCHES
20
15
10
5
0
MILLIMETERS
500
400
300
200
100
JODHPUR
SHEO
1901-1905
1906-1910
1911-1915
1916-1920
1926-1930
1931-1935
1941-1944

FIG. 1·5

CHAPTER - II

GEOLOGY OF THE REGION WITH SPECIAL REFERENCE TO THE WATER BEARING PROPERTIES OF THE DIFFERENT LITHOLOGICAL FORMATIONS.

2.1 HISTORY OF THE WORK DONE

The earliest work done on the geology of the area is by Blanford(1877) and Oldham(1886) . This was followed by the work of La Touche (1902), Holland & Christie (1909), Heron (1932), Krishnan (1952) and Ghosh (1952). At present the investigations associated with Ground Water conditions and mineral deposits are being taken up by the Central Arid Zone Research Institute, Exploratory Tube Wells Organisation, Geological Survey of India and Rajasthan underground water Board.

2.2 SUMMARY OF THE GEOLOGIC HISTORY

The history of the geomorphic evolution of the present land forms and the river system of Western Rajasthan is much older than the Himalayan rivers and the extensive alluvial plains formed by them.

The following appears to be the general sequence of events in this region as described by Krishnan and Ghosh:-

(1) Originally in Archean epoch rocks now constituting the Aravalli System were laid down as sediments - predominantly argillaceous but with minor arenaceous and calcarious intercalations. Sedimentation was followed by orogenies during which the sediments were metamorphised into slates, phyllites, schists with minor associated quartzites, and were compressed in tight folds, which in places were overturned-the fold axes generally trending north-north-west, sub-parallel to the trend of the structural axis of the Aravalli Range.

(2) During the ensuing Eparchean interval widespread denudation and peneplanation occurred in the region.

(3) In Purana (Algonkian) epoch on the eroded surface of the Aravalli rocks were deposited arenaceous, argillaceous and calcareous sediments which were folded and metamorphosed. These rocks consisting of the Delhi system and the Aravalli metamorphics were intruded by batholiths and stocks of Erinpura, Jalore and Siwana granites. Possibly as a late phase of the same magmatic period, extravasation of the felsic lavas and pyroclastics of the Malani volcanic series occured along the western side of the Pali region.

(4) Subsequent to their extrusion, the Malani volcanics were apparently gently folded. Erosion then followed with development of a surface of low to moderate relief that was cut on Aravalli, Jalore and Malani rocks.

(5) Possibly in late Purana (Algonkian) or early Paleozoic time the Vindhyan sandstone member was laid down on this surface as a stream deposit. The sandstone member may have originally extended over a larger part but has been reduced in extent by subsequent erosion.

(6) There is a break after the Vindhyans till Permocarboniferous times. In Permocarboniferous times, an arm of sea over Western Rajasthan extended along the Narbada valley to the region of Umaria in Madhya Pradesh. This period was marked by extensive glaciation as evidenced by the boulder beds at Bap and Pokaran.

(7) In the Jurassic period, the sea had extended into the Narbada valley. The peneplain of Western Rajasthan was invaded by an arm of the sea from the south - west direction. In Jaisalmer area, the deposits were laid under alternating marine, fluviatile and deltaic conditions.

(8) During the succeeding Eocene epoch, extensive marine transgressions inundated a large portion of what is now the western desert in western Rajasthan. Both marine sediments containing nummulites as well as estuarine sediments containing lignite were deposited near Barmer, Jaisalmer and Bikaner. The geological history of western Rajasthan during the Middle and Upper Tertiary periods is not clear due to the concealment of the deposits by blown sand. It is conjuctured that the sea gradually withdrew.

(9) During Quaternary era, aeolian and stream sediments have been deposited in the region.

(10) The evolution of the present land-form is due to the fluvial environment of pleistocene and sub-recent times. A well integrated drainage system during this period was responsible for the alluvial deposits of the region. After this the desiccation started due to change of climate and as a result of this wind became the prominent agency of aggradation and degradation. The wind initiated the aeolin erosion, deflation and accentuating the mechanical disintegration of the rocks. The wind-blown sand was deposited against obstructions, resulting in the formation of sand dunes.

2.3 STRATIGRAPHY

The greater part of Western Rajasthan is covered by alluvium and wind blown sand. Rock outcrops occupy a little more than 12,950 sq. miles or roughly 7% of the total area of Western Rajasthan. Scattered outcrops of older geologic formations are met with at great intervals of distance. Hence any complete or detailed geological mapping of Western Rajasthan has been handicapped. However, from isolated geological maps, the general stratigraphic relations have been established on a regional scale. Plate 2.1 shows the geology of the region.

The general sequence, character and water bearing properties of the rock units of the region are shown in Table 2.1 and are described in more detail in the following paragraphs.

2.4 PHYSICAL CHARACTER OF ROCKS

RECENT SERIES

(a) Wind Blown Sand:- It is derived from the disintegration of older local rocks as well as that carried by wind action from Runn of Kutch. The unconsolidated sand lies on aluvium or bed rock in thin blankets which are generally less than 10ft. thick. High sand dunes are formed most commonly along the large water courses. The dunes are generally of transverse type - being oriented at right angle to the direction of prevailing winds. In a larger part of Bikaner and Jaisalmer they are longitudinal, i.e. parallel to wind direction. The dunes are considered to have been shaped principally by south-westerly winds which blow steadily in the region from April to September.

The sands are generally fine to medium-grained and well rounded and well-sorted by wind action. The sand grains consist predominantly of quartz but ferromagnesian minerals and feldspars may also be present. Fragments of Malani rhyolites are also common at places.

(b) Younger Alluvium:- The younger alluvium comprises generally of unconsolidated stream laid silt, sand and gravel which occur principally in narrow discontinuous bands along the channels of larger water courses. Thus it lies mainly along the flood plains of Luni and its tributaries.

Except in this area, alluvial deposits are not common. But it is more probable that there are and have been alluvial valleys in the geological past - recent or remote - which have been blanketed off by encroaching sands. In fact from one exploratory tube well near Sikar, about 134 meters (440 ft) of unconsolidated stratified material has been recorded. Their alternately graded nature, strongly characteristic of an alluvial cycle, points towards the existence of alluvial valleys hidden under a blanket of sand.

In most places the deposits are predominantly medium to coarse sand, of which the grains are largely quartz with subordinate feldspars and ferro - magnesian minerals. The pebbles, cobbles and gravel may consist of quartz, limestone, granite, slate, phyllite, schist, volcanics or almost any of the bedrock types present in the region. The relative abundance ~~and [illegible]~~ of various rock types in the gravels of a particular stream depends on the prevalence and distribution of types of bedrock in the catchment area.

Owing to the evaporation and transpiration of ground water in younger alluvium, the younger alluvium along large water courses is commonly impregnated with salt. Extensive efflorescences of salt are generally associated with younger alluvium along Luni, Bandi, Sukri and other streams of the region. In other places along these streams, the alluvial deposits are impregnated with cement of lime-carbonate which locally form hard resistent ledges.

Pleistocene Series

Older Alluvium:- This occurs extensively near Pali but in most places the deposits are relatively thin and discountinuous. The deposits are derived in part from the erosion and stream transpart of bed rock debris and in part from in situ weathering of bedrock. The transported materials are commonly poorly sorted silt or sand with gravel present in subordinate degree. The materials derived from in situ weathering of rock include unsorted angular fragments of resistant parent rock in finer matrices of silt and sand.

Generally near the land surface the older alluvium is partly consolidated through cementation by secondary lime-carbonate or "kankar". In the area lying between Dilara and Jelwas "kankar"-impregnated alluvium occurs as terrace remnants which stand out conspicuously from the surrounding plains. These remnants are capped by kankar pans which are comparatively resistant. The remnants range in dimension from a few tens of feet up to perhaps 150 to 300 feet(45 to 90 Metres). They usually rise to about 10 to 15 feet (3 to 5 Metres) above the surrounding flats.

Hard pans composed essentially of calcium carbonate with subordinate admixture of silt and sand are widespread in the region. Such hard pans of "kankar" are commonly deposited on planate bedrock surfaces and form surficial capping layers as much as 20 feet(6 Metres) or more thick. At many places in well sections the lime carbonate is observed to extend down in vein-like bodies from the capping layer almost to the water table. Such "kankar" veins generally follow bedding planes, joints or other tabular partings in the bedrock and locally are observed to replace slate, phyllites, schist, granite, volcanics and other rock types prevalent in the region.

Kankar hard-pans such as occur in the Pali region are relatively common in those regions of the world with arid to semi-arid climates. The formation of kankar pans appears to take place principally in the zone of soil water and in adjacent parts of the zone of vadose water but is not necessarily related to evaporation of water from the zone of saturation. Factors which appear to favour the formation of kankar pans include the following as given by Taylor (46):-

(1) An arid to semi-arid climate with annual rainfall less than 20 inches.

(2) A net excess of evaporation over precipitation.

(3) A relatively stable or slowly degrading land surface.

(4) Deep weathering of a parent bedrock such as granite, slate, volcanics and other types so as to bring about chemical break down of calcium-bearing minerals in these rocks. The resulting calcium hydrates may then be available for combination with carbonic acid entrapped in rain water and in the soil water to form soluble calcium bicarbonate.

(5) Calcium carbonate may then be precipitated in the soil zone from calcium bicarbonate solutions and may then be accumulated by a process of gradual accretion.

Calcium carbonate is transported along with sand from extraneous sources by wind action. He suggests that rain falling on such sands may dissolve out the lime carbonate which is latter precipitated in the soil zone as "kankar" when the moisture evaporates.

Eocene System

Nummulitic Limestone, Sandstone and Shales:- Sandstones and shales of Eocene age are exposed extensively in the area to the north - west of Jaisalmer and in the Kolayat - Palana - Bikaner area. They generally occur as isolated inliers in recent sand. In Jaisalmer, however, these Tertiaries are seen distinctly to overlie the older rocks of Jaisalmer series. The Tertiary rocks are either horizontal or they dip slightly towards the west. In Palana area bands of lignite are known to be associated with the sandstones and shales at depth and they do not crop out on the surface. Also at Botia in Barmer district, bands of lignite have been recorded at depth.

Mesozoic System

Barmer Sandstone:- Cropping out from the alluvium, they occur locally in several exposures in Barmer district. The rock is locally indurated and hard, but is sometimes soft. According to earlier work and interpretations, a provisional cretaceous age has been assigned to them.

Jurassic System

(a) Jaisalmer Series:- Jaisalmer series consisting of limestones, sandstones and shales are very commonly exposed in a large area around Jaisalmer and to its north, west and south-west. These formations are either horizontal or they show a slight westerly dip.

(b) Lathi Series:- Lathi series consisting of a coarse to fine grained, white to grey colored sandstones are commonly exposed between Lathi and Jaisalmer on Pokran - Jaisalmer road and near Bap and Nokh. Outcrops have been located long Pokaran-Chec road also. Due to favourable lithological character, these rocks retain and yield maximum amount of water in this desert area. They support a good vegetation of desert cactus and Sewan grass which are locally used as cattle fodder.

Permo-Carboniferous Series

Tillite Beds:- At Bap near Phalodi and at Pokaran, two exposures of doubtful tillite beds have been observed and a Permo-carboniferous age could possibly be assigned to them; but evidence is not very conclusive.

Vindhyan System

Limestone, Sandstone and Shale:- Rocks of the Vindhyan system are widely exposed throughout Western Rajasthan. They are most common in Jodhpur, Nagaur and Bikaner districts and partly also in Pali and Jaisalmer districts. Exposures are best seen around Jodhpur city and along Jodhpur Pokaran road.

Only upper Vindhyan formations consisting of buff to cherry red quartzitic sandstones with thin alternating bands of shale and limestone are seen everywhere. The rocks are well stratified and joined; attitude of beds is almost horizontal, but towards the west a distinct westerly dip can be observed though small in magnitude.

Purana (Algonkian) System

(a) Malani Volcanites:- Commonly the Malani volcanites form low isolated hillocks and hummocky masses which rise slightly above surrounding plains. They consist principally of stratified rhyolite lavas interbedded with less common lavas of intermediate to mafic composition and with occasional beds of indurated tuffs and breccias. These rocks are the products of rather intense vulcanism during which relatively quiet eruptions of lava were interspersed with explosions of pyroclastic materials. The textures of the rocks range from porphyritic to glassy. In rhyolite porphyries the phenocrysts are commonly pink feldspar and quartz blobs of about 2 to 5 mm length set in an aphanitic or glassy groundmass are relatively common. Locally associated with Malani volcanics are small mafic intrusions. In most of the rhyolite beds except near the surface, the joint planes are quite tight.

(b) Granites:- Two varieties of granites have been recognised in this region. One is more felsic and is generally of pink to red color and is known as Jalore granite, the other variety is more mafic and is grey to greyish green in color and is known as Siwana Granite. The pink variety is intrusive into the grey variety and therefore is slightly younger in age.

(i) Jalore Type:- This lithological type is the most predominant of the two granites and is composed of orthoclase, felspar with some quantity of plagioclase, biotite, hornblende and muscovite. Biotite is prominent among the accessory minerals. Texture of the rock varies from fine grained to coarse grained. Phenocrysts of felspars are very frequent in the coarse variety. Bedding planes and foliations are the common features of this type of granite. It is moderately resistant to weathering and forms cliffs and hills rising to elevations of 734.6, 839.4, 466.5, 359.7 and 507.8 m from M.S.L. in Rona hills (near Jalor), Korana Hills near Modi south of Alwara & Takhatpura and in the rest of the region it forms hummocks and low lying hillocks which are well eroded. The Jalore granite has also intrusive relationship with Aravallis . Three sets of joints are well developed in granites, i.e. vertical, horizontal and inclined. The vertical joints penetrate to greater depths. Weathering is more effective along these joint planes. These joint planes are tight but have widened up near the surface due to weathering.

(ii) Siwana Granite:- This type occupies lesser area and is relatively localised. It is composed predominantly of plagioclase felspar and lesser amounts of orthoclase felspar, quartz and ferromagnesian minerals. The last two components are present in very small quantities. Of the ferromagnesian minerals, hornblende and sphene are more common than biotite. This variety is generally non-foliated and non-porphyritic. The Siwana type is very susceptible to weathering and erosion due to which it has been eroded down to wide, level plains having a thin cover of alluvium. It attains a maximum height of 975.4 m in the hill about 4 miles south of Piplun, 545.6 m near Devandi and 587.7 m near Than.

Archaean System

Aravalli Granite - Gneiss and Slates:- The oldest formations of granite - gneiss and schists are restricted to near the Aravalli ranges towards the east. In Churu and Sikar districts, extensive exposures are scattered within the wind blown sands and these have not yet been systematically mapped. They have been provisionally termed as "ANCIENT CRYSTALLINES." It is more than likely that they belong to the older gneissic complex which has actually been struck as bed rock in a borehole at Sikar.

In addition to the Aravalli granite and the Siwana granite, an interesting report has been made by Taylor (46) of the occurrence of granite in the vicinity of Sankra, district Jaisalmer, far away from these two known granite formations. Possibly they may be erratic boulders. These show typical hummocky weathering and are medium to coarse grained with only quartz, white felspar, biotite and hornblende as constitutents. Along weathered planes of joints, the color changes to pink or brick red.

The Aravalli rocks are predominantly slates with minor interbedded quartzites. Locally the slates may grade into hard shales or into phyllites and schist. Originally the Aravalli rocks were probably deposited as sediments which were predominantly argillaceous but with minor arenaceous and calcareous bands.

Relict ripple marks and current-bedding structures are present in quartzitic slates at quarries on hill " 754" about 2 miles south of Khairla. These features suggest that some of the original Aravalli sediments may have been deposited under shallow-water & terrestrial conditions.

In archaean epoch the original Aravalli sediments were subjected to regional metamorphosism. However, as pointed out by Heron (1935) the intensity of metamorphism was evidently not uniform but varied considerably from place to place. In some localities of the Pali region relatively unmetamorphosed bands of shale are associated with the ubiquitous slates which elsewhere in the region may locally pass into phyllites and schists of higher metamorphic grade.

The rocks of the Aravalli group are generally dark brown, greenish gray and dull purple in colour. The slates are commonly composed of quartz grains with kaolinitic and micaceous material as interstitial filling. The rock is usually hard and compact with cleavage and joint planes highly developed. In good exposures bedding are generally readily apparent but elsewhere they may be obscured by jointing and cleavage. Characteristically near the surface the slate weathers out in chips and rhombohedral cleavage fragments. The slates are very commonly traversed by numerous veinlets and narrow irregular stringers of quartz that follow bedding, joint and cleavage planes. Where the slates have weathered away the vein quartz commonly remains in a residual blanket of angular quartz rubble. Thin quartzite beds occur interbedded with the slates from place to place in the region although always of minor importance. For example about 1½ miles west-southwest of Jadan(District Pali) beds of hard brittle quartzite

2 to 3 inches thick are intercalated with greenish-grey shaly slates. Similarly about 10 miles south-southeast of Sanesni thick brown quartzites are interbedded with thin-bedded quartzitic slates. Hard hematitic quartzites crop out in a band extending north-northeast from mile post 96.2 on the Pali Ajmer highway toward ~~highway-tower~~ Khotawas. The rock is dark brownish red in colour and is cut by numerous reticulated veinlets of quartz. In places the rock is jasperized.

The Aravalli rocks have been moderately to intensely folded - probably during the same orogenic movements which began in the Aravalli Range during Archaean epoch. The fold axes and strike of the Aravalli rocks generally trend northeast to north-northeast sub-parallel to the structural trend of the Aravalli Range. Vertical dips are often observed in outcrops and dips greater than 50° are common. The rocks are isoclinally folded and at places overturned. However, owing to lack of good exposures no attempts has been made during the present study to map the regional structure of the Aravalli slates.

The Aravalli slates are generally susceptible to erosion and in much of the region they have been reduced to wide level plains which are commonly covered by a thin veneer of alluvial deposits or "kankar" sand. In places, however, the Aravalli rocks are more resistant and form conspicuous buttes, and ridges. Perhaps most prominent of these is Junagarh butte (elevation 1,478 ft) located about 7 miles east of Pali. This cone-shaped butte rises some 650 feet above a pliable platform of Aravalli slates. Extending north-northeast for 3 to 6 miles from Junagarh butte is a ragged chain of buttes about 100 to 245 feet high. These apparently form a discontinuous strike ridge in Aravalli slates.

2.5 WATER BEARING PROPERTIES OF DIFFERENT LITHOLOGICAL FORMATIONS

The principal water bearing properties of the rocks are porosity, effective porosity or specific yield, specific retention, permeability and direction of maximum ease of percolation. These properties control the entrance of water into water bearing formations, their capacity to hold, transmit and deliver water; and confinement and concentration of percolation to the direction of maximum ease of movement. Hydrologic properties depend chiefly on porosity, size of openings or interstices and their shape, arrangements, interconnection and continuty.

Rock formations and the openings therein are the results of primary geologic processes which form the rock and the secondary processes that modify them, either increasing or decreasing their porosity and permeability, Geologic processes acting on the rocks may change or induce entirely new hydrologic structure which controls the motion of underground water. The hydrologic characteristics of the sedimentary alluvial deposits may be inherited from the parent rock formation.

The water bearing properties of the different lithological formations met with in the region are described in the following paragraphs.

(a) Wind Blown Sand:- Over the greater part of Western Rajasthan, the surficial sandy flats lie above the regional zone of saturation and these are rather thouroughly drained. Locally, however small patches of aeolian sands and dunes may contain perched ground water bodies when the sands rest on impervious bed rocks.

The static water table in this formation lies at depths ranging from 1.68 m to 91.44 m. Good aquifers do not develop in this formation. The discharge per well varies from 0-5 litres/sec to 15 litres/sec. Most of the wells in this formation have moderate to poor discharge potential. Groundwater in this lithological unit is always alkaline and the average sodium, potassium, calcium, magnesium and sulphate contents are higher and the carbonates and bicarbonates lower.

(b) Younger Alluvium:- In the bands of younger alluvium along the large water courses, ground water moves in shallow underflow conduits which are interrupted from place to place by bed rock outcrops.

The static water table in this formation lies at depths ranging from 1.5 m to 22.5 m. Most of the wells in this strata have poor to moderate yields. The low capacities of wells in these relatively permeable deposits are due in large measure to their thinness and discontinuty. The discharge per well varies from 36 K litres/ day to 140 K litres/ day (8000 gallons/day to 31,000 gallons/day). The average salinity of water is markedly higher in this formation because of the concentration of salts by evaporation and transpiration in areas of ground water discharge which lie principally along the larger water courses. The average bicarbonate content is considerably lower but average chloride and sulphate contents are markedly higher.

(c) Older Alluvium:- Water in the older alluvium moves largely ~~throu~~ through interstitial openings in the more pervious sand and gravel beds which lie in the zone between the water table and underlying bed rock.

The static water table in this formation lies at depths ranging from 1.5 m to 24 m. The sustained discharging capacities of wells range from about 18 K litres/ day to 136 K litres/day (4000 gallons/day to 30,000 gallons/day). The low yields of wells in the older alluvium are due to its lack of areal continuity, to its thinness, to its poor sorting and to low permeability which has resulted from the secondary cementation by lime carbonate.

The average chemical quality of water in older aluvium is slightly better than that in the younger alluvium but inferior to the quality of water in bed rock formations. The average bicarbonate and sulphate contents are moderate but the chloride contents is somewhat higher.

The alluvial section at Sikar extends to a depth of about 115.8 m. It has a combined thickness of 26.1 m of water bearing granular material composed chiefly of fine to medium grained moderately sorted sandstone with plenty of calcareous material. These are probable water-yielders and the depth to water table is about 26 m.

(d) Nummulitic Limestone, Sandstone and Shales:- These are, in general, poor water yielders except in some local granular patches. The principal water bearing beds are thin bands of friable sandstone and soft conglomerates which are interrelated with lime stone.

The static water table lies at depths ranging from 61 to 106.7 meters. The yield of the wells vary from 68 K litres/ day to 73 K litres/ day (1500 gallons/day to 16000 gallons/day) The quality of water vary from fresh to highly saline. The alkalinity is high and the average sulphate content is higher.

Some of the wells in this formation are tapping perched water table zone.

(e) Dammar Sandstone:- It is apparently an important water bearing formation. The wells in this formation yield moderate quantities of water along joints and crevices in the rocks. The rocks themselves are relatively compact and fine grained. In the Barmer sandstone, down to depth of 243.8 m around Botia, about 106.7 m of fine to very coarse grained, moderate to poorly sorted, sandstones were encountered below the regional level of saturation. The material examined from the section showed high porosity.

The static water table lies below a depth of about 76.2 m. The yield data of this formation are not available, but a dug well 45 m (150') deep in Barmer located in this formation is reported to yield 32 K litres/hr(7000 gallons/hr) by pumping but it is also reported that this well cannot stand sustained pumping of more than 5 hours.

The chemical quality of water shows variation from moderately saline to saline. The water is slightly alkaline.

(f) Jaisalmer Series:- A regional zone of saturation is present in the strata of Jaisalmer series of inter-bedded shales,sand stone and limestones which yield water mostly along joints and bedding planes and consequently the specific capacity is low.

The static water table usually lies between 61.0 and 106.7 m below the land surface. The daily capacities of open wells as observed around Jaisalmer city, varies between 14K litre/day to 113 K litre/day(3,000 gallons/day to 25,000 gallons/day). The water in this strata shows a concentration of sulphates and total dissolved solids and is also alkaline in character.

(g) Lathi Series:- The regional zone of saturation lies in this formation, which is fairly extensive in the Jaisalmer- Barmer districts. Exploratory drilling has proved that the Lathi group of sandstones is the most prolific group of water yielding rocks. In the Lathi series, down to a depth of 305 m, about 171 m of water-bearing granular zones were penetrated in which fine to medium grained, well sorted, red, grey and yellow sandstones and fine to coarse grained well sorted grey to pink sandstones predominate. The sandstones at lower levels are at times calcareous. Plenty of water occurs in the openings between sand grains of these friable sandstones. Irrigation tube wells with large capacities can tap enough water from these formations.

The static water table in this region lies at depths ranging from 30.5 to 39.1 m. The yield from dug wells is 45 to 67 K litre/day (10000 to 15000 gallons/day). This yield is poor compared to the yield of as high as 182 K litre/ Hr (40,000 gallons/hr) from deeper aquifers. The thickness of the Lathi formations is more than 305 metre (1000 ft.) The water from the dug well zone is moderately hard and alkaline.

(h) Tillite Beds:- These beds are limited in extent and thickness. They are generally not water bearing as they are mostly above the regional zone of saturation.

(i) Vindhyan Lime Stone Members:- The lime stone band in the Pali region contains the regional water table and is one of the most important water bearing horizon. The maximum thickness of the lime stone penetrated in well sections is about 120 ft(36 m) but it is probable that a thickness of at least 150 ft.(45 m) or more is attained in this band. In most places bedding planes are not well defined and regular joint systems are lacking. However, irregular systems of fracture partings are generally present. Openings resulting from the solution by percolating waters are present but not well developed due to low solubility and the lack of distinct bedding and joint planes. The net permeability of Vindhyan lime-stone is therefore relatively low compared to other limestone formations of the world. The ground water occurs mostly through irregular fractures and to a limited extent through bedding planes and solution cavities where those are present.

The static water table lies at depths ranging from 10.7 to 91.5 m. The yield from the wells ranges from 35 to 125 K litre/day (7500 to 28,000 gallons/day). The chemical quality of water is very good. The average content of bicarbonate, chloride and sulphate is relatively low.

(j) Vindhyan Sandstone Member:- The bedding and joint planes are well developed in the sand stone member. Water is contained in the tubular openings along the joint and bedding planes. These sandstones have a porosity of 2-5 per cent.

The static water table lies at depths ranging from 61.0 to 76.2 m. Wells may tap 25 to 70 K litre/day (5000 to 15000 gallons/day) although some wells have yield as high as 180 K.Litre/day (40,000 gallons/day) or as little as 25 K Litre /day(5,000 gallons/day).

(k) Malani Volcanites:- For the most part, Malani rocks are highly indurated and relatively impervious. However, some ground water circulates through the rocks along bedding planes, joints, sheeting and other secondary tabular partings. The yield of a well in Malani Volcanics depends on the number and width of the partings encountered in the well section below the water table. Near the land surface, joints and other secondary partings may be fairly numerous and closely spaced. With increasing depth, the partings tend to close and disappear so that deep percolation of water is retarded. The water holding capacity of these rocks has also gone down by about 60% due to deposition of secondary salts.

The static water table lies at depths ranging from 7.6 to 38.1 m below ground level. The discharging capacities of the wells range from 10 to 30 K Litres/day (2000 to 7000 gallons/day). The average bicarbonate, carbonate and sulphate content of the water is high whereas sodium, potassium, calcium, magnesium and chloride contents are of moderate order.

(1) Jalore Granite:- Circulation of water in Jalore Granite occurs through surficial mantles of disintegrated rock and through joints sheeting and other minor partings. By weathering process, the fresh rock near the surface breaks down in situ by disintegration of constituent mineral grains and by decomposition through hydration of feldspars and ferromagnesian minerals. The resulting weathered product of disintegrated granite or "gruss" has a markedly higher capacity to store and transmit water than the fresh unweathered rock. Thus the thickness and extent of "gruss" mantle is of considerable importance with respect to local availability of ground water. The thickness of the gruss generally varies from 12 to 18 m.

As a rule the water yielding capacity decreases with increasing depth. The condition is due to the gradual decrease with depth of the number and width of joints and other partings and to the absence of gruss below the limit of surficial weathering. The water holding capacity of these rocks has also decreased due to deposition of secondary salts.

The static water table lies at depths ranging from 2.44 m to 128.32 m - but in general upto 30 m. The yield from dug wells in the region ranges from 25 to 70 K Litre/day (5000 to 15000 gallons/day). The average bicarbonate and sulphate contents of water in the Jalore granite lie near the general average.

However, the average chloride content is higher.

(m) Siwana Granites:- These have very poor water potential. The static water table lies at depths ranging from 9.75 to 75.85m. The discharge potential of the wells varies from 0.37 litres/sec to 33.0 litres/sec (.08 to 7 gallons/day). Average carbonate and bicarbonate contents of water are of high order, whereas the average sodium, potassium, calcium, chloride and sulphate contents are of low order.

(n) Aravali Slates:- These are generally devoid of water except in having limited quantities along joints, cleavages or bedding planes enlarged by the process of weathering. The arid climate does not favour deep weathering and formation of pockets of granular material, which in other more humid areas are found capable of storing and yielding water.

The static water table lies at depths ranging from 7.7 to 30.5 m below ground levels. The discharging capacity of the wells ranges from 10 to 30 K litres/day(2000 to 7000 gallons/day). The average carbonate and bicarbonate contents of the water in Aravali slates are of high order, whereas average sodium, potassium, calcium, chloride and sulphate contents are of low order.

TABLE 2.1

GENERAL STRATIGRAPHIC SECTION OF THE REGION

Geological age: Era	Geological age: Period	Geological Unit	Lithologic character and occurance	Water bearing characteristic
CENOZOIC	RECENT	Wind blown sand	Buff- coloured medium to fine grained wind-blown sand in thin mantles over bed rock and alluvium. At several places forms high dunes also. Occupies greater part of the whole region.	Generally lies above the regional water table
		Younger alluvium	Unconsolidated silt, sand and gravel derived from erosion of older rocks and alluvium. Deposited along large stream channels. Thickness rarely greater than 40' and average is about 20'	Yields moderate to meagre supplies of salty water to ~~salty water~~ to shallow wells from discountinuous under-flow conduits along large water cources.
	PLEISTO-CENE	Older alluvium	Poorly sorted semi-consolidated silt, sand and rubby gravel. In part trans-ported and in part derived in situ from bed rocks.	Yields moderate to meagre supplies of brackish to salty water to wells where present in zone of saturation.
	EOCENE	Nummulitic limestones sand-stones fullers earth, shales lignite and bauxite	Sandstones & shales are exposed in north-west of Jaisalmer and in the Kolayat-Palana- Bikaner area. In Palana area bonder of lignite are associated with sandstones and shales at depth.	The greater part of this strata lies above water table which is a depth of about 100 m. in the area.

(Contd)

Geological age: Era	Geological age: Period	Geological Unit	Lithologic character and occurrence	Water bearing characteristic
MESOZOIC	CRETACEOUS	Barmer sand stone	Fine to very coarse grained, moderate to poorly sorted sand stones occuring to depths as much as 244 meters near Barmer and 107 meters near Botia	An important water bearing formation. The water table is at on depth of about 76.2 meters from the land surface.
	JURASSIC	Jaisalmer Series	Consist of lime stone, sand stones and shales; locally restricted; exposed in large area around Jaisalmer.	A regional zone of saturation is present in the strata. But specific capacity is low because the yield of water is mostly along joints and bedding planes.
		Lathi Series	Consist of coarse to fine grained, white to grey colored sandstones. Exposures are common between Lathi & Jaisalmer, with slight westerly dip.	Plenty of water occurs in the openings between the sand grains of the friable sand stones. Irrigation tube wells with large capacities can be constructed in this strata.
PALEOZOIC	[illegible]-CARBONIFEROUS.	Tillite Beds	Occur at Bap near Phalodi and at Pokaran in limited extend and thickness.	Generally lie above the regional water table.

(Contd)

Geological age: Era	Period	Geological Unit	Lithologic character and occurance	Water bearing characteristic
PRECAMBRIAN	PURANA (ALGONKIAN)	Vindhyan Limestone sandstone and shale.	Buff to cherry-red quartzitic sandstones with alternate bands of shale and lime stone. Well stratified and jointed; altitude mostly horizontal but bearing a small distinct westerly dip towards the west.	Yield moderate to meagre supplies of water from fractures, joints and bedding planes.
		Malani volcanities.	Hard red, buff and grey porphyritic and aphanitic rhyolite lava flows intercalated with indurated bedded tuffs and breccias. Occur extensively near Jodhpur, Pali and Pokran.	Yield meagre supplies of brackish to salty water to wells from joints, fractures and bedding planes where those are present in the regional zone of saturation.
	ARCHAEAN	Jalore Granite and Siwana Granite.	Coarse grey equigranular biotite-hornblende granite and fine to medium-grained pink granite.	Yields moderate to meagre supplies of fair to salty water from joints and cleavage planes and from grues where present in the zone of saturation.
		Aravalli granite gneisses shales and schists.	Dark grey and brown slates with minor ferruginous quartzites, phyllites and mica schists.	Yields moderate to meagre supplies of fair to slightly salty water to wells from joints, cleavage and bedding planes where present in the zone of saturation.

CHAPTER - III

GROUND - WATER HYDROLOGY

3.1 THE HYDROLOGIC CYCLE

The hydrologic cycle includes all movements of water vapor in the atmosphere, condensation to liquid and solid states in the atmosphere; precipitation of liquid and solid water on the ground surface; evaporation and melting of ice and snow on the ground surface, including partial return to the vapor state in the atmosphere; evaporation and flow of water on the surface, including partial return to the vapor state in the atmosphere, and movement of water toward the ocean; and evaporation and transpiration of water on the ground surface and from the surface of the ocean back to the vapor state and to the atmosphere.

It is necessary to study the entire cycle in order to understand subsurface-water motions. The hydrologic cycle may be long or short. It may be summarised, begining with the short cyclic movement and ending with the longer and more complicated.

(1) Vapor condenses to rain, snow, or fog and vaporises again before the water reaches the earth's surface.

(2) Vapors condenses in the atmosphere into rain or snow which reaches the surface of the earth and is then evaporated before the water gets underground. This evaporation may be directly from the rain water before it forms runoff, from streams, lakes, or the ocean. The water gets back into the atmosphere without an underground journey.

(3) Water vapor condenses and falls as snow or rain on the ground and seeps below the surface. The water which enters the soil may return to the atmosphere by the following methods

(a) It may be held as soil moisture and returned directly by transpiration and evaporation; or (b) it may become "gravity" or "vadose" water and seep down to the saturated zone. After water reaches the saturated zone, it may percolate as free-moving water through pervious material, the opening of which are interconnected, or it may move as confined water in and through ground-water conduits.

Ground water escapes when the water table is close to, or intersects, the surface. Direct discharge from the water table may take place in three ways:(1) by effluent seepage and spring flow, (2) by evaporation from the capillary fringe when the latter extends to the ground surface, and (3) by transpiration. Probably more water is lost by evaporation and transpiration from the capillary fringe than by effluent seepage. When the water table transects the surface, a swamp or spring is produced. The subsurface motions of water are discussed in detail in para 3.5.

3.2 THE GENERAL GROUND WATER EQUATION

The general ground-water equation is a mathematical statement of the disposition of rainfall which, on reaching the surface of the earth, is returned to the atmosphere by evaporation and transpiration, collects to form stream flow, or seeps into the subsurface reservoirs. It may be written

$$R = E + S + I$$

where R is rainfall; E, evaporation and transpiration loss; S, water discharged from the area as stream flow; and I, the ground-water increment. The ground-water increment(I) is the unknown and desired quantity and could be calculated if the other three factors could be measured.

The application of the ground water equation to the estimation of ground water resources of any region is discussed further in chapter IX.

3.3. MODE OF OCCURANCE OF GROUND WATER:

The mode of occurance of ground water is shown in figure 3.1 and table 3.1.

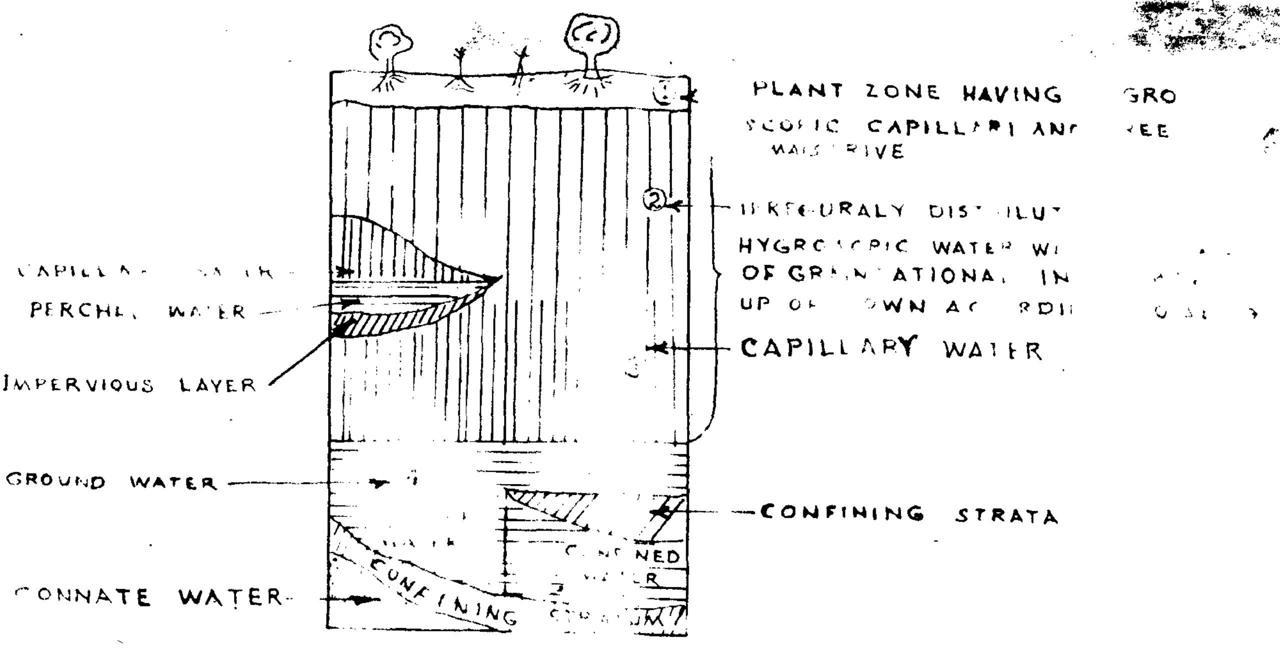


FIG [illegible] CURENCE [illegible] DI[illegible]UTION OF SUP[illegible] WATER

Water occurs underground in two great zones separated by the water table. The occurrence and movements in these two zones are markedly different. The water table exists only in water-bearing formations which contain openings of sufficient size to permit appreciable movement of water. It is generally considered to be the lower surface of the zone of suspended water and the upper boundary of the zone of saturation, as defined by Meinzer, which extends down as far as there are interconnected openings. The water table may be defined as the contact plane between free ground water and the capillary fringe, and is located by the level at which water stands in boreholes tapping free water or by the water levels in water-table wells. The water of the saturated zone is usually denominated ground water or phreatic water. Meinzer's term suspended water is used in this text for all occurrences of subsurface water above the water table.

Zone of Aeration or Zone of Suspended Water:- The zone of aeration is of interest to the geologist because it is in this

that destructive chemical action and disintegration of rocks occur. It is the zone that Van Hise has denominated the 'belt of weathering,' in which the oxygen of the atmosphere assisted by moisture, carbonic acid, the organic acids, and locally by sulphuric acid, acts on the rocks and manufactures the manifold products of weathering.

The water of the zone of aeration includes 'stored water' and 'moving water' (vadose or gravity water). The stored water occurs as attached films on the surfaces of openings and as wedge-shaped bodies at the junctures between interstices. The stored water above the capillary fringe is herein called 'pellicular water'. The capacity of the soil to hold pellicular water is

TABLE 3.1

ZONE OF INTERCONNECTED OPENINGS				SOIL WATER Limited to the soil and reached by roots
	UNSATURATED ZONE (ZONE OF AERATION)	SUSPENDED WATER	VARIETIES OCCURRING THROUGHOUT ZONE OF SUSPENDED WATER	PELLICULAR WATER Adheres to rock surfaces throughout zone of aeration and is not moved by gravity but may be abstracted by evaporation and transpiration.
				GRAVITY OR VADOSE WATER Moves downward by force of gravity throughout zone.
				PERCHED WATER Occurs locally in the zone above an impervious barrier.
				CAPILLARY WATER Occurs only in the capillary fringe at the bottom of the zone.
	SATURATED ZONE	(BOUND WATER (PHREATIC WATER)		FREE WATER Occurs below the water table and is bounded by the first effective confining stratum.
				CONFINED WATER Occurs beneath a confining stratum
				FIXED GROUND WATER Occurs in subcapillary openings, not moved by gravity.
				CONNATE WATER Water entrapped in the rocks at the time of their formation.
Zone of Discontinuous openings.				INTERNAL WATER

called 'field capacity' by agricultural experiementers. The excess water over field capacity of the soil and over pelliculer water of the entire zone of aeration up to "maximum water-holding capacity" is free to travel downward toward the water table and is referred to as ' gravity water,' 'gravitational water, or vadose water.' Water moves freely under the control of gravity only after the grains or rock surfaces have been coated with pellicular water. If these films have been removed by evaporation or transpiration, they must be reformed before seepage can take place.

The ' belt of soil water' which constitutes the upper portion of the zone of aeration is limited to the surface layer penetrated by roots. It varies in thickness from a few inches, where solid rock is covered with a thin veneer of soil, to a seldom occurring maximum of 60 ft. Active root development occurs chiefly within 10 ft. of the surface. The belt of soil water is the great reservoir of available soil moisture upon which plant life depends. Information as to the occurrence and distribution of water in the soil is derived chiefly from studies of the agricultural scientist and from geological study of the products and processes of weathering. Recent studies of soil moisture, transpiration, and evaporation have greatly modified ideas regarding the occurrence and movements of water in the soil.

'Soil moisture' is subdivided by the soil scientist according to its availability to plants, depending on the force of attachment to surfaces of soil particles. Water that is held loosely and is easily abstracted by root action may be called 'available moisture'. It is limited by field capacity on one hand as and the 'wilting coefficient'on the other. A second portion is is unavailable or available with difficulty and is commonly called 'unavailable moisture'. Unavailable moisture is divided into two portions: that occasionally available with difficulty, which is limited by the wilting coefficient and the hygroscopic coefficient; and that completely unavailable, which is held in the soil below the hygroscopic point.

The ' hygroscopic coefficient' has been variously defined, but may be considered to mark the limit of moisture that can be held at the ground surface in equilibrium with atmospheric water vapor. Residual moisture below the hygroscopic limit may be called fixed moisture and probably includes moisture held in colloidal combination by the molecular forces of adhesion and condensation.

The 'capillary fringe' lies above the water table and is in contact with it. The water of the fringe is held above the water table by capillarity, which is defined as the property of tubes with hairlike openings when immersed in water to raise and hold water above the static level of the water in which they are immersed. This water may be accurately denominated capillary water or fringe water.

The capillary fringe is from a fraction of an inch to 10 ft. thick, depending upon the size of the interstices and texture of the material just above the water table. If the depth to the water table is equal or less than the height of capillary lift, the capillary fringe will discharge ground water by evaporation, or if the capillary fringe extends upon the zone penetrated by roots, ground water will be discharged by transpiration. Unlike pellicular water, the capillary fringe has unbalanced surface energy necessary to raise water to the height of capillary lift.

The limit of capillary lift varies inversely with the diameter of the capillary openings. Capillary movement is relatively rpaid in the larger capillary openings of small lift(1 to 3 ft.) and slow in smaller tubes with higher lift (up to 10 ft.)

'Perched Water Table' Within the zone of aeration an impervious stratum below pervious deposits may support a body of saturated material, the upper limit of which is a perched water table. Underlying the saturated pervious material and separating it from the main water table are partly saturated formation of the zone of aeration.

Zone of Saturation:- As all openings in the zone of saturation are filled, unbalanced film forces which develop only at air-water surfaces and which are important in the zone of aeration are ineffec-ective. The controlling factors in this zone are geologic structure, hydrologic characteristics of water-bearing materials, and hydraulic gradient.

Free, Confined, and Fixed Ground Water:- If water moves through an inter-connected body of pervious material unhampered by impervious confining material, it may be denominated free ground water moving under the control of the slope of the water table as distinguished from confined water which moves in strata, conduits, or arteries under the control of the difference in head between the intake and discharge areas of the confined water body. If water is confined in compressible material (Chiefly sand and gravel) and if high artesian pressure in the confined aquifer is reduced by pumping, the aquifer may be compressed by by weight of overlying material supported in part by artesian pressure; or if the confining strata are uncompacted, the reduction of pressure in the aquifer may allow water to be pressed overlying material. 'Fixed ground water' is held in small openings (chiefly subcapillary in size) which resist water movement under the usual hydraulic gradients existing underground. It is to be distinguished from pellicular water which exists only in undersaturated material.

3.4 GROUND WATER RESERVOIR

The term ' groundwater reservoir' is widely used to denote rock formations where groundwater is accumulated under conditions that make it suitable for development and use. 'Groundwater basin', 'aquifer' , 'water-bearing formation' are other terms that are used sometime in the similar sense. Such reservoirs have some points of similarity with surface reservoirs, but the dissimilar in too many ways. They are usually larger in areal extent and also in total storage capacity. Annual recharge is usually much less in proportion to storage capacity than the proportionate annual supply to surface reservoirs. Also, whereas the total storage capacity of surface reservoirs, whether natural or artificial, is not always completely utilised because their outlets may be at an elevation above their bottom, the water level in groundwater reservoirs may be drawn down considerably below the elevation of their natural outlets. Groundwater reservoirs may serve as regulators of stream flow, maintaining such flow over long periods of time during periods of deficient rain rainfall. Naturally surface reservoirs such as lakes, ponds and marshes also serve as regulators of stream flow, but they seldom are able to maintain such flow for comparable periods of time.

The total capacity of groundwater reservoirs is not always so important in their utilization like that of surface reservoirs. Many surface reservoirs may be drawn very low each year or, in the case of cyclic storage, every few years. This does not occur so frequently in the case of groundwater reservoirs. The maximum lowering of water in them is usually limited by economic reasons. Because of the lower ratio of annual recharge to storage capacity and the relatively large storage capacity of ground water reservoirs, average annual discharge may exceed annual recharge for much longer periods than is the case with surface reservoirs, wherein normally the average annual recharge and discharge are maintained in equality. This makes it difficult to recognise immediately a condition of apparent-overdraft in groundwater reservoirs.

3.5 MOTIONS OF GROUND WATER

There are four distinct types of movement of subsurface water, two of which occur exclusively above the water table, one type may occur above or below the water table, and one occurs only in the zone of saturation. Each type has its own particular characteristics and is controlled by laws quite different from the others, and each has been given a distinctive name in this text.

Above the water table the principal movements are:(1) Seepage which takes place chiefly in a downward vertical direction. (2) Capillary rise. (3) Ground-water turbulent flow may occur in large openings above or at the water table, or below the water table if large openings and free exit and entrance of water exist. (4) Percolation occurs only in the saturated some in interconnected openings under ordinary hydraulic gradients existing underground.

Seepage from the ground surface to the water table is first a slow, diffused movement by which the surfaces of all openings are wetted and, second, a downward movement of gravity water on the films coating the openings . The movement is complicated by the presence of ground air which is displaced in part by the downward seeping water and completely by a rising water table. There is no mathematical equation capable of indicating the rate of seepage from the ground surface to the water table because the time necessary to wet the sides of the openings and to drive out ground air is an unknown variable.

Capillary movement is confined to water movement in the capillary fringe.

Ground-water turbulent flow may occur in openings of large size, such as fractures or tubular openings, and possibly in interstices in very coarse sedimentary and alluvial material under high hydraulic gradients sufficient to develop turbulent movement. However, natural ground-water gradients are usually too small to develop turbulent flow except in large conduits above or at the water table, in conduits below the water table where free escape permits rapid movement, or in the vicinity of intake of a pumping well.

Percolation (laminar flow) is slow movement of water in interconnected pores of saturated granular material under hydraulic gradients commonly developed underground. Resistance to movement developed by friction of the moving water against the surfaces of innumerable grains constituting the water-bearing material determines the permeability of the material, which average diameter of the pores. Much steeper gradients are necessary to force water through fine material than through coarse material and velocity of percolation decreases in fine material until it becomes inappreciable in fine silt and clay.

3.6. RECHARGE OF GROUND WATER

One of the most difficult problems to decide in regard to any ground-water development is how much of the water pumped is taken from storage and how much is supplied from the replenishable surface or subsurface sources. The latter quantity is dependent on the size and location of the intake area, the permeability of the surface material and the quantity and distribution of the natural precipitation available for recharge. The 'stage' of the reservoir must be determined by measuring the elevation of the water tables in wells. Because the water surface is not a plane, as in a surface reservoir, many wells must be used.

Under normal conditions, as pumping continues, the cone of depression deepens and expands until (1) it intercepts a surface stream which is adequate to support the well discharge under the given conditions, (2) it encompasses an area that will support the well yield under the prevailing rate of [illegible] surface infiltration or (3) it intercepts areas of discharge and reduces this discharge by an amount equal to the well withdrawal. Most frequently, the well yield is obtained from a combination of two or more of these sources. If the total water available from the several sources is less than the pumping rate, progressive decline of water level may occur to a degree determined by the excess of discharge over recharge. Ultimately the net discharge cannot be greater than the available recharge from all sources.

Recharge of the water in the zone of saturation from the sources above the surface involves the following three steps:-

(1) The infilteration of the water from the surface into the soil and other rock materials that lie directly below the surface.

(2) The downward movement of water through the materials that comprise the zone of aeration.

(3) The delivery of a part of the water to the water table, where it enters the zone of saturation. A part of the water that seeps into the zone of aeration is returned to the surface or into the atmosphere by evaporation and transpiration and consequently is lost so far as ground water recharge is concerned.

The factors that influence the recharge of ground water are:-

(1) Drainage

(2) Rainfall intensity

(3) Porosity of the ground

(4) Pre-rain saturation condition of the soil.

(5) Atmospheric humidity

(6) Vegetation cover.

3.7 WATER TABLE

The water table is the boundary between the saturated zone and the zone of suspended water. It records the level to which the subsurface reservoir is filled, the quantity of ground water in storage, and the depth to the water supply in any particular area. From its fluctuations, additions to and subs tractions from ground-water storage may be calculated if the specific yield of the formations saturated or dewatered by the change in level is known.

The water table separates two regions where the forces acting and the resulting motions of subsurface water are different. Above the water table molecular, colloidal, and film forces are important and the interaction of these forces and the force of gravity produce the complex motions herein denominated seepage and capillary rise. Below the water table the force of gravity is not appreciably affected by other forces, except locally where heat is important, and the resulting movement is usually percolation but occasionally ground-water turbulent flow.

The slope or profile of the water table is a graphic representation of the rate of percolation and permeability of water-bearing materials. The slope varies directly as the velocity and inversely as the permeability. This is the fundamental law governing the interpretation of water-table slope. Ground-water movement is always in the downslope direction of the water table and if permeability is constant the fastest motion and largest quantity of water moving are in the direction of maximum slope.

The water-table outcrop delimits the surface areas subject to influent and effluent seepage. Influent seepage occurs where the water table is below ground surface and stream influent seepage takes place where the water table is below the level of stream beds. Effluent seepage starts at the intersection of the water table with the ground surface and continues throughout the area in which the water table is at the surface.

The outcrop of the water table is marked by the uppermost appearance of effluent seepage, the surface indications of which are springs, the upper limit of permanently moistened areas, occasionally of swamps, and the change in vegetation from non-phreatophytes to phreatophytes. In an area cut by stream erosion the water table first outcrops where the stream intersects the water table and at the point the stream changes from influent to effluent. The outcrop normally continues down-stream near or at the margins of the lowlands bordering the stream and may include large areas of bottom lands. In an undrained desert valley the water-table outcrop delimits the central evaporation and swamp area from the dry desert slopes above. If gullies reach the evaporation area, the water-table outcrop may extend some distance up the gullies.

Topography is important in controlling the depth of the water table below the surface, as well as its shape. Under the ground surface the water table is a "subdued replica" of surface topography. A flat area, undissected by streams and without a low point of ground-water discharge, will be saturated to the surface if evaporation and transpiration are not capable of discharging all effluent seepage. A deeply dissected regions usually has a deep water table.

From the purely geological view point the water table separates, the belt of weathering, oxidation, rock decomposition and solution, from the underlying belt of mineral precipitation and rock cementation.

Contour maps of the water table are graphic representations of the hydraulic slopes of the water table and are the basis for studies of the direction and rate of motion of free water, of drainage of ground water by pumping or drainage ditches and natural streams, and recharge of ground water from all sources, and indicate changes in velocity of percolation or permeability of formations or both.

CHAPTER - IV

ORIGIN AND MODE OF OCCURRENCE OF GROUND WATER AND WATER TABLES IN THE REGION

4.1 REGIONAL DISTRIBUTION OF GROUND WATER BASINS IN NORTH INDIA

Auden (2) has prepared a regional map showing the ground water basins or troughs and buried ridges in northern India. This has been based mainly on the chart-15 of the Survey of India Geodetic report for 1936. This map has been reproduced as Plate 4.1.

The main ground water basins are as follows:-

(a) The Gangetic basin, extending from Meerut to North Bihar and Bengal. Geodetic evidence indicates that the alluvium of this basin attains a maximum thickness of over 6,000 feet in North Bihar, where there is the most pronounced negative gravity anomaly. South of the Ganga the alluvium rapidly becomes thinner, and forms a veneer resting upon the old topography, remnants of which occur as characteristic lines of hills.

(b) The Punjab alluvial basin, extending between Amritsar and Ludhiana, has been shown by gravity work carried out by the Punjab Irrigation Research Institute and the Survey of India to be of the order of 4,000 feet in depth. It is separated from the Gangetic basin by a submerged extension of the Aravalli range, and is bounded on the south-west side by the almost submerged Delhi-Shahpur ridge of pre-Cambrian rocks. The greatest negative gravity anomalies lie near the junction of the Punjab alluvium with the Siwalik rocks.

(c) The Indus basin, which forms a trough in front of the Baluchistan ranges on the west side and the Delhi-Shahpur ridge on the north-east side. The map shows the basin extending in a south-east direction to Bikaner, but it is probable that the recent deposits are relatively thin except between Multan and the Montano zone. It is presumed that this basin narrows in a southward direction, skirts round the Jaisalmer platform, and joins up with the trough of deep alluvium in Gujarat.

(d) The Jacobabad basin.

So far as north-western India is concerned, the major structural elevation is represented by the Aravalli range which strikes N.E.-S.W. from Delhi to Palanpur. The visible portion of this range represents only the main orientation of its axis, but partially submerged extensions of the range show that it originally had a fan-shaped development, which includes a concealed ridge striking northwards from Narnaul, and the N.W.-S.E., past the visible inliers of Sangla and Kirana, to Shahpur at the foot of the Salt Range. The Aravalli range forms the pre-Cambrian backbone of the peninsula, which has resulted in the Pleistocene and Recent alluvial downwarps, formed in response to the late Himalayan movements, being confined to the three distinct basins of the Ganges, Amritsar-Ludhiana, and Multan, rather than forming one continuous zone. Notwithstanding the impression gained from the geological map of India, which shows a continuous spread of alluvium extending from Karachi to Lahore, Delhi and Lucknow, the alluvium is in reality divided by the submerged pre-Cambrian and Palaeozoic rocks of the Aravalli range into three discrete basins, with only very superficial continuity.

Pre-Cambrian, Palaeozoic, Mesozoic, and Tertiary formations lie on the west side of the Aravalli range and represent part of the peninsular shield which has not succumbed to orogenic movements of the Aravalli range without any downwarping until the Multan trough is reached. Western Rajasthan forms a part of this peninsular shield, which has now been partially covered by recent wind-blown sands, and is strikingly contrasted from the main ground-water basin which lies to the north-west. Such zones of deeper covering of windblown sands and alluvium as may lie on the top of the peninsular shield along former drainage lines are, from a geological point of view, superficial phenomena which have no relationship with the tectonic downwarps discussed above. If they are proved to exist by geophysical surveys, they may be of importance from the point of view of developing the ground-water resources of western Rajasthan, provided the depth to the water table is not excessive and salinity is not too high, but they are not comparable to the Ganga and Amritsar-Ludhiana alluvial basins of thick sediments, well replenished by perennial rivers, in which very large quantities of ground-water exist.

Western Rajasthan and the Indus Basin are thus virtually cut off from the Ganga and Punjab alluvial basins by concealed extensions of the Aravalli Range. Indeed, the so-called Delhi-Shahpur ridge (more correctly termed the Loharu-Shahpur ridge in view of later studies) is considered to be the main geological factor responsible for the building up of ground-water in the intensely irrigated tracts of the two Punjabs, and the creation of the present serious condition of water logging in the canal-commanded area. There is consequently no continuous ground-water basin extending from the Himalayan foothills to western Rajasthan, or even to Multan. Moreover, such ground-water as spills over the Loharu-Chhapar ridge moves south-westwards into the Indus basin, by-passing the elevated tract of western Rajasthan.

The above discussion clearly brings out the fact that the only source of ground water in western Rajasthan is the direct precipitation over the area itself.

4.2 MODE OF OCCURRENCE OF GROUND WATER IN WESTERN RAJASTHAN

In Western Rajasthan, Ground water occurs both as free ground water in shallow dug wells and also as confined ground water in deep bored tube wells. The yield from the wells drawing water from the confined aquifers is considerably higher. Locally some small perched water bodies are also present in the younger formations.

4.3 SOURCES OF RECHARGE OF GROUND WATER IN WESTERN RAJASTHAN

The important sources of recharge of ground water in western Rajasthan are as follows:-

(a) Influent Seepage From Rain-Fall:- Aportion or occasionally all of rainfall sinks into the ground, a portion may run off, and a portion or all may be evaporated. Influent seepage from rainfall which reaches the water table is called the ground-water increment from rainfall. Rainfall is usually of short duration and between storms, field capacity may be so reduced that rain cannot completely replenish pellicular water depleted by transpiration and evaporation, and wherever such a deficiency exists, there will be no contribution to ground water. Under these conditions even pervious materials will not conduct rain water to the water table. Rainfall penetration to the water table may also be prevented by an impervious stratum between ground surface and water table.

Rainfall is practically the only source of recharge of ground water in this region. However, a very large portion of the precipitation is lost by evaporation, either immediately or by being drawn up later from the zone of aeration. These losses are of the order of 85-100% of the total rainfall. Losses due to transpiration or suspended storage in the zone of capillary fringe are correspondingly small. The net recharge in the zone of saturation is small.

(b) Influent Seepage From Streams:- Streams can be classed in general as influent or effluent-influent if they flow above the water table and contribute water to it; effluent if they flow at a lower level than the water table and receive contributions of ground water.

Luni river and its tributaries form the only river system of the region. These streams are influent ephemeral streams whose discharge is directly proportional to the precipitation. In small freshets, water remains in the zone of aeration and there is no contribution to the ground water. The net ground water recharge from these streams is very small. However, locally the water table near the flood plains of these streams is higher.

(c) Seepage From Irrigation Reservoirs:- As in the case of streams, this source also contributes very little for the recharge of ground water. The exact extent of the recharge from these tanks and their canals can not be correctly assessed in absence of the data of seasonal fluctuation of the water table in the commanded area of these tanks.

(d) Seepage from Perennial Irrigation Channels:- The Gang Canal, Bhakra Canal and Rajasthan Canal systems are drawing their waters from the Punjab rivers for irrigating lands in Sri-Ganganagar, Bikaner and Jaisalmer districts of Rajasthan. These canal systems are shown on plate No. - 4.3. The seepage from these canal systems will ultimately have a considerable effect on the ground water recharge.

It has been experienced in case of irrigation channels in Punjab and the Upper Ganga Canal system in western U.P. that the water table in the region has risen considerably after continued application of irrigation water. In these areas the tube well irrigation is not only possible but has become absolutely essential to prevent the water logging conditions in the area.

The conditions in western Rajasthan have very striking and relevant differences with the conditions in Punjab and U.P. In western Rajasthan the rainfall is very small. The soil is sandy and dry, water table is very low and there is no replenishing of ground water by influent seepage from streams. The Punjab and U.P. areas receive a substantial amount of ground water recharge from perennial rivers rising in the high rainfall foothill zones. However in long term, with the changes in the soil conditions resulting from prolonged application of irrigation waters, the ground water conditions in the areas commanded by these canal systems are likely to undergo a radical change. At this stage it is not possible to make an assessment of this change or the time that elapses before there is a marked change in the ground water conditions.

4.4 WATER TABLE CONTOURS

A water table contour map is a map of the upper surface of the saturated zone. It is constructed from measurements of depth to water in bore holes or in open wells.

Between 1932 and 1937, the survey of India determined the depth of water table in open dug wells over a wide area in Sind, Rajasthan and Punjab during the course of a resurvey. This map given by Auden (2) is reproduced as plate No.4.2.

The shape of the water table contours above M.S.L. as given in the Survey of India charts corresponds approximately to the elevated ground above the 150 metre (492' , say 500 feet) countour which juts out westwards into Jaisalmer. It points to a quaquaversal outward hydraulic gradient-northwards, westwards and southwards- and does not lend support to the view given out in press notices that an underground lake receiving water, by implication, centripetally from a surrounding catchment, exists in Western Rajasthan.

The highest ground-water contour west of longitude 73½° is the 800 foot contour which strikes S.W.-N.E from Sheo towards Pokaran, and then eastwards, just north of Jodhpur city, towards Osian and Merta. North of this ground-water divide the hydraulic gradient is towards the north; south of the divide it is southwards. We have no knowledge of the contours of the basement formations, and to what extent these may depart from the contours of the water-table. But the coincidence of the ground-water divides with the main concentration of inliers of Vindhyan rocks, suggests that the divide conforms to a flat submerged ridge of sedimentary formations running east-west north of Jodhpur. That is to say, there is little evidence in favour of supposing that the ground-water divide represents a zone in which the thickness of the saturated zone is great. More likely the saturated zone is thin there, and lies astride an old water-shed.

The 500-ft. water-table contour cuts the Luni river between the Luni Junction and Balotra in a manner which suggests that the river is slightly influent, and feeds the water table. This relationship is more pronounced along the Indus river, where the 100-foot water-table contour shows a marked southward bulge half way between Sukkur and Hyderabad(Sindh). There is a slight tendency towards centripetal water-table contours down-stream of Balotra, but this is a region where the Luni river water, and presumably the adjacent ground water, is decidedly saline.

The main line of subsurface drainage would appear to run just east of longitude 70° , from Gotaru in Jaisalmer to Chachro in Thar Parkar (Pakistan). In this region, however, the water-table is of great depth, and virtually inaccessible.

Water is likely to accumulate where submerged ridges cut across existing drainage lines. The reasonable good yields obtained from wells on the banks of the Luni river near Samdari and Balotra may be explained in part by the proximity of masses of rhyolite, and the probable concealed extensions of impervious volcanic rocks at shallow depths below the river acting as dams to sub-surface flow.

In 1947, the Geophysical Section of the Geological Survey of India carried out electrical resistivity observations in the tract of western Jodhpur between Shergarh and Phalound. Ermisch (17) came to the conclusion that no continuous water table exists in the region studied, but that the scanty rainfall which reaches the basement of rhyolites and other ancient rocks collects in depressions as small isolated reservoirs, with widely varying salinity.

4.5 DEPTH OF WATER TABLE BELOW GROUND SURFACE

From the point of view of irrigation and other utilisation of ground water, it is desirable to know not only the true gradients of the water table surface relative to the sea level but also the depth of water table below ground surface.

A map showing the contours depths of water table below the ground surface is attached as Plate 4.3 . This map is based on the preliminary generalised map showing depths of water table below ground surface prepared by Auden (2) . The contours have been extended over the entire region of western Rajasthan from data collected from other sources. Auden's map gave the contours at 100' intervals, but in map attached as Plate 4.3 , contours at smaller intervals have also been plotted for the areas for which some data could be collected.

Auden's map was prepared on the basis of chart 8 of the geodetic report for 1938 which gave the elevation of water table above mean sea level. These contours were superimposed on 1"=16 miles International sheets showing ground contours. From the intersections of the water table contours with the ground surface contours, subtraction provided an indication of the depth of water table below the surface.

Hoon(23) had collected data of the static water levels in the open wells in Rajasthan Canal area. Similarly Basu(5) and Taylor (46) have also given the depths of static water table at various villages in their reports. These villages were located on the map and the depths of water table marked thereon. From these the contours were interpolated and extended.

The contours in the area served by Gang Canal system were extended with the help of the maps showing the depths of water table in that area prepared by the Chief Engineer, Irrigation, Rajasthan.

The report on the Basic resources of Central Luni Basin published by the Central Arid Zone Research Institute(4) gives a map showing the Geolithology and Static water level of the Lower Luni Basin. The Research Report No.2 of the Rajasthan underground water board (22) gives a map showing the water table depths in Jalore district. The contours in these areas have been modified according to the maps given in these reports.

It is seen that over very large areas of western Rajasthan the water-table lies at a depth of more than 200 feet, and that throughout the greater part of the region it lies at a depth exceeding 100 feet. Regardless, therefore, of the quantity and quality of the water available, the pumping lift for the purpose of irrigation will be high. For example, Mehta reports that 17 dug wells around Jaisalmer range in depth from 150 to 360 feet, [illegible] and have an average depth of 243 feet. The average depth of the water in these wells is 7 feet, so that the generalised water-table is thus at a depth of 236 feet below ground level. In actuality, neither the ground surface nor the water-table is quite flat, but the average depth is of value in giving a statistical indication of depth of the water table in the vicinity of Jaisalmer. Exceptional depths exceeding 400 feet are recorded in the Rajputana Gazetter.

In the limited neighbourhood of Luni & Sukri rivers, water table is high at depths less then 50' below ground surface.

NORTH - WEST INDIA

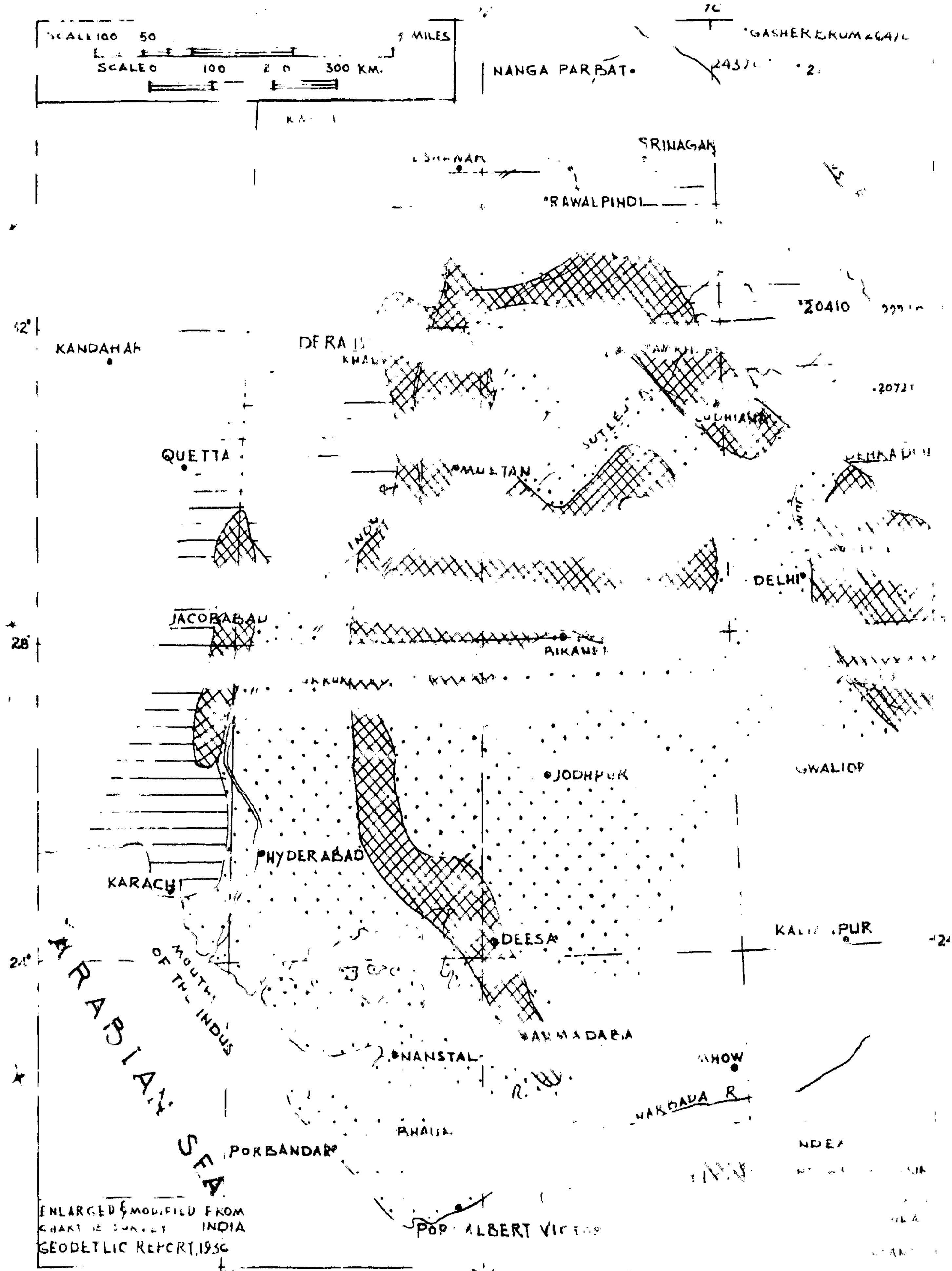
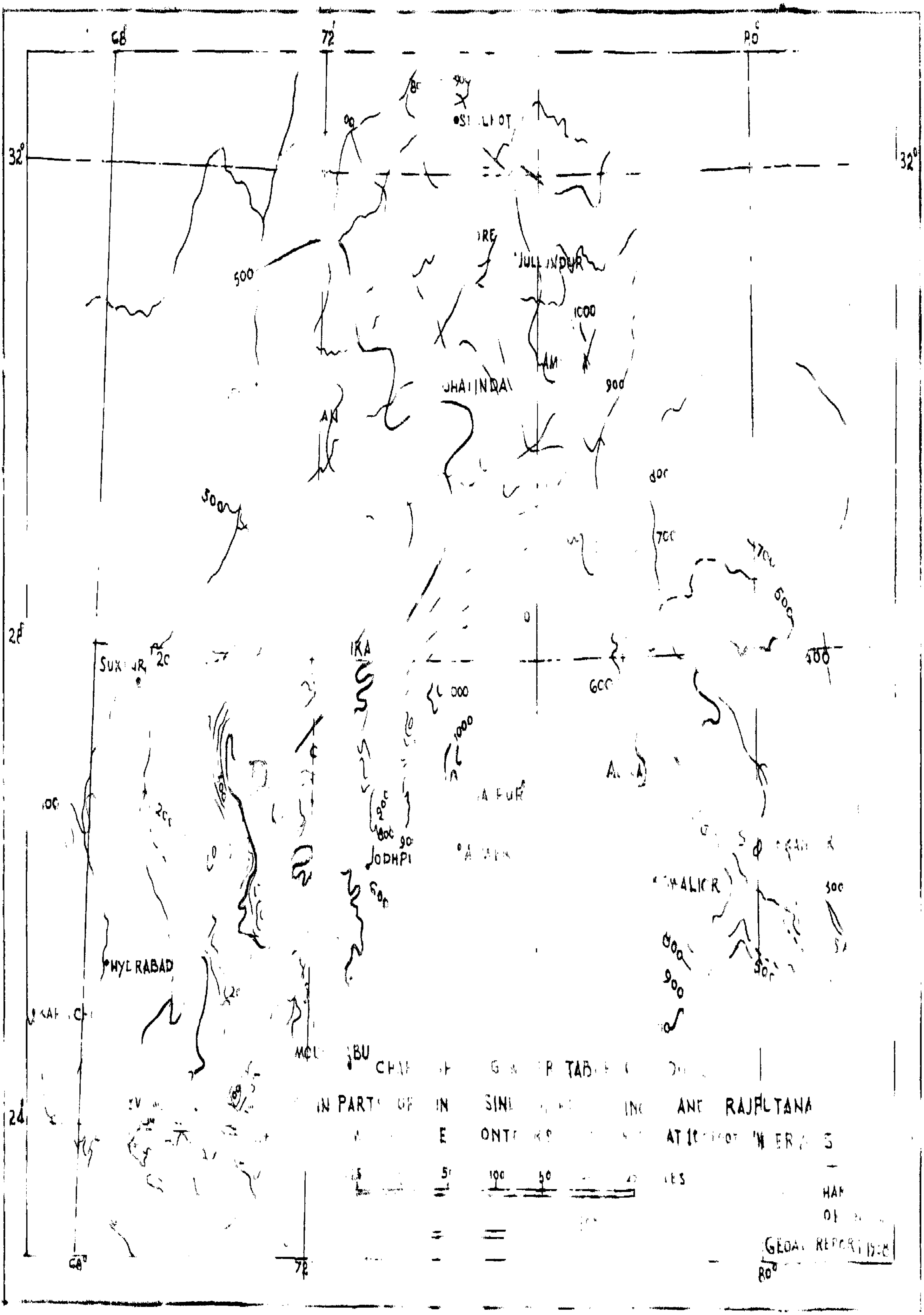


PLATE 4.1



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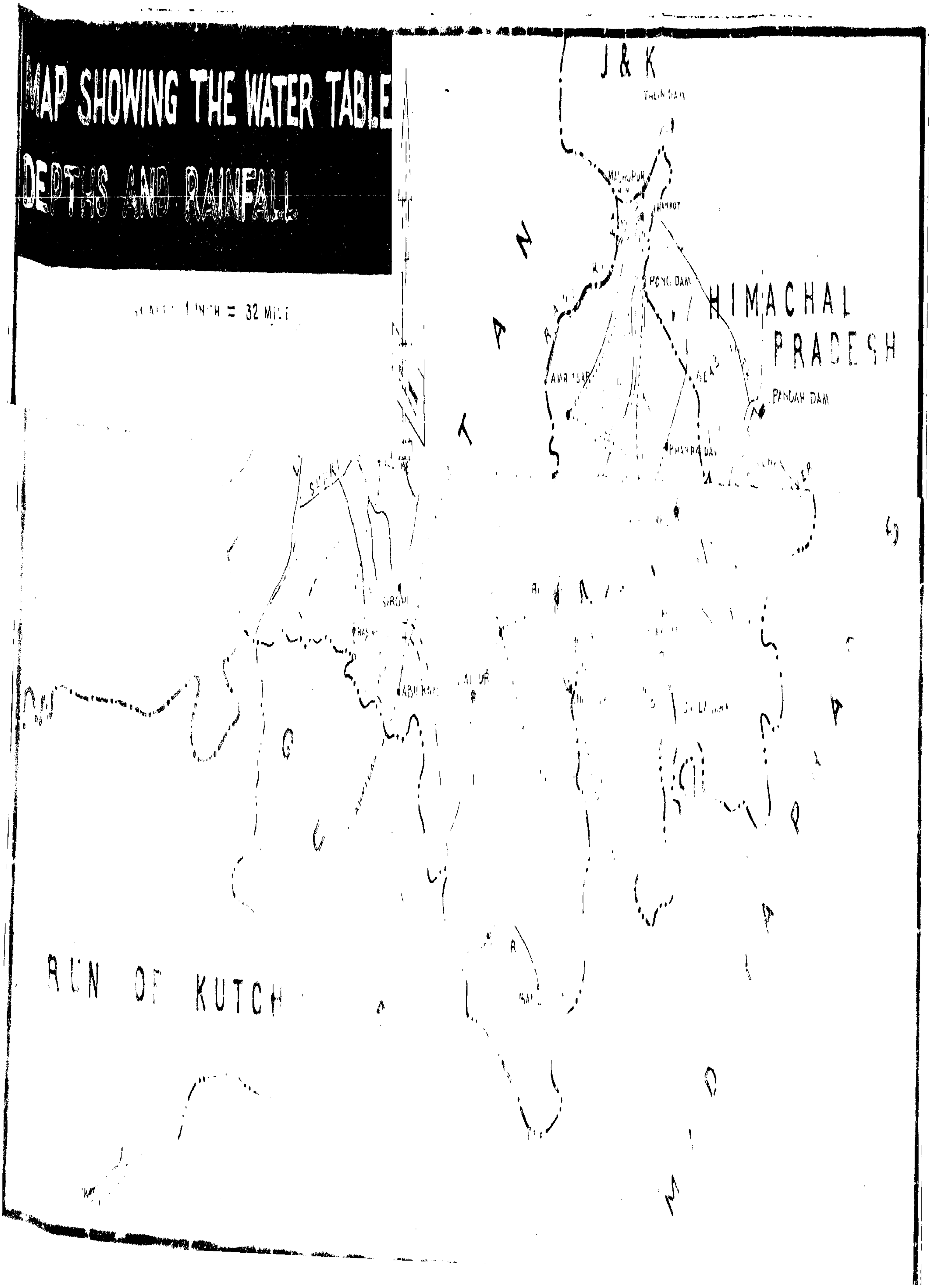
MAP SHOWING THE WATER TABLE DEPTHS AND RAINFALL



CHAPTER - V

HISTORY OF GROUND WATER DEVELOPMENT IN WESTERN RAJASTHAN

5.1 Dug wells constituted an important sources of water supply in the past in Western Rajasthan and continue to be so till present day. As far back as 1909, the Rajputana Gazetteer had described the use of well water for drinking purposes in the area. A few extracts from the Rajputana Gazetteer are quoted below to show this:-

(1) Jaisalmer State:- " The villages are few and far between, sparsely populated, and consist, as a rule, of some circular huts of brushwood collected round a well of brackish water. In many cases the well water, which is drinkable in the cold season, becomes actually poisonous in the hot weather. The average depth of the wells is said to be about 250 feet, but one measured some years ago by an officer of the Great Trigonometrical Survey of India was found to be 490 feet deep."

(2) Jaisalmer Town:- " The water supply is derived from five wells, varying in depth from 236 to 300 feet; the best well, known as Jaisalu, never fails and the water is excellent."

(3) Jodhpur State:- " The desolation becomes more absolute and marked as one proceeds westwards, and of the northern and north-western portion, known as the Thar, it has been said that there are ' more spears than spear-grass heads', and 'blades of steel grow better than baldes of corn.' Villages are few and far between, cultivation is every where poor and precarious, and water is exceedingly scarce, often 200 to 300 feet below the surface and generally brackish. A well measured by an officer of the Great Trigonometrical Survey of India at the village

of Bhakri (in the Phalodi District) in 1874 was found to be 450 feet in depth and 5 feet 4 inches in diameter."

(4) Bikaner City:- " The total number of wells in the city and fort is forty-five, of which five are fitted with pumping engines, water is found from three to four hundred feet below the surface and though not plentiful, is generally excellent in quality."

(5) Luni River:- " The Luni or salt river, the Lonavari or Lavanavari of Sanskrit writers, rises in the hills south-west of Ajmer city in 26° 25' N. and 74° 34' E., and is first known as the Sagarmati. It is for the most part merely a rainy weather river, and in the hot months melons and the *singhara* nut (Trapa bispinosa) are grown in considerable quantities in its dry bed. In heavy floods, which however are rare, the river overflows its banks in the districts of Mallani and Sanchor; the local name of the overflow is 'rel', and on the soil thus saturated fine crops of wheat and barley are grown. The Luni is, however, most capricious and erratic; on one bank it may be a blessing, on the other a curse . As far as Balotra the water is generally sweet, but lower down it becomes more saline in character till, on the edge of the Rann of Cutch, the three branches of the river are described as reservoirs of concentrated brine. Drinking water is obtained from November to June from wells sunk on the banks a few feet below the level of the bed, and from these wells considerable tracts are irrigated. This has given rise to the local proverb that half the produce of the country, so far as cereals are concerned is the gift of the Luni".

5.2 Sipper as early as in 1921, examined the possibilities of increased and improved water supply in the Jodhpur area in connection with a proposed change of railway line from narrow to broad gauge from the Luni junction in the east to Khokharpar in the west. Out of the 10 stations examined, he recommended sinking of new wells in some and deepening of the already existing ones in the others. Sipper's study did not solve the problem finally and it had again to be examined by the Jodhpur Railway administration in 1939. In their report, they describe the various steps taken to increase the supply in different railway wells either by increasing their diameter or by driving down tubes through their bottom.

5.3. Apart from the interests of the railway, other aspects of the problems have arisen such as the question of water supply to the city of Jodhpur. In this connection Edgar in 1931, discounted the possibility of deriving large quantities of water from the Jodhpur sandstones and recommended suitable modifications in the existing Kailana and Balsamand reservoirs, and also the construction of a new reservoir in the Golasni valley.

5.4 Another and probably the most important aspect of the problem has been the provision of water for agricultural purposes in the Jodhpur area. The position in this respect has been aggravated by a gradual fall in the water table and a consequent decrease in the yield of existing wells. Ferguson observed a fall of as much as 25 ft. in the water table during the period 1930-39. He attributed this partly to consecutive cycles of deficient rainfall and partly to excessive electrical pumping, diversion of surface run-off into storm water drains and extensive paving of city streets. Nevertheless, the potentialities of the region for the development of ground water resources have in certain circle consistently been believed to be high. Popular, and in some cases even highly educated opinion, has it that a number of subterranean streams running out at different levels to the sea exist in the region, and they could be utilised for the purposes of urban and rural water supply as also for agricultural development.

5.5 A Committee of Stampe, Heron and Taylor after examining witnesses and a voluminous data including the geodetic map of India, map showing depth of wells in the area and other details, came to the conclusion that, based on the available evidence, there are no prospects of improving the water supply problem. (for irrigation) by means of tubewells in Marwar (which included Barmer district) and even if such cases did exist at all it would not be economical due to deep water table and low yield of the water bearing strata as well as the prevalance of bed rock at shallow depths. The committee also presented details of tubewell scheme in U.P. for comparision and to show that the conditions of Rajasthan do not favourably comparable to that of U.P.

An alternative, which they suggested, was a greater utilisation of the stored surface water, however meagre it might be, and of such open wells as receive a more copious supply from the saturated sands adjacent to local hills where the rainfall is greater. For augmenting drinking-water supplies, the Committee recommended deepening and improving existing wells and sinking some new ones.

5.6 Geophysical(resistivity method)investigation was carried out (1949) by Ermisch and other officers of Geological Survey of

India, for locating depth to water and thickness of water bearing zones and also location of sweet and saline water bearing zones. The investigation was carried out between Ghorgarh-Phalsund area (lying to the east of the exploratory area of Jaisalmer-Barmer region). It was concluded that the water bearing zone was very thin and probably discontinuous which would explain the difference in quality in different wells. It was also observed that a thin layers of drinkable water floated over brine in Phalsund area.

Mehta (1949) carried out investigation for water supply around Jaisalmer and reported that the dug wells in Jaisalmer range in depth from 150 to 360 feet and have an average depth of about 243 ft.

5.7 The Rajasthan Underground Water Board carried out some boring operations near Samdari along the Luni Basin for examination of the ground water condition. As per observations of Saha, the ground water conditions under the Luni basin near Samdari are favoured by an underground ridge of rhyolite which is explained as the reason for the satisfactory yield of the large diameter well (about 40,000 gph) which was earlier given much publicity by some sources as the reported find of huge reserves of underground water in Luni basin. Due to prevalence of bed rock at shallow depths, tubewell irrigation is not considered feasible along Luni basin.

5.8 Auden (2) deals in a general way with all the aspects of ground water conditions of Western Rajasthan. While dealing with the ground water conditions of Western Rajasthan, Auden considered that Jaisalmer sandstones, shales and limestones of Jurassic age, as well as Barmer sandstones of Cretaceous age and Nummulite formations near Bikaner of Eocene age and possibly the Vindhyan Sandstones and limestones of Algonkian to early Paleozoic age can be considered to provide some useful quantities of water. While comparing the conditions of Indo-gangetic alluvial basin with that of W.Rajasthan, Auden feels that the conditions in the latter being not favourable, "present indications are that the quantity of water available for irrigation in many parts of Western Rajasthan are limited." It was also mentioned that instead of a centri-petal drainage around an "underground lake" which was supposed to exist, the migration of ground water should be quaquaversally outwards from the centre of Rajasthan. Evidence of ground water [illegible] contours was also quoted in support for this conclusion. Dr. Auden recommended geophysical investigations(Seismic refraction methods) which might throw some light on the bed rock topography and also possible courses of underground drainage which might exist under a cover of windblown sand whose thickness cannot be ascertained by other means.

5.9. A systematic geohydrological investigation was carried out by Taylor, Roy, Sett and Sen of the Geological Survey of India (1951-52) in the adjoining Pali region of Jodhpur division and the results are published in Bulletin No.6 of Geological Survey of India. Due to the unfavourable geohydrological condition of the Pali region which is essentially composed of Archaean and Purana formations with a superficial cover of quaternary alluvium, the authors conclude that there is no scope for tubewells in the Pali region. The problems of salinity of ground water and yield of the rock formations were also discussed in detail.

5.10 The Exploratory Tube Wells Organisation of the Government of India started the field work in 1955. Ten exploratory bore hole sites were taken up during the first phase of the project in 1955-56. These were located in the districts of Jaisalmer, Barmer, Bikaner, Jodhpur, Churu and Sikar. The sites were selected by senior officers of the Geological Survey of India after geological reconnaissance. The exploration was intended to provide geohydrological data to enable further recommendations regarding ground water development for irrigation in such areas which were considered feasible on the basis of these explorations.

Based on the observations of these bore holes, the report 'Geology and Ground Water conditions of Parts of Rajasthan by Basu, Guha and Rao was published by the Geological Survey of India in 1966. The report gives the water bearing characteristics of different type of formations and suggests the areas suitable for future ground water exploration. This report has been discussed in details in the subsequent chapters.

5.11 During 1957 and 1959 the Rajasthan Underground Water Board carried out drilling of two boreholes at Barmer in Barmer district and two boreholes one at Ramgarh and the other at Banda to the north and north west of Jaisalmer in Jaisalmer district. Of the two boreholes drilled at Barmer, one borehole (Bore Hole No.1) was drilled to a depth of 1003'-10" ending in Black clay and Kankar. The borehole was drilled through bentonite clay at the top and black clay and shales and shales with some black stones. From the description of the log it seems this borehole must have been drilled in Tertiary formation. The borehole was abandoned due to absence of granular zones. Another bore-hole was also drilled at Barmer to a depth of 832 ft. through bentonite clays, black clays, sandstone (Black), and some black clay and Kankar was met with at the bottom. The borehole was cased with slotted section between 445-803 ft. Gravel packing was also done in the annular space around casing. The well, however, did not yield any discharge during pumping and as such it was abandoned. This borehole too appears to have been drilled through Tertiary clays. Of the two boreholes drilled by Rajasthan Underground Water Board to the north and north west of Jaisalmer, the borehole at Banda was drilled to a depth of 462 feet ending in green shales. Gravel, harde sandstone as wellas shale and coarse sand were encountered between 362-442 ft. The bore hole was drilled through limestone intercalated with variegated shales (Eocene). The borehole was cased by placing slotted section against the granular zones described above. The discharge during pumping was 2000 g.p.h. for a draw down of 35 feet below a static level of 280 feet.

The borehole at Ramgarh was drilled through bentonite clays, Kankar and Gravel alternating with bolck clays and some sand (Tertiary) to a depth of 457 feet. This borehole was also drilled through Eocene formation. The borehole was cased with slotted sections placed against the granular zones and the yield on pumping was about 20,000 g.p.h. for a draw down of 30 feet below a static level of 150 feet. It was gathered that the quality of water was too poor to be utilised for drinking purposes. Results of Chemical analysis of waters from the above two wells are however not available.

5.12 The Basic Resources Division of the Central Arid Zone Research Institute with headquarters at Jodhpur is also taking up the study of ground water resources in Western Rajasthan. By the application of the technique of arial photo-interpretation for integrated survey of natural resources, a study was made of an area of 10,000 sq. Km. of the Central Luni River Basin to prepare a rapid reconnaissance survey report of the region. The Divisional report No.63/1 on Basic resources of Central Luni Basin, Western Rajasthan of the Divisional of Basic Resources gives the result of this survey. The area was divided in five zones for the purposes of ground water exploration and a detailed study was made of the water bearing properties of the different lithological formations. The quality of the ground water occuring in various formations was also investigated. This aspect has been described in details in Chapter VIII.

This general study is now being followed up by detailed reconnaissance survey of natural resources of the various Development Blocks. The detailed report for land transformation plan for Ahora and Sella blocks have so far been published. In these reports the water bearing nature of the lithological formations, distribution of ground water depth zones, chemical quality of ground water and discharge potential of the formations has been studied. The whole blocks have been divided in four Ground Water Exploitation zones(i) Over exploited zone(ii) Sparsely exploited zone (iii)Under exploited zone(iv)Un-exploited zone Suggestions have been made for putting in tube wells for drinking water as well as for irrigation purposes.

5.13 The underground Water Board functioning under the administrative control of the Agriculture Department of Government of Rajasthan has been taking up the work of sinking tube wells, boring in existing dug well and deepening of wells by rock drilling and blasting.

A research scheme for research on open wells and tube wells sanctioned by the Government of Rajasthan in 1961 is being operated by this organisation. The objective of the scheme is to conduct research on wells, their designs construction and methods of boring and deepening for improving discharge under varying conditions of sub-soil geology and hydrology.

The research report on Jalore District has been submitted by the organisation to the Government. These deal exhaustively with the development of ground water resources for irrigation purposes in the area. A scheme for constructing 250 tube wells in Jalore district is also being considered by the Government.

The organisation is now proposing to take up the systematic study for assessment of the ground water resources of Western Rajasthan. This study will include the detailed study of geology and topography, geophysical investigations for ground water followed by actual drilling using the electrical logging method, hydrological observations by pumping of main bore holes and also hydrological observations on the observation bore holes to correctly assess the factors like permeability, transmissibility, storage co-efficient etc. Finally the estimation of the Ground Water Recharge by studying precipitation, inflow and outflow from the region and evapotranspiration losses will be taken up.

5.14 The Exploratory Tube Well Organisation has also extended the scope of its work after the completion of the first phase of their explorations in 1959. The second phase of operations commenced in September, 1959 as a continuation of the first phase of the project with the distinction that the entire drilling fleet was manned by Indian technicians. Unlike in the first phase, the entire project in all its aspects is brought under the unified control of the Exploratory Tube Wells Organisation, where a Geological Wing has been added to collect and advise on matters relating to geohydrological problems.

So far the organisation has not been able to take up a phased programme of exploration, because of lack of adequate funds. The present programme having been taken up under the 'Grow more food' campaign, the sites for drilling are selected according to the pressing demand for irrigation and domestic water, where other means of water are either inoperative or non-feasible.

At the selected sites, first a pilot hole is driven and it is electrically logged to ascertain whether the well has to be abandoned due to insufficient yield or whether it has to be converted into a production well. If it is to be converted into a production well, its size is enlarged. After drilling and conducting the quality and quantity tests on the aquifers, the wells are handed over to the Public Health Engineering Department of the Government of Rajasthan for further development.

No systematic geological mapping or studies for assessment of ground water have so far been taken up. A more detailed study has, however, been done on the Lathi aquifers of Jaisalmer district, which is the most promising aquifer, and an assessment of the total water potential of this lithological formation has been made (52)

5.15 The Geological Survey of India is also proposing to undertake the systematic Geophysical surveys of the region for systematic geological mapping and ground water studies. An Engineering Geology Division recently opened at Jaipur is incharge of these investigations.

CHAPTER -VI

HYDRAULICS OF GROUND WATER MOVEMENT AND ITS APPLICATION TO EXPLORATION AND ASSESSMENT.

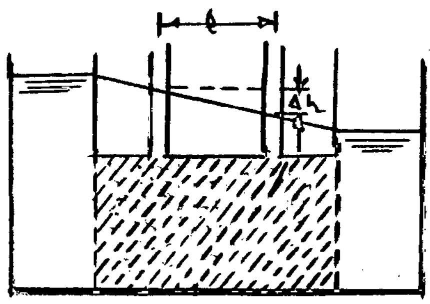
6.1 LAMINAR FLOW AND DARCY'S LAW

The groundwater in the interstices of the permeable strata in the zone of saturation is, as a rule, moving very slowly and very steadily. Such movement is termed LAMINAR FLOW, also stream line or viscous flow.

Ground water flow was not amenable to general treatment based on scientific principles until H.DARCY had devised from his experiments the law, commonly known as DARCY'S LAW which states that for laminar flow, the rate of flow varies directly as the hydraulic gradient.

In Darcy's experiment if 'Q' is the discharge through the body of sand, the corresponding difference in piezometric head is ' Δh ' and 'l' is the length of seepage path between piezometers, the hydraulic gradient 'i' is given by

$$i = \frac{\Delta h}{l}$$



Percolation Experiment
(after Darcy)

Since uniformity of hydraulic gradient is not certain, the above equation may be expressed more rigourously in the form

$$i = \frac{dh}{ds} \qquad -(1)$$

The seepage velocity (v) is given by

$$v = \frac{Q}{A}$$

where 'A' denotes the cross sectional area perpendicular to the direction of flow. 'v' is therefore not the true velocity of flow in the capillary pores between adjacent sand particles, but an imaginary mean over the gross area of the vessel containing sand. In Darcy's experiment arrangements are made for 'v' to remain constant across the whole area 'A'. In practical problems, however, 'v' is usually a function of the point of observations and the vigorous general form of the above equation for seepage velocity is

$$v = \frac{dQ}{dA} \qquad -(2)$$

Generally $\qquad v = f(i)$

But for Laminar seepage flow, according to Darcy

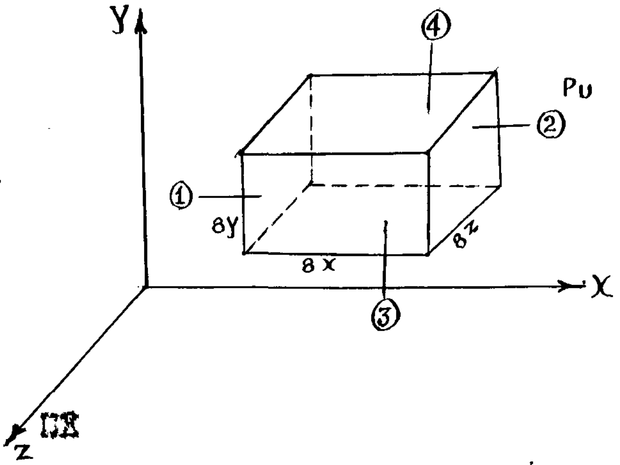
$$v = Ki$$

where 'K' is a constant called the Co-efficient of permeability.

6.2. <u>GROUND WATER FLOW AS POTENTIAL FLOW</u>

Any seepage flow which exactly obeys Darcy's law can be shown to be a potential flow which satisfys Laplaces equation.

Consider the continuity equation of seepage flow which expresses the fact that matter can neither be created nor destroyed. In order to develop continuity equation, consider an elementary parallelopiped with sides δx, δy and δz. See Fig. Let P (x, y, z) be the centre of parallelopiped and let u, v, and w represent the velocities in x, y and z directions respectively at point P. Let ρ represent the mass density of the fluid. Then



mass of fluid passing through area $\delta y\ \delta z$ passing through P = ρ u $\delta y\ \delta z$. Because (ρu), in general, varies in x direction (for given y and z values) the mass flowing through face 1 will be

$$= \rho v\ \delta y \delta z - \frac{\partial}{\partial x}(\rho v\ \delta y\ \delta z)\frac{\delta x}{2}$$

$$= \delta y\ \delta z\left[(\rho v) - \frac{\partial}{\partial x}(\rho v)\frac{\delta x}{2}\right] \qquad -\ (3)$$

Similarly mass flowing out through face 2 due to component of velocity is

$$= \rho u \delta y\ \delta z + \frac{\partial}{\partial x}(\rho v\ \delta y \delta z)\ \frac{\delta z}{2}$$

$$= \delta y \delta z\left[\rho v + \frac{\partial}{\partial x}(\rho v)\ \frac{\delta x}{2}\right] \qquad -\ (4)$$

Hence net rate of inflow of mass through face 1 and 2 is obtained by subtracting equation (4) from (3)

$$\text{i.e.} = \delta y\ \delta z\left[(\rho v) - \frac{\partial}{\partial x}(\rho v)\frac{\delta x}{2} - (\rho v) - \frac{\partial}{\partial x}(\rho v)\frac{\delta x}{2}\right]$$

$$= -\delta x\ \delta y\ \delta z.\ \frac{\partial}{\partial x}\ (\rho v)$$

Similarly net rate of mass inflow through faces 3 and 4 is

$$= -\delta x\ \delta y\ \delta z.\ \frac{\partial}{\partial y}\ (\rho v)$$

And the net rate of mass inflow through the other two faces perpendicular to z axis is

$$= -\delta x\ \delta y\ \delta z.\ \frac{\partial}{\partial z}\ (\rho w)$$

Since($\rho\,\delta x \delta y\,\delta z$) represents the mass of fluid in the parallelopiped $\frac{\partial}{\partial t}(\rho\,\delta x \delta y\,\delta z)$ i.e. $\delta x\,\delta y\,\delta z\frac{\partial \rho}{\partial t}$ represents the rate of change of mass of the parallelopiped. Evidently the total rate of mass inflow into the parallelopiped through all the six faces must be equal to the rate of change of mass of parallelopiped. or

$$\delta x \delta y \delta z \frac{\partial \rho}{\partial t} = -\frac{\partial}{\partial x}(\rho u)\delta x \delta y \delta z - \frac{\partial}{\partial y}(\rho v)\delta x \delta y \delta z - \frac{\partial}{\partial z}(\rho w)\delta x \delta y \delta z \quad \text{------ (5)}$$

Dividing both sides of eq.(5) by the volume of the parallelopiped $\delta x \delta y \delta z$ equation(5) becomes

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0 \quad \text{---- (6)}$$

This is continuity equation in cartestian co-ordinate system. This equation is applicable for

i) Steady or unsteady flow

ii) Uniform and nonuniform flow

iii) Compressible as well asincompressible fluids.

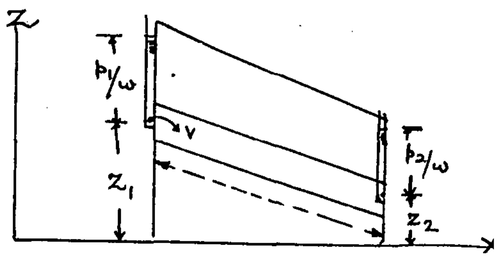
If the fluid is incompressible, the mass density ρ does not change with x, y, z or t. Hence $\frac{\partial \rho}{\partial t} = 0$. Therefore, for incompressible fluids, equation(6) reduces to the form

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad \text{--------- (7)}$$

For a flow which obeys Darcy's law the velocity is proportional to the hydraulic gradient considering a two dimensional flow in x-z plane, the piezometric head <u>h</u> at any point is given by

$$h = \frac{p}{w} + z$$

where p denotes the pressure intensity at any point under consideration, z the elevation at that point and w the unit weight of water



The resultant velocity at any point

$$v = ki = k\frac{dh}{ds}$$

$$= K\frac{\partial\left[p/w + z\right]}{\partial s} = \frac{\partial\phi}{\partial s}$$

where $$\phi = K\left(\frac{p}{w} + z\right)$$

In the generalised case of three dimensional flow, the three components of velocity are given by

$$u = \frac{\partial\phi}{\partial x}$$

$$v = \frac{\partial\phi}{\partial y}$$

$$w = \frac{\partial\phi}{\partial z}$$

substituting these values in equation(7) we have

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \qquad \text{-(8)}$$

This is the La Places equation and the solution of this equation under proper boundary conditions gives the solution of the particular seepage flow problem.

<u>Boundry Conditions</u>

(i) fixed impermeable boundary - The component of the velocity, perpendicular to the boundary, must be zero. If n is in the direction perpendicular to the fixed boundary, $\frac{\partial\phi}{\partial n} = 0$ at the boundary.

(ii) The counterpart to (i) is provided by a seepage flow feeding (or fed by) an open body of water with a free surface, such as a lake or a river. The boundary between the ground water and the open water(the bed of the latter) is clearly a surface of constant piezometric head, and ϕ = const or $\frac{\partial \phi}{\partial \rho} = 0$, where $\partial \rho$ is any short distance measured along the bed.

(iii) Free surface (unconfined flow). The pressure at the surface (water table) is atmospheric, $p = p_a$ = const, and $z = y$, so that the function

$$\phi = k\,[y + p_a/\omega]$$

In all theoretical investigations it has to be assumed that there is no noticeable exchange of water between the capillary fringe and the body of ground water as defined. The water table may, therefore, be considered to consist of innumerable stream lines, and $\frac{\partial \phi}{\partial n} = 0$. The absolute value of the velocity vector is

$$|v| = v = \frac{\partial \phi}{\partial s} = k \sin \theta$$

where θ denotes the slope of the water table.

(iv) The further case of the aquifer and the ground water in it finishing in the open (so giving rise to free flow, as in springs on a slope or flow down the face of a trench) had, until recently lacked clear definition. F.Weinig observes that all along the free flow down the open slope the pressure is atmospheric, $p = p_a$. If $d\sigma$ is an element of any path along the surface slope, and α the angle of elevation of this element above the horizontal, the component of the surface velocity will be

$$v_\sigma = \frac{\partial \phi}{\partial \sigma} = k \sin \alpha$$

In certain cases the water table may be assumed to be tangential to the surface slope, so that $V = v_\sigma$. Where the surface slopes is vertical (seepage to a trench), this assumption has been shown to coincide with the condition of maximum discharge. The same proof is valid for any slope of surface.

(v) In the case of a free water table to which a known vertical seepage flow q is added from above, the assumption may be made, according to Weinig, that the velocity at any point in the water table is the resultant of the vertical velocity of the flow q and of the ground-water velocity tangential to the water table. The pressure at all points of the water table is again p_a.

In most practical problems several of the above boundary conditions occur simultaneously; there are some cases where the boundary conditions cannot be predicated at all, and more numerous ones where the point of transition from one condition to another cannot be predicted.

6.3 DEFINITIONS

Porosity:- The physical property of a rock that defines the degree to which it contains interstices is termed porosity and is expressed quantitatively as the percentage that the interstitial volume is of the total. The porosity of a material is dependent on the inter-relation of size, shape and pattern of channelling in relatively soluble rock such as limestone; or in size, shape and manner of sorting of its component parts in unconsolidated or pervious sedimentary material, or on the size, shape and pattern of fracturing in the dense sedimentary igneous and metamorphic rocks.

The porosity of rock or unconsolidated material may range from considerably less than 1% to more than 50%. In general porosity greater than 20% is considered as large, 5 to 20% as medium and less than 5% as small.

Specific Yield:- When saturated rocks or soils are drained under the action of gravity, it is found that the volume of water yielded by draining is less than the volume of voids space indicated by the total porosity of the material because of the pellicular water that is retained by molecular attraction. The quantity of water yielded by gravity drainage from saturated water bearing material is termed the specific yield and is expressed as a percentage of the total volume of the material drained.

Specific Retention:- The quantity of water retained by the material against the pull of gravity is termed the specific Retention or Field Capacity and is again expressed as the percentage of the total volume of the material.

It is evident that the sum of specific yield and the specific retention of a material is equal to its porosity.

If evaporation is prevented, the greater part of the water retained by a column of rock or sand and gravel, after draining for 24 hours will be retained almost indefinitely as a film held by molecular adhesion on the walls of the interstices. The greater the amount of total interstitial surface in a rock or unconsolidated material the greater is its specific retention. It is found that, as the effective diameter of grain decreases, the specific retention generally increases, because the total exposed surface area increases with decreasing grain size.

Thus the large specific retention of the clay will result in a very small specific yield, whereas the reverse would be true for the coarse grain.

Determinations of the specific yield or specific retention by lab. methods are limited by the difficulties of securing undisturbed and representative samples. In addition, the short sample columns used in the laboratory cannot duplicate the very long capillary tubes that probably exists in the thick sections found in the field. As for permeability, the most satisfactory determination of specific yield are made in the field through the medium of pumping tests.

Permeability and Transmissibility:- The capacity of a formation for transmitting water is measured by its co-efficient of permeability, which is defined by Meinzer as the rate of flow of water in gallons per day through a cross-sectional area of 1 sq.ft. under a hydraulic gradient of 1 ft/ft at a temperature of 60°F.

The term co-efficient of transmissibility is defined as the rate of flow of water in gallons per day through a vertical strip of aquifer 1 ft wide and extending the full saturated height under a hydraulic gradient of 100% at 60° F.Temp.

The permeability of granular material varies with the diameter and degree of assortment of the individual particles. Laboratory determinations of the co-efficient of permeability are made by measuring the discharge or the time rate of change in head, for the percolation of measured quantity of water through a known area and volume of soil sample. The devices used are known as Permeameters. It would seem advisable to apply laboratory methods only to consolidated materials or cores of unconsolidated materials. Further caution should be exercised because the volume of material used in permeameter tests represents only an infinitesimal sample of a formation that is generally quite heterogeneous.

Field determinations of permeability are made by either the velocity or potential method. In the velocity method one well is used for the injection of salt, dye, or an electrolyte. Two or more wells are used as observation stations to determine the time rate of travel of the injected substance through the water bearing material. Fluorescein is generally used for the dye method and can be detected by eye or in more dilute form by colorimeter . The chemical or salt method requires periodic sampling and analysis of water from each observation well to determine the time of arrival of the salted solution. The electrolyte method requires periodic readings of electric conductivity of water in each observations well. Measurements of the water-table gradient, the distance between observation wells, and the time of travel of the injected material provide the basis for determining the permeability of the material over the path of travel. In as much as the velocity of flow through most ground water aquifers is measured in terms of a few feet per day; it is necessary that velocity observations be confined to small areas in order to secure results within a reasonable time. This method measures the velocity of the fastest thread of water that happens to intersect the two wells, and not necessarily the average velocity within the wells. This method would be unpractical for sampling adequately any hetrogeneous aquifer that has large variations in vertical and horizontal permeability.

Potential methods of determining permeability are based on measurements of the amount and rate of drawdown or recovery of water-level in observation wells at different distances from a well that is either pumping or recovering from pumping respectively.

Storage Co-Efficients- For unconfined aquifers, the specific yield defines the amount of water that is available. But for confined aquifers, there is no unwatering of the material when water is withdrawn unless the hydraulic head drops below the top of the aquifer. Consequently the term specific yield can not apply to these conditions. A co-relative term, the 'Storage

Co-efficient' is applied to confined aquifers and this is defined as the volume of water that the aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head component normal to that surface.

Hydrostatic pressure in such a reservoir exerts a force that acts against the superimposed impervious material, the weight of which is supported partly by this hydraulic pressure force and partly by the soil grains of the aquifer. A reduction in hydrostatic pressure, increases the load on solid grains of the aquifer so that being elastic and probably not completely compacted, it is further compressed and some water is forced from it. Also some additional water is released from storage owing to the fact that water is elastic and expands when the pressure is reduced.

Artesian aquifers are believed to possess volume elasticity which remains unchanged under normal conditions of recharge and discharge so that,

$$S_t = S_w + S_k$$

Where S_t = Total load exerted on a unit area of the aquifer

S_w = that part of S_t borne by water

S_k = that part of S_t borne by grains directly.

Thus in a vertical prism with a base area 1 ft. square and a height equal to the thickness of the confined aquifer, the storage coefficient equals the volume of water (in cubic feet) released from storage when piezometric head on this prism is lowered by 1 ft.

Again in a unit prism in an unconfined aquifer if the water table is lowered a unit distance 'x', usually the water that is thereby released represents, for practical purposes, the gravity drainage from the x portion of the aquifer prism. Theoretically, however, a slight amount of water comes from the portion of the saturated prism in accordance with the principles discussed for the confined case. Usually the volume of water attributable to compressibility is negligible in proportions to total volume of water released and can be ignored for the unconfined flow . The storage coefficient is then sensible equal to the specific yield. The storage coefficient may have an order of the magnitude ranging from say 0.50 to 0.30 for the unconfined aquifers x. as against 0.0001 to 0.001 for the confined aquifers.

6.4 THEORY OF ORDINARY PERFECT WELL

Assumptions:- The theoritical-mathematical treatment of a radial gravity flow of ground water to a single, ordinary, perfect well is based on Dupuit Thiem's theory of well hydraulics. For the derivation of an analytic expression between the yield, Q of the well, and permeability of soil, K, the following assumptions are made:-

1. The soil is a homogeneous, uniform, porous medium of infinite areal extent.
2. The perfect well is installed and taps groundwater from the entire thickness of the permeable, water bearing stratum.
3. There exist an unconfined, uniform, steady, laminar; and radial ground-water flow to the cylindrical well from a concentric boundary.
4. For small inclinations of the free surface of the ground water gravity flow system, the streamlines can be taken as horizontal.
5. The horizontal velocity is independent of the depth.
6. The hydraulic gradient is equal to the slope of the tangent at any point on the depression curve of the free groundwater table.
7. The coefficient of permeability, K, of the soil is constant at all times and at all places.

8. The well is being pumped continuously at a uniform rate untill the flow of water to the well is stablized.

Dis-regarding the limiting assumptions, Dupuit-Thiem's theory can be applied to practical problems relative to groundwater flow. Of course the success of this theory depends to a great extent, upon how the assumed conditions underlying it are met in nature.

Assume a single, perfect well system as shown, the outside radius of the well is $r=r_0$. The riginal static groundwater table, which at the same time is the zero draw-down, is at elevation t-t. The thickness of the water bearing strata is H units. Upon pumping, the water table in the well lowers down by an amount of S, termed the drawdown. At the sametime the groundwater level around well also lowers . The dewatered zone in the soil, ABCD takes the form of an inverted funnel or cone of depression. The maximum drawdown Smax, is at and within the well. The depression line ABCD, representing the groundwater table is called the depression line or the pumping groundwater table. The radial distance, R, where drawdown, S, is zero, is termed the radius of influence of the well.

The rate of flow Q, of water into the well at stabilized flow upon pumping expressed by Darcy's law is

$$Q = VA = kiA \quad (m^3/Sec) \qquad 1$$

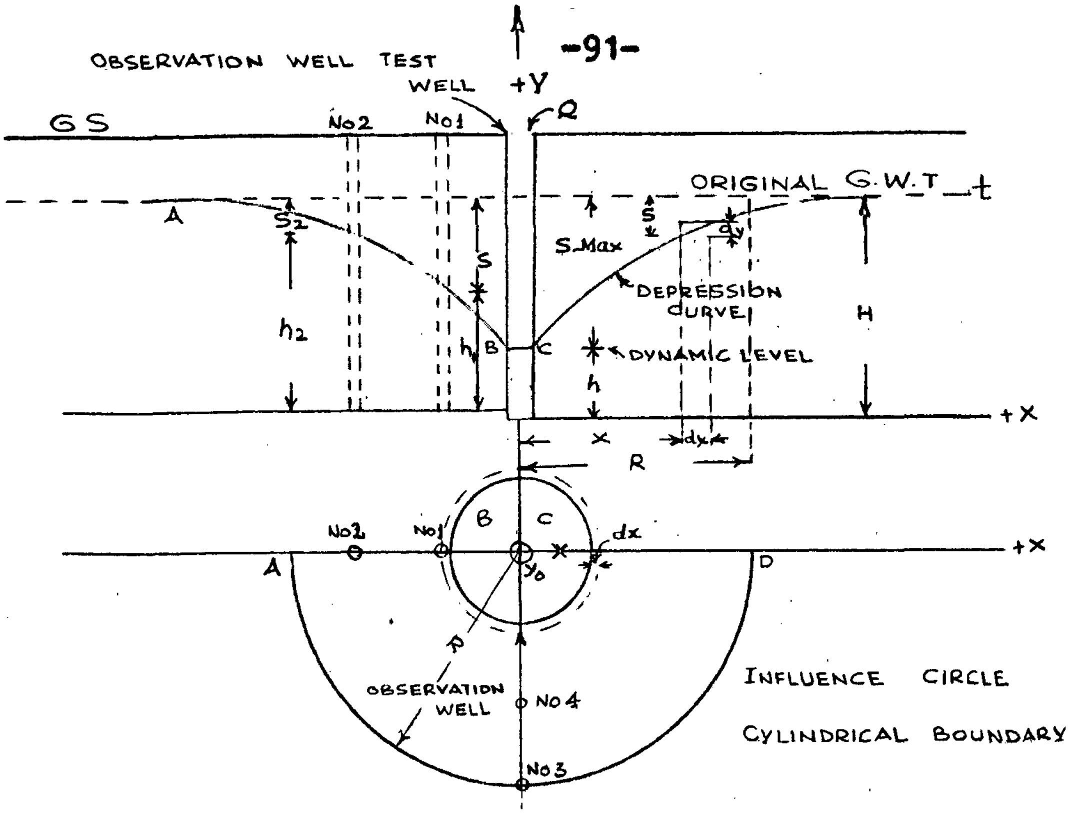
Where V = flow velocity in m/sec

A = flow area, in m^2

$i = \frac{dy}{dx} = \tan\alpha$ = hydraulic gradient.

dy = change in Y - corrdinate of the depression curve.

dx = change in x " " "



Then area, A, through which the flow of water to the well takes place, is a vertical circular cylinderical surface (below the depression curve) with a radius, x, and height y;

$$\therefore \quad A = 2\pi xy$$

While a particle of water approaches the center of the well by an amount dx, the groun-water table experiences a depression, or loss of gradient = dy.

If there exists a continuous, uniform radial flow over an impermeable strata then the rate of flow across any cylinderical area, A, is equal to the flow into the well and, in turn pumped out of it

$$\text{i.e. } Q = K \frac{dy}{dx} \, 2\pi xy \qquad -(9)$$

Separation of variable gives the following differential equ.

$$y \cdot dy = \frac{Q}{k \cdot 2\pi} \cdot \frac{dx}{x} \qquad -(10)$$

The boundary condtions for integrating Eq(II) are

(1) where the depression line intersects the vertical outside surface of the well, $x = r_0$ any $y = h$; here h = depth of the water in the well.

(2) When $x = R$, $y = H$ at pts (A and D).

Integrating between these limits

$$\int_h^y y\,dy = \frac{Q}{2\pi K} \int_{r_0}^{x} \frac{dx}{x}$$

$$\text{or } (y^2 - h^2) = \frac{Q}{\pi K} \text{Log}\left(\frac{x}{ro}\right) \qquad -(11)$$

which is the general equation of the depression line. Integrating between $x_1 = r_0$ and $x_2 = R$ and between $y_1 = h$ and $y_2 = H$

$$\int_h^H y\,dy = \frac{Q}{2\pi k} \int_{r_0}^{R} \frac{dx}{x}$$

$$\text{or } H^2 - h^2 = \frac{Q}{\pi k} \log \frac{R}{ro} \qquad -(12)$$

From which Q , discharge can be calculated as

$$Q = \frac{\pi k\,(H^2 - h^2)}{\log \frac{R}{ro}} = \frac{\pi k\,(H-h)\,(H+h)}{\log \frac{R}{ro}} \qquad -(13)$$

In practice, R is to be substituted by such a distance from the well, at which, after pumping a certain amount of water the depression of the natural water table in the water bearing soil layer has no longer any practical significance.

6.5 THE THIEM FORMULA

If the observations of the level of draw down are taken in two observation wells located at distances r_1 and r_2 from the main well, we have by integrating equaction (10) between limits $x = r_1$ and $x_2 = r2$ and between $y_1 = h_1$ and $y_2 = h_2$ we have

$$\int_{h_1}^{h_2} y\,dy = \frac{Q}{2\pi k} \int_{r_1}^{r_2} \frac{dx}{x}$$

$$\text{or } h_2^2 - h_1^2 = \frac{Q}{\pi k} \log \frac{r_2}{r_1}$$

$$= \frac{\pi k}{Q} \quad (h_2 + h_1)(h_2 - h_1)$$

If the draw down is small then $h_2 + h_1 = 2m$

and $h_2 - h_1 = S_1 - S_2$

where m is the thickness of the aquifer

$$\therefore \log \frac{r_2}{r_1} = \frac{\pi k}{Q} \cdot \cdot 2m (S_1 - S_2)$$

The co-efficient of transmissibility

$$T = Km$$

$$\therefore \log \frac{r_2}{r_1} = \frac{2 \pi T}{Q} (S_1 - S_2)$$

$$\text{or} \quad T = \frac{2.303Q \log_{10} \frac{r_2}{r_1}}{2 \pi (S_1 - S_2)} \qquad -(14)$$

This is called the Thiem formula.

6.5 EXTENT OF CONE OF DEPRESSION

Duringpumping a cone of depression is formed by the removal of water and the slope of this cone of pumping depression develops slowly until it is sufficient to generate a movement of water towards the well equal to the amount of water pumped. The movement of water toward the well is normal to the contours of cone of depression and the cross sectional area through which water percolates toward the well is a cylindrical surface the dimentions of which vary directly with distance from the well. The slope therefore is a maximum at the well because the water pumped is moving through a minimum cross-sectional area and hence with maximum velocity. The slope flattens at a decreasing rate with distance from the well and with corresponding

Theoritically, if a well were pumping from a ground water basin or reservoir which receives no ground water additions or from which no discharge takes place, a cone would develope which would extend to the margins of the basin and the water table throughout the entire basin would finally be adjusted to the pumping level of the well. However no natural ground basin without discharge exists. The water table is an inclined surface which slopes towards the discharge area and pumps draw on water moving in the direction of water table slope. A cone of depression forms around the well, the boundary of which is the ground water divide which delimits the water moving towards the well.

The Depuits formula given in para 6.4 above and several other similar formula of the Equilibrium Type include the determination of R, the distance from the pumped well at which draw down of water level is inappricïable. It is rather difficult to determine this value of R. Several investigators have given arbitrary values to be used for R:-

Slichter	:: 600 ft.
Muskat	:: 500 ft.
Tolman	:: 1000ft.

According to Tolman (49) the value of 'R' usually lies between 100 & 10,000 ft. He suggest that a value of 1000 ft may be used. The error introduced because of an incorrect value of 'R' in determination of the Discharge of Field permeability will be small because large variation in the value of R makes only a small difference in the value of discharge. The following table shows values of$\left(\frac{1}{\log_{10}\frac{R}{r}}\right)$ for several value of R and r.

TABLE 6.4

R In Feet	WELL DIAMETER = 2 r						
	4 in.	8 in.	12 in.	24 in.	48 in.	120 in.	240 in.
100	0.36	0.40	0.43	0.45	0.58	0.77	1.00
200	0.32	036	0.38	0.43	0.50	0.62	0.77
500	0.28	0.31	033	0.37	0.41	0.50	0.58
1000	0.26	0.28	0.30	0.33	0.37	0.43	0.50
2000	0.24	0.26	0.27	0.30	0.33	0.38	0.43

6.7 LIMITATIONS OF THE EQUILIBRIUM FORMULAE

A factor for time does not appear in the formulae of the equilibrim type described above. In these formulas only the ultimate condition of the ground water system is considered; thus the period of pumping has been assumed as infinite and no consideration is given to the differing hydrologic conditions that exist prior to stability.

Observations on the behaviour of water table around pumped wells made in connection with pumping tests by the United States Geological Survey and Cooperating parties show that the form of the cone of depression reaches essential stability in a small area around a pumped well in a relatively short time after pumping begins. However the area of essential stability expends very slowly and a considerable period of pumping is necessary for the cone to reach an approximate equilibrum from very far from the pumped well.

The basic assumption of the formulae of equibrum type that equilibrum is reached is for practical purposes valid for only a small area around a pumped well. Beyond this small area, the assumption is for from true. There is, of course, an apprfciable draw down of water far beyond the area in which the cone of depression attains an equiliburim form.

6.8 NON EQUILIBRIUM HYDRAULICS OF WELLS

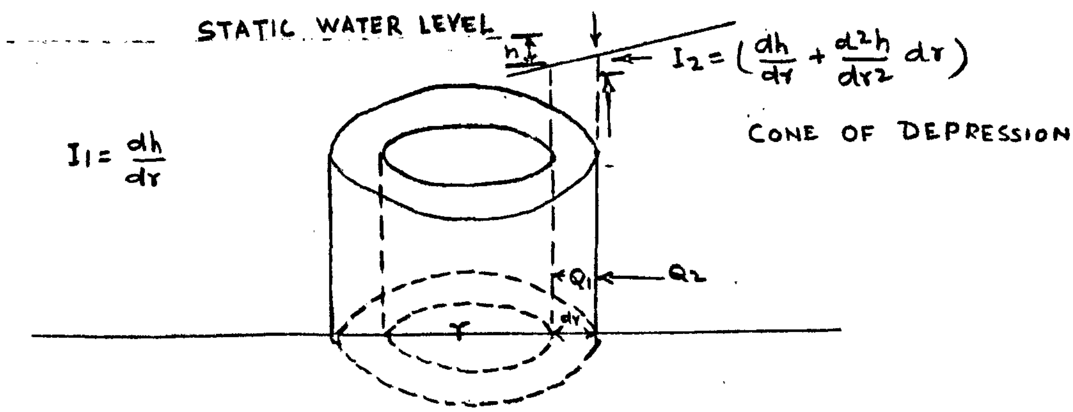
The disregard of the unstable conditions of ground water flow has been due, at least in part, to the difficulties involved in methemetical treatment. A major advancement in ground water hydraulics was made by Theis in 1935 with his development of non-equilibrium formula which introduces the time factor and the specific yield or co-efficient of storage. This formula was derived by analogy between flow of ground water and the flow of heat by conduction.

Theis first presented in 1935 an analysis of well flow which took into account the effect of time and storage characteristics of the aquifer. The original development of this equation was based on an anology of flow of heat towards a sink, or point, where heat is removed at a uniform rate. Accordingly, hydraulic pressure is analogous to temperature, pressure gradient to temperature gradient, permeability to thermal conductivity, and specific yield, or storage coefficient, to specific heat.

Jocob has now derived the very same formula using hydraulic concepts only for the confined flow. When a well penetrating an extensive aquifer is pumped at an constant rate, the influence of discharge travels with time (due to expansion of water & compression of sand) and would do so indefinitely unless interfered by some natural recharge boundaries. Hence the product of the rate of decline of head and storage coefficient, integrated over the area of influence, should equal the constant discharge. The differential equation applying this situation is:-

$$\frac{d^2h}{dr^2} + \frac{1}{r} \frac{dh}{dr} = \frac{S}{T} \frac{dh}{dt} \quad \text{.......(15)}$$

This equation is derived in "Hydrology" by Wisler & Brater, on first principles as below:



Taking the Q_1 and Q_2 as discharges entering through any two annular cylindrical surfaces distance dr apart and applying the principle of conservation of matter

$$Q_1 - Q_2 = \frac{dv}{dt} \quad \text{..........(16)}$$

i.e., $(Q_1 - Q_2)$ difference must be drawn from storage. Here dv represents change in volume within the cylindrical shell of thickness dr.

If T = Co-efficient of transmissibility in cuft per day per ft.

From Darcy,

$$Q_1 = - T. \frac{dh}{dr} \quad 2. \pi \quad r$$

For Q_2 the hydraulic gradient can be expressed by the rate of change in slope $\frac{dh}{dr}$ as second derivative.

$\therefore \quad I_2 = I_1 + \frac{d^2h}{dr^2} \, dr$ = Slope or gradient of the piezometric surface at the outer face of the cylinder.

$$= \frac{dh}{dr} + \frac{d^2h}{dr^2} \, dr$$

and $\therefore \quad Q_2 = -T\left(\frac{dh}{dr} + \frac{d^2h}{dr^2} \cdot dr\right) \; 2\pi\,(r + dr)$

If $\quad S$ = storage coefficient,

$$\frac{dv}{dt} = 2\pi r.\, dr.\, \frac{dh}{dt} \; S \quad \ldots\ldots\ldots\ldots(17)$$

. substituting from (17), Equation (16) can now be expressed as

$$-T \frac{dh}{dr} \, 2. \quad r + T\left(\frac{dh}{dr} + \frac{d^2h}{dr^2} \, dr\right) 2\pi(r+dr)$$

$$= 2\pi r\, dr.\, \frac{dh}{dt} \, .S$$

Solving algebrically and dividing through by $2\pi r.\, T.dr.$ and neglecting differentials higher than of first order yields -

$$\frac{d^2h}{dr^2} + \frac{1}{r} \frac{dh}{dr} = \frac{S}{T} \frac{dh}{dt} \quad \ldots.(18)$$

Unsteady Drawdown method based on Type curve solution

Solution of equation (15) can be obtained if the well is replaced by constant strength mathematical sink so that,

Limit

$$r \to o \quad \left(r \frac{dh}{dr}\right) = \frac{Q}{2\pi T} \quad \text{for } t \geq 0$$

Other boundary conditions are,

$h = h_0$ as $r \longrightarrow \infty$, for $t \geq 0$

at $t < 0$, $h = h_0$ for all values of r

The solution, that satisfies these conditions, for equation (15) is non-dimensionally

$$h = h_0 - \frac{Q}{4\pi T} \int_{u=\frac{r^2 S}{4 T t}}^{\infty} \frac{e^{-u}}{u}\, du$$

which yields,

Drawdown at distance R = s = $(h_0 - h) = \frac{Q}{4\pi T} W(u)$ .... (19)

W(u) is also written as

$Ei\left(-\frac{r^2 S}{4 T t}\right)$ and called exponential integral

W(u) represents the integral value called 'well function' for which tables exist for different values of $u = \frac{r^2 S}{4 t T}$ or $u = \left(\frac{S/4T}{t/r^2}\right)$

The following assumption may be noted:-

(1) The aquifer is homogeneous and isotropic .

(2) The aquifer is of constant thickness and infinite areal extent.

(3) The well diameter is infinitesimal and it completely penetrates the aquifer.

(4) Water taken from storage is discharged instantaneously with the decline in head.

(5) Non-pumping piezometric surface is horizontal.

(6) During pumping the streamlines are horizontal so that $i = \frac{dh}{dr}$ Equation (19) is known as Theis equation of unsteady flow and is used very widely now for the analysis of aquifer characteristics as potential water supply source. This Equation

(19) which is dimensionless, when converted to U.S.G.S. Units becomes -

$$s = \frac{114.6\ Q}{T} \quad W(u) \qquad (20)$$

$$\text{and } u = \frac{7.48\ r^2 . S}{4\ T.t} = \frac{1.87\ r^2\ S}{T.t.} \qquad (20\ a)$$

$$\text{or } S = \frac{\frac{Tt}{u}}{1.87\ r^2}$$

$$= \frac{T\ (t/r^2)}{1.87\ (1/u)}$$

In this form, the units are given below-

s = drawdown at any point in foot

Q = constant well discharge in G.p.m.

T = aquifer transmissibility in g.p.d/ft.

(i.e. per ft. width of entire depth of aquifer)

r = distance of any point in foot from the well axis, where 's' is observed.

t = time since pumping commenced in days.

S = coefficient of storage in gls. per foot decline in head i.e. piezometric surface, obtained by multiplying S with 7.48, to make it consistent with units of T.

Obviously as T is both inside the integral W(u) and outside, equation (20) cannot be solved directly from the discharge drawdown data. Equation (20) and (20a) are, therefore, rewritten for graphical solution by logarithmic plot as below:

$$W(u) = \left(\frac{T}{114.6\ Q}\right) s \qquad (21a)$$

$$\text{or } \log W(u) = \log \left(\frac{T}{114.6\ Q}\right) + \log s \qquad (22a)$$

$$\text{and } \frac{1}{u} = \left(\frac{Q}{1.87\,S}\right)\left(\frac{t}{r^2}\right) \qquad (21b)$$

$$\text{or } \log \frac{1}{u} = \log\left(\frac{Q}{1.87\,S}\right) + \log\left(\frac{t}{r^2}\right) \qquad (22b)$$

Since the terms within the brackets are constants in equations (21a) and (21b), the term W(u) will vary with the term $\frac{1}{u}$ in the same manner as s will vary with $\frac{t}{r^2}$.

In other words, the two plots should have similar characteristics, similar to Fig. 6.1 the hydrograph depicting observational data of well no.1 as given in table No.6.2.

From published tables values of W(u) and u given in table 6.1 (from which $\frac{1}{u}$ can be determined) a type curve can be plotted. Similarly the aquifer test data will provide values of s, t and r. If these two curves are plotted on arithmetic plotting paper, they will exhibit a general similarity of shape but they will not be identical in shape and curvature. This follows from the fact that the variables in the right half of equations (21a) and (21b) are multiplied by different constants as indicated within brackets. With logarithmic plotting, multiplications become additions as in Eqns. 22 (a) and 22(b). Besides, the logarithmic plotting magnifies small values in the data and permits coverage of large ranges.

The two plots i.e., the one for type curve taking W(u) as ordinate and $\frac{1}{u}$ as abscissa and the other of actual data shown in table 6.2 for the observation wells distant 500 ft. and 1000 ft. from the pumped well with values of s as ordinate and t r^2 as abscissa are plotted logarithmically on separate sheets.

Of the two curves, the one with W(u) and $\frac{1}{u}$ is called type curve and plotted on a tracing paper so that it can be superimposed on the other pertaining to the observational data.

while superposing the coordinate axes are kept parallel and yet the maximum matching is obtained. This is shown in Fig.6.2. In this position, the scales of one graph will prove to be displaced with respect to the scales of the other. This follows from the nature of equations 22 (a) and 22(b) which indicate respectively the displacement of vertical scale by the amount $\log \frac{T}{114.6Q}$ and the displacement of the horizontal scale by the amount $\log \frac{T}{1.87\,S}$.

The solution now requires selecting a convenient match point as shown in Fig. 6.2 for use in computing the coefficients of transmissibility and storage. In Fig.6.2 the coordinates of the match point are:

$$s = 1.15 \quad \frac{t}{r^2} = 2.9 \times 10^{-8}$$

$$W(u) = 1.0 \quad \frac{1}{u} = 3.05$$

From equation (20) knowing Q = 500 g.p.m.

$$T = \frac{114.6\,Q}{s} \quad W(u)$$

and by substitution,

$$T = \frac{114.6 \times 500}{1.15} \times 1.0$$

$$= 50{,}000 \text{ g.p.d/ft.}$$

Similarly, from equation (20a)

$$S = T \frac{\frac{t}{r^2}}{1.87 \frac{1}{u}}$$

and by substitution

$$S = \frac{50{,}000(29 \times 10^{-8})}{1.87 \times 3.05}$$

-4

6.9 RECOVERY METHOD

When the pump is turned off the recovery of water levels in wells No.(1) and (2) can be observed and the same for well No.1 is indicated in figure 1. hydrograph. It will be noticed that one day after the pumping stopped, there is recovery of 6.57 ft. which exactly equals drawdown observed one day after pumping commenced. However the recovery is taken from the level at which the water would have been had pumping continued.

This agreement is not fortuitous but suggests that recovery is merely the reverse of drawdown i.e. a recovery test is merely a negative drawdown test. Stated in another way, the well may be assumed to have continued pumping during the recovery test but at the instant recovery commenced an imaginary recharge well is started which puts water back in the aquifer at the same location with a recharge rate equal to the pumping rate. Thus instead there will be a rise or recovery of water level in the observational well in response to the activity of the imaginary recharge well.

Type curve solution:- Again a type curve or graphical solution is applicable as shown in fig. 6.1 . The type curve shows ordinate of $W(u)$ increasing and is replotted for the use in the recovery method, but it is essentially the same curve.

Similarly the recovery data is an upside-down version of drawdown plot of fig. 6.3 . Again it is possible to superpose the data curve on the type curve and find the match point as before. From the coordinates of the match point, the same equations can be solved again to find very much the same values of T and S and thus establish a useful check

6.10. JACOB'S MODIFIED NON-EQUILIBRIUM EQUATIONS (STRAIGHT LINE SOLUTION)

This method though approximate and easier, is not necessarily less accurate. It is of fairly general application for artesian and also free aquifer wells if the drawdown is a small percentage of the saturated thickness of the aquifer. In some cases the accuracy is improved.

$$\therefore \quad W(u) = -0.5772 - \log_e u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!}$$

and considering the value of u in the form.

$$u = \frac{S/4T}{t/r^2}$$

it is clear that for large values of t/r^2 as compare with the small though constant factor $S/4T$, the value of u is usually small. Hence approximation of the series can be tolerated by the first two terms only when u becomes less than 0.02 or $\frac{1}{u}$ greater than 50. This is shown as point A of the type curve earlier. After this modification there is almost straight line variation between W(u) and log (1/u) in the form

$$W(u) = \log_e \left(\frac{1}{u}\right) - 0.5772$$

which is essentially linear, for values of $(\frac{1}{u})$ greater than 50 (Point A). The straight line, shown in Fig. 6.3, when extended intercepts the $W(u) = 0$ line at point B where $\frac{1}{u} = e^{0.5772} = 1.78$. Also it can be noted in the curve shown in Figure 6.3 that for small values of u (or larger than 50 of $\frac{1}{u}$) Theis type curve becomes nearly asymptotic with the straight line with slope (2.3) as the logarithmic plotting is to the base 10.

Hence as a near approximation, the non-dimensional equation become

$$s = \frac{Q}{4\pi T} \left(-0.5772 - \log_e u \right)$$

$$= \frac{Q}{4\pi T} \left(\log_e \left(\frac{1}{u} \right) - \log_e e^{0.5772} \right)$$

Substituting for

$$u = \frac{r^2 . S}{4 T . t}$$

$$s = \frac{Q}{4\pi T} \left(\log_e \frac{4 . T . t}{r^2 . S \, e^{0.5772}} \right)$$

$$= \frac{Q}{4\pi T} \log_e \frac{2.25 \, T . t}{r^2 . S} \quad \text{---(23)}$$

This modified non-equilibrium equation can be written in several forms depending on the requirement of the observed data.

For the data examined with type curve solution for the two observation wells, Equation (23) can be rewritten as,

$$s = \frac{2.3 \, Q}{4\pi T} \left(\log_{10} \frac{t}{r^2} - \log_{10} \frac{S}{2.25 T} \right) \quad (24)$$

The only variable terms in Equation (24) are s and $\log_{10} \frac{t}{r^2}$ so that if a semi log plot of s and $\log \frac{t}{r^2}$ is made a straight line plot should result, as obtained in figure 6.3.

The slope of this straight line equation is the constant quantity $\frac{2.3 \, Q}{4\pi T}$ as in (24), while from the plot the slope is obtained as $\frac{s}{\log \frac{t}{r^2}}$

$$\text{Hence, } \frac{2.3 Q}{4\pi T} = \frac{\Delta s}{\Delta \log \frac{t}{r^2}}$$

Solving for the only unknown

$$T = \frac{2.3\,Q}{4\,\pi}\left(\frac{\log\frac{t}{r^2}}{s}\right)$$

Observing s on one log cycle for the straight line and substituting the same,

$$T = \frac{2.3\,Q}{4\,\pi\,\Delta s} \qquad \ldots\ldots\ldots\ldots(25)$$

The equation (25) has remain non-dimensional so far. Coverting it into U.S.G.S. unit i.e. , T in gls/day /ft. and Q in g.p.m.

$$T = \frac{264.Q}{s} \qquad \ldots\ldots\ldots(26)$$

Figure 6.3 shows the straight line semi log plot of the data with s values as ordinates on arithmetic scale and t/r^2 as abscissa on Logarithmic scale for both the wells; Since Δ S on one log cycle is 2.64 ft.,

$$T = \frac{2.64\,Q}{s} = \frac{264 \times 500}{2.64}$$

$$= 50{,}000 \text{ g.p.d./ft.}$$

To find the storage coefficient the straight line is produced towards the origin to intersect the abscissa for obtaining the value of t/r^2 for zero value of s. Thus the term within the bracket for Equation can be equated to zero.

$$\text{Hence } \log_{10}\frac{S}{2.25\,T} = \log_{10}\left(\frac{t}{r^2}\right)$$

$$\text{or } S = 2.25\,T\left(\frac{t}{r^2}\right)$$

Converting to U.S.G.S. Units

$$S = 0.3.\,T\left(\frac{t}{r^2}\right) \qquad \ldots\ldots\ldots(27)$$

Using Equation (27) to find storage efficient.

$$S = 0.3\ T\ (\frac{t}{r^2})$$

$$= 0.3 \times 50,000 \times (1.33 \times 10^{-8})$$

$$= 2.0 \times 10^{-4}$$

Thus from both type curve and straight line method of Jacob, identical values of T and S have been obtained.

6.11 <u>DOUBLE SLOPE METHOD FOR PUMPING TEST ANALYSIS</u>

Equation (19) can be written in the form

$$s = \frac{C}{T}\ W(u) \qquad (28)$$

in which C is a constant containing the discharge of the well.

The theoritical graph of the draw down 's' versus time 't' on semilogrithmic paper, with the time plotted on logrithmic scale, has the property

$$\frac{ds}{d \log (t)} = \frac{2.30C}{T}\ W'(u) = m \qquad (29)$$

The theoritical graph of the slope 'm' versus reciprocal of time $\frac{1}{t}$ plotted on logrithmic scale, has the property

$$\frac{dm}{d \log \frac{1}{t}} = \frac{(2.30)^2 C}{T}\ W''(u) = m' \qquad (30)$$

Consequently

$$\frac{m'}{m} = 2.30 \frac{W''(u)}{W'(u)} = 2.30\ f(u) \qquad (31)$$

in which f(u) may be referred to as the "double slope function".

PROCEDURE

Depending on the type of flow system under consideration and the data collected from the field pumping tests, the general proceedure for determining the hydraulic properties of through the application of the double slope method is as follows:-

(1) Plot drawdown s verses time t on semilogrithmic paper- the time being plotted on the logrithmic scale.

(2) Choose several points on the (s-log t) curve, measure the slope m of the tangent at each point and record the corresponding time.

(3) Plot on the same paper the measured slope 'm' verses the reciprocal of the corresponding time $\frac{1}{t}$ with $\frac{1}{t}$ being plotted on the logrithmic scale.

(4) Choose few points on the (m-log $\frac{1}{t}$) curve and measure the slope m' of the tangent at each point.

(5) Compute the value of f(u) & u from equation (31) for the known values of m & m' at each point.

(6) Compute the value of the co-efficient of transmissibility T from equation (29) as well as the known value of m

(7) Compute the value of co-efficient of storage s by the relationship

$$u = \frac{r^2 s}{4\,Tt}$$

TABLE 6.1

ue of W(u)and u for non-equilibrium formula[1] W(u)= -E(-u)

$N\times10^{-15}$	$N\times10^{-14}$	$N\times10^{-13}$	$N\times10^{-12}$	$N\times10^{-11}$	$N\times10^{-10}$	$N\times10^{-9}$	$N\times10^{-8}$
33.9616	31.6590	29.3564	27.0538	24.7512	22.4486	20.1460	17.8435
33.8662	31.5637	29.2611	26.9585	24.6559	22.3533	20.0507	17.7482
33.7792	31.4767	29.1741	26.8715	24.5689	22.2663	19.9637	17.6611
33.6992	31.3966	29.0940	26.7914	24.4889	22.1863	19.8837	17.5811
33.6251	31.3225	29.0199	26.7173	24.4147	22.1122	19.8096	17.5070
33.5561	31.2535	28.9509	26.6483	24.3458	22.0432	19.7406	17.4380
33.4916	31.1890	28.8864	26.5838	24.2812	21.9586	19.6760	17.3737
33.4309	31.1283	28.8258	26.5232	24.2206	21.9180	19.6154	17.3128
33.3738	31.0712	28.7686	26.4660	24.1634	21.8608	19.5583	17.2557
33.3197	31.0171	28.7145	26.4119	24.1094	21.8068	19.5042	17.2016
33.2684	30.9658	28.6632	26.3607	24.0581	21.7555	19.4529	17.1503
33.2196	30.9170	28.6145	26.3119	24.0093	21.7067	19.4041	17.1015
33.1731	30.8705	28.5679	26.2653	23.9628	21.6602	19.3576	17.0550
33.1286	30.8261	28.5235	26.2209	23.9183	21.6157	19.3131	17.0106
33.0861	30.7836	28.4809	26.1783	23.8758	21.5732	19.2706	16.9680
33.0453	30.7427	28.4401	26.1375	23.8349	21.5323	19.2298	16.9272
33.0060	30.7035	28.4009	26.0983	23.7957	21.4931	19.1905	16.8880
32.9683	30.6657	28.3631	26.0606	23.7580	21.4554	19.1528	16.8502
32.9319	30.6294	28.3268	26.0242	23.7216	21.4190	19.1164	16.8138
32.8968	30.5943	28.2917	25.9891	23.6865	21.3839	19.0813	16.7788
32.8629	30.5604	28.2578	25.9552	23.6526	21.3500	19.0474	16.7449
32.8302	30.5276	28.2250	25.9224	23.6198	21.3172	19.0146	16.7121
32.7984	30.4958	28.1932	25.8907	23.5881	21.2855	18.9829	16.6803
32.7676	30.4651	28.1625	25.8599	23.5573	21.2547	18.9521	16.6491
32.7378	30.4352	28.1326	25.8300	23.5274	21.2249	18.9223	16.6197
32.7088	30.4062	28.1036	25.8010	23.4985	21.1959	18.8933	16.5907
32.6806	30.3780	28.0755	25.7729	23.4703	21.1677	18.8651	16.5625
32.6532	30.3506	28.0481	25.7455	23.4429	21.1403	18.8377	16.5351
32.6266	30.3240	28.0214	25.7188	23.4162	21.1136	18.8110	16.5085
32.6006	30.2980	27.9954	25.6928	23.3902	21.0877	18.7851	16.4825
32.5753	30.2727	27.9701	25.6675	23.3649	21.0623	18.7598	16.4572
32.5506	30.2480	27.9454	25.6428	23.3402	21.0376	18.7351	16.4325
32.5265	30.2239	27.9213	25.6187	23.3161	21.0136	18.7110	16.4084
32.5029	30.2004	27.8978	25.5952	23.2926	20.9900	18.6874	16.3848
32.4800	30.1774	27.8748	25.5722	23.2696	20.9670	18.6644	16.3619
32.4575	30.1549	27.8512	25.5494	23.2471	20.9446	18.6420	16.3394
32.4355	30.1329	27.8303	25.5277	23.2252	20.9226	18.6200	16.3174
32.4140	30.1114	27.8088	25.5062	23.2037	20.9011	18.5985	16.2959
32.3929	30.0904	27.7878	25.4852	23.1826	20.8800	18.5774	16.2748
32.3723	30.0697	27.7672	25.4646	23.1620	20.8594	18.5568	16.2542
32.3521	30.0495	27.7470	25.4444	23.1418	20.8392	18.5366	16.2340
32.3323	30.0297	27.7271	25.4246	23.1220	20.8194	18.5168	16.2242
32.3129	30.0103	27.7077	25.4051	23.1026	20.8000	18.4874	16.1948
32.2939	29.9913	27.6887	25.3861	23.0835	20.7809	18.4783	16.1758
32.2752	29.9726	27.6700	25.3674	23.0648	20.7622	18.4596	16.1571
32.2568	29.9542	27.6516	25.3491	23.0465	20.7439	18.4413	16.1387
32.2388	29.9362	27.6336	25.3310	23.0285	20.7259	18.4233	16.1207
32.2211	29.9185	27.6159	25.3133	23.0108	20.7082	18.4056	16.1030
32.2037	29.9011	27.5985	25.2959	22.9934	20.6908	18.3882	16.0856
32.1866	29.8840	27.5814	25.2789	22.9763	20.6737	18.3711	16.0685
32.1698	29.8672	27.5646	25.2620	22.9595	20.6569	18.3543	16.0517
32.1533	29.8507	27.5481	25.2455	22.9529	20.6403	18.3378	16.0352
32.1370	29.8344	27.5318	25.2293	22.9267	20.6241	18.3215	16.0189
32.1210	29.8184	27.5150	25.2133	22.9107	20.6081	18.3055	16.0029
32.1053	29.8027	27.5001	25.1975	22.8949	20.5923	18.2898	15.9872
32.0898	29.7872	27.4846	25.1820	22.8794	20.5768	18.2742	15.9717

6.6	32.0746	29.7719	27.4693	25.1667	22.8641	20.5616	18.2590	15.9564
6.7	32.0595	29.7569	27.4543	25.1517	22.8491	20.5465	18.2439	15.9414
6.8	32.0446	29.7421	27.4395	25.1369	22.8343	20.5317	18.2291	15.9265
6.9	32.0300	29.7275	27.4249	25.1223	22.8197	20.5171	18.2145	15.9119
7.0	32.0156	29.7131	27.4105	25.1079	22.8053	20.5027	18.2001	15.8976
7.1	32.0015	29.6989	27.3963	25.0937	22.7911	20.4885	18.1860	15.8834
7.2	31.9875	29.6849	27.3823	25.0797	22.7771	20.4746	18.1720	15.8694
7.3	31.9737	29.6711	27.3685	25.0659	22.7633	20.4608	18.1582	15.8556
7.4	31.9601	29.6575	27.3549	25.0523	22.7497	20.4472	18.1446	15.8420
7.5	31.9467	29.6441	27.3415	25.0389	22.7363	20.4337	18.1311	15.8286
7.6	31.9334	29.6308	27.3282	25.0257	22.7231	20.4205	18.1179	15.8153
7.7	31.9203	29.6178	27.3157	25.0126	22.7100	20.4074	18.1048	15.8022
7.8	31.9074	29.6048	27.3023	24.9997	22.6971	20.3945	18.0919	15.7893
7.9	31.8947	29.5221	27.2895	24.9869	22.6844	20.3818	18.0792	15.7766
8.0	31.8821	29.5795	27.2769	24.9744	22.6718	20.3692	18.0666	15.7640
8.1	31.8697	29.5671	27.2645	24.9619	22.6594	20.2568	18.0542	15.7516
8.2	31.8574	29.5548	27.2523	24.9375	22.6171	20.3445	18.0419	15.7393
8.3	31.8453	29.5427	27.2401	24.9376	22.6350	20.3324	18.0298	15.7272
8.4	31.8333	29.5307	27.2282	24.9256	22.6230	20.3204	18.0178	15.7152
8.5	31.8215	29.5189	27.2163	24.9137	22.6112	20.3086	18.0060	15.7034
8.6	31.8098	29.5072	27.2046	24.9020	22.5995	20.2969	17.9943	15.6917
8.7	31.7982	29.4957	27.1931	24.8905	22.5879	20.2853	17.9827	15.6801
8.8	31.7868	29.4842	27.1816	24.8790	22.5765	20.2739	17.9713	15.6687
8.9	31.7755	29.4729	27.1703	24.8678	22.5652	20.2626	17.9600	15.6574
9.0	31.7643	29.4618	27.1592	24.8566	22.5540	20.2514	17.9488	15.6462
9.1	31.7533	29. 4507	27.1481	24.8455	22.5429	20.2402	17.9378	15.6352
9.2	31.7424	29.4398	27.1372	24.8346	22.5320	20.2294	17.9268	15.6243
9.3	31.7315	29.4290	27.1238	24.8238	22.5212	20.2186	17.9160	15.6136
9.4	31.7208	29.4183	27.1157	24.8131	22.5105	20.2079	17.9053	15.6028
9.5	31.7103	29.4077	27.1051	24.8025	22.4999	20.1973	17.8948	15.5922
9.6	31.6998	29.3872	27.0946	24.7920	22.4895	20.1869	17.8843	15.5817
9.7	31.6894	29.3868	27.0843	24.7817	22.4791	20.1765	17.8739	15.5713
9.8	31.6792	29.3766	27.0740	24.7714	22.4688	20.1663	17.8637	15.5611
9.9	31.6690	29.3664	27.0639	24.7613	22.4587	20.1561	17.8535	15.5509

U/N	$Nx10^{-7}$	$Nx10^{-6}$	$Nx10^{-5}$	$Nx10^{-4}$	$Nx10^{-3}$	$Nx10^{-2}$	$Nx10^{-1}$	N
1.0	15.5409	13.2383	10.9357	8.6332	6.3315	4.0379	1.8229	0.2194
1.1	15.4456	13.1430	10.8404	8.5379	6.2363	3.9436	1.7371	0.1860
1.2	15.3586	13.0560	10.7534	8.4509	6.1494	3.8576	1.6595	0.1584
1.3	15.2785	12.9759	10.6734	8.3709	6.0695	3.7785	1.5889	0.1355
1.4	15.2044	12.9018	10.5993	8.2968	5.9955	3.7054	1.5241	0.1162
1.5	15.1358	12.8328	10.5303	8.2278	5.9266	3.6374	1.4645	0.1000
1.6	15.0709	12.7683	10.4657	8.1634	5.8621	3.5739	1.4092	0.08631
1.7	15.0103	12.7077	10.4051	8.1027	5.8016	3.5143	1.3578	0.17465
1.8	14.9531	12.6506	10.3479	8.0455	5.7446	3.4581	1.3098	0.06471
1.9	14.8990	12.5964	10.2939	7.9915	5.6906	3.4050	1.2649	0.05620
2.0	14.8477	12.5451	10.2426	7.9402	5.6394	3.3547	1.2227	0.04890
2.1	14.7989	12.4964	10.1938	7.8914	5.5907	3.3069	1.1829	0.04261
2.2	14.7524	12.4498	10.1473	7.8449	5.5443	3.2614	1.1454	0.03719
2.3	14.7080	12.4054	10.1028	7.8004	5.4999	3.2179	1.1099	0.03250
2.4	14.6654	12.3628	10.0603	7.7579	5.4575	3.1763	1.0762	0.02844
2.5	14.6246	12.3220	10.0194	7.7172	5.4167	3.1365	1.0443	0.02491
2.6	14.5854	12.2828	9.9802	7.6779	5.3776	3.0983	1.0139	0.02185
2.7	14.5476	12.2450	9.9425	7.6401	5.3400	3.0615	0.9849	0.01918
2.8	14.5113	12.2097	9.9061	7.6038	5.3037	3.0261	0.9573	0.01686
2.9	14.4762	12.1736	9.8710	7.5687	5.2687	2.9920	0.9309	0.01482
3.0	14.4423	12.1397	9.8371	7.5348	5.2349	2.9591	0.9057	0.01305
3.1	14.4095	12.1069	9.8043	7.5020	5.2022	2.9273	0.8815	0.01149
3.2	14.3777	12.0751	9.7726	7.4703	5.1706	2.8965	0.8583	0.01013
3.3	14.3470	12.0444	9.7418	7.4395	5.1399	2.8668	0.8361	0.008939
3.4	14.3171	12.0145	9.7120	7.4097	5.1102	2.8379	0.8147	0.007891
3.5	14.2881	11.9855	9.6830	7.3807	5.0813	2.8099	0.7942	0.006970
3.6	14.2599	11.9574	9.6548	7.3526	5.0532	2.7827	0.7745	0.006160
3.7	14.2325	11.9300	9.6274	7.3252	5.0259	2.7563	0.7554	0.005448
3.8	14.2059	11.9033	9.6007	7.2985	4.9993	2.7306	0.7371	0.004820
3.9	14.1799	11.8773	9.5748	7.2725	4.9735	2.7056	0.7194	0.004267
4.0	14.1546	11.8520	9.5495	7.2472	4.9482	2.6813	0.7024	0.003779
4.1	14.1299	11.8273	9.5248	7.2225	4.9236	2.6576	0.6859	0.003349
4.2	14.1059	11.8032	9.5007	7.1985	4.8997	2.6344	0.6700	0.002969
4.3	14.0823	11.7797	9.4771	7.1749	4.8762	2.6619	0.6546	0.002633
4.4	14.0593	11.7567	9.4541	7.1520	4.8533	2.5809	0.6397	0.002336
4.5	14.0368	11.7342	9.4317	7.1295	4.8310	2.5684	0.6253	0.002073
4.6	14.0148	11.7122	9.4097	7.1075	4.8091	2.5474	0.6114	0.001841
4.7	13.9933	11.6907	9.3882	7.0860	4.7877	2.5268	0.5979	0.001635
4.8	13.9723	11.6697	9.3671	7.0650	4.7667	2.5068	0.5848	0.001453
4.9	13.9516	11.6491	9.3465	7.0444	4.7462	2.2871	0.5721	0.001291
5.0	13.9314	11.6289	9.3263	7.0242	4.7261	2.4679	0.5598	0.001148
5.1	13.9116	11.6091	9.3065	7.0044	4.7064	2.4491	0.5478	0.001021
5.2	13.8922	11.5896	9.2871	6.9850	4.6871	2.4306	0.5362	0.0009086
5.3	13.8732	11.5606	9.2682	6.9659	4.6681	2.4126	0.5250	0.0008086
5.4	13.8545	11.5519	9.2494	6.9473	4.6495	2.3948	0.5140	0.0007198
5.5	13.8361	11.5336	9.2310	6.9289	4.6313	2.3775	0.5034	0.0006409
5.6	13.8181	11.5155	9.2130	6.9109	4.6134	2.3604	0.4930	0.0005708
5.7	13.8004	11.4878	9.1953	6.8932	4.4958	2.3437	0.4830	0.0005085
5.8	13.7830	11.4804	9.1782	6.8758	4.5785	2.3273	0.4732	0.0004532
5.9	13.7659	11.4633	9.1607	6.8588	4.5615	2.3111	0.4637	0.0004039
6.0	13.7491	11.4465	9.1440	6.8420	4.5448	2.2953	0.4544	0.0003601
6.1	13.7326	11.4300	9.1275	6.8254	4.5283	2.2797	0.4454	0.0003211
6.2	13.7133	11.4138	9.1112	6.8092	4.5122	2.2642	0.4366	0.0002864
6.3	13.7003	11.3978	9.0952	6.7932	4.4962	2.2494	0.4280	0.0002555
6.4	13.6846	11.3820	9.0795	6.7775	4.4806	2.3346	0.4197	0.0002279
6.5	13.6691	11.3665	9.0640	6.7620	4.4652	2.2201	0.4115	0.0002034

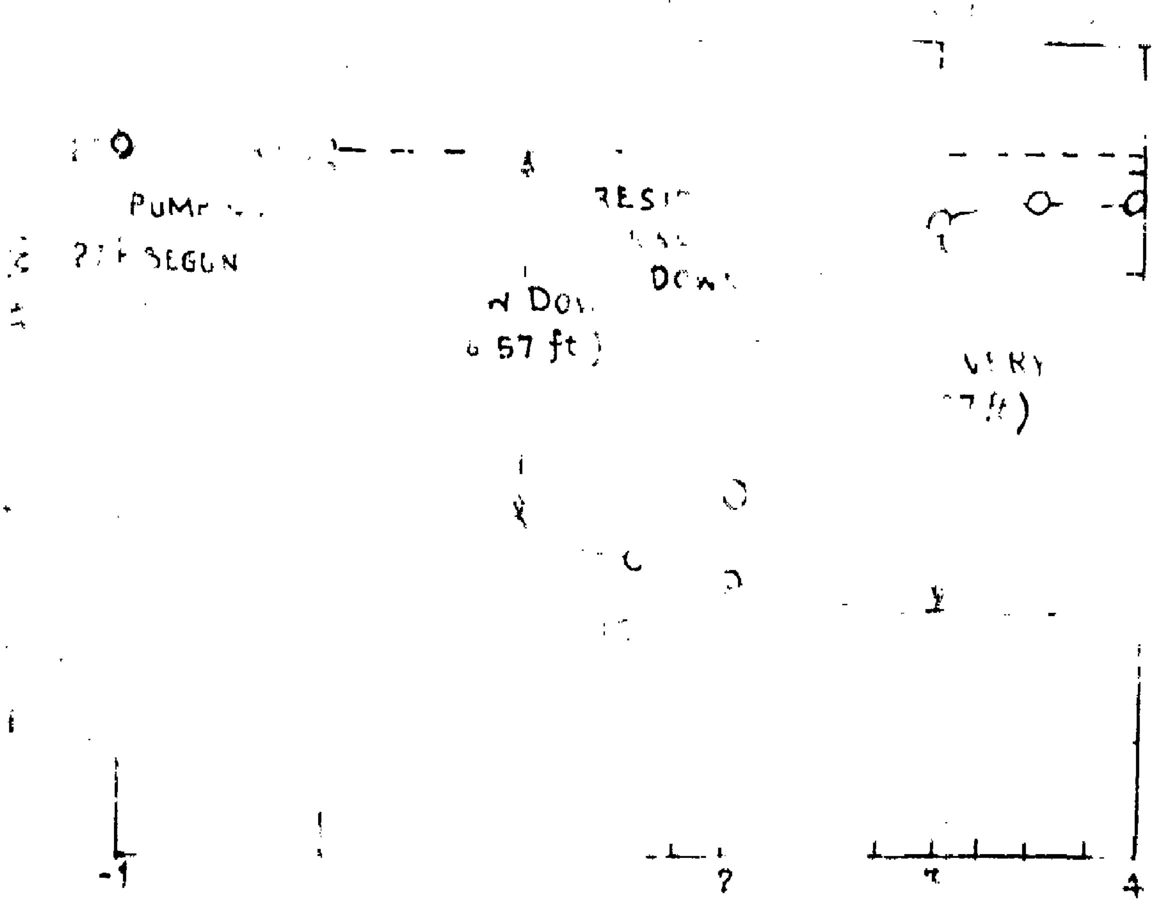
6,6	13,6538	11,3512	9,0487	6,7467	4,4501	2,2058	0,4035	0,0001816
6,7	13,6388	11,3362	9,0337	6,7317	4,4351	2,1917	0,3961	0,0001621
6,8	13,6240	11,3214	9,0189	6,7169	4,4204	2,1779	0,3883	0,0001448
6,9	13,6094	11,3068	9,0043	6,7023	4,4059	2,1643	0,3810	0,0001293
7,0	13,5950	11,2924	8,9899	6,6879	4,3916	2,1508	0,3738	0,0001155
7,1	13,5808	11,2782	8,9617	6,6737	4,3775	2,1376	0,3668	0,0001032
7,2	13,5668	11,2642	8,9617	6,6598	4,3636	2,1246	0,3599	0,0009219
7,3	13,5550	11,2504	8,9479	6,6460	4,3500	2,1118	0,3532	0,00009219
7,4	13,5394	11,2368	8,9343	6,6324	4,3364	2,0991	0,3467	0,00007364
7,5	13,5260	11,2234	8,9209	6,6190	4,3231	2,0867	0,3403	0,00006583
7,6	13,5127	11,2102	8,9076	6,6057	4,3100	2,0744	0,3341	0,00005886
7,7	13,4997	11,1971	8,8946	6,5927	4,2970	2,0623	0,3280	0,00005263
7,8	13,4868	11,1842	8,8817	6,5798	4,2842	2,0503	0,3221	0,00004707
7,9	13,4740	11,1714	8,8689	6,5671	4,2716	2,0386	0,3163	0,00004210
8,00	13,4614	11,1589	8,8563	6,5543	4,2591	2,0269	0,3106	0,00003767
8,1	13,4490	11,1464	8,8439	6,5421	4,2468	2,0155	0,3050	0,00003370
8,2	13,4367	11,1342	8, 8317	6,5298	4,2346	2,0042	0,2996	0,00003015
8,3	13,4246	11,1220	8,8195	6,5177	4,2226	1,9930	0,2943	0,00002699
8,4	13,4126	11,1101	8,8076	6,5057	4,2107	1,9820	0,2891	0,00002415
8,5	13,4008	11,0982	8,7967	6,4939	4,1990	1,9717	0,2840	0,00002162
8,6	13,3891	11,0865	8,7840	6,4822	4,1874	1,9604	0,2790	0,00001936
8,7	13,3776	11,0750	8,7725	6,4707	4,1759	1,9498	0,2742	0,00001733
8,8	13,3661	11,0635	8,7610	6,4592	4,1646	1,9393	0,2694	0,00001552
8,9	13,3548	11,0523	8,7497	6,4480	4,1534	1,9290	0,2647	0,00001390
9,0	13,3437	11,0411	8,7386	6,4368	4,1423	1,9187	0,2602	0,00001245
9,1	13,3326	11,0300	8,7275	6,4258	4,1313	1,9087	0,2557	0,00001115
9,2	13,3217	11,0191	8,7166	6,4148	4,1205	1,8987	0,2513	0,000009988
9,3	13,3109	11,0083	8,7058	6,4040	4,1098	1,8888	0,2470	0,000008948
9,4	13,3002	10,9976	8,6951	6,3934	4,0992	1,8781	0,2429	0,000008018
9,5	13,2896	10,9870	8,6845	6,3828	4,0887	1,8695	0,2387	0,000007185
9,6	13,2791	10,9765	8,6740	6,3723	4,0784	1,8599	0,2347	0,000006439
9,7	13,2688	10,9662	8,6637	6,3620	4,0681	1,8505	0,2308	0,000005771
9,8	13,2585	10,9559	8,6534	6,3517	4,0579	1,8412	0,2269	0,000005173
9,9	13,2483	10,9458	8,6433	6,3416	4,0479	1,8320	0,2231	0,000004637

TABLE 6.2

Date (July 52)	Hour	Elapsed time Min.	t days	$\frac{t}{r^2}$	Drawdown* s ft.	Depth to water ft.
			Well No.1 (r= 600 ft.)			
5	2400					25.00
6	0600					25.00
	1200					25.00
	1800					25.00
	2400**	0	0	0	0	25.00
7	0004	4	0.00278	1.1X10-8	0.44	25.44
	0015	15	0.0104	4.2X10-8	1.50	26.50
	0055	55	0.038	1.5X10-7	2.83	27.83
	0305	185	0.13	5.2X10-7	4.22	29.22
	1200	720	0.50	2.0X10-6	5.76	30.76
	2400	1440	1.0	4.0X10-6	6.57	31.57
8	1200	2160	1.5	6.0X10-6	7.04	32.04
	2400	2880	2.0	8.0X10-6	7.32	32.32
			Well No.2 (r=1000 ft.)			
5	2400					25.10
6	0600					25.10
	1200					25.10
	1800					25.10
	2400	0	0	0	0	25.10
7	0030	30	0.0208	2.1x10-8	0.89	25.99
	0155	115	0.080	8.0X10-8	2.16	27.26
	0640	400	0.278	2.8X10-7	3.53	28.63
	2400	1449	1.0	1.0X10-6	4.94	30.04
8	2400	2880	2.0	2.0X10-6	5.75	30.85

--* Values in this column are derived from the depth to water measurements made in the observation well and given in the next column.

** Pumped well begins discharging at 600 gpm.



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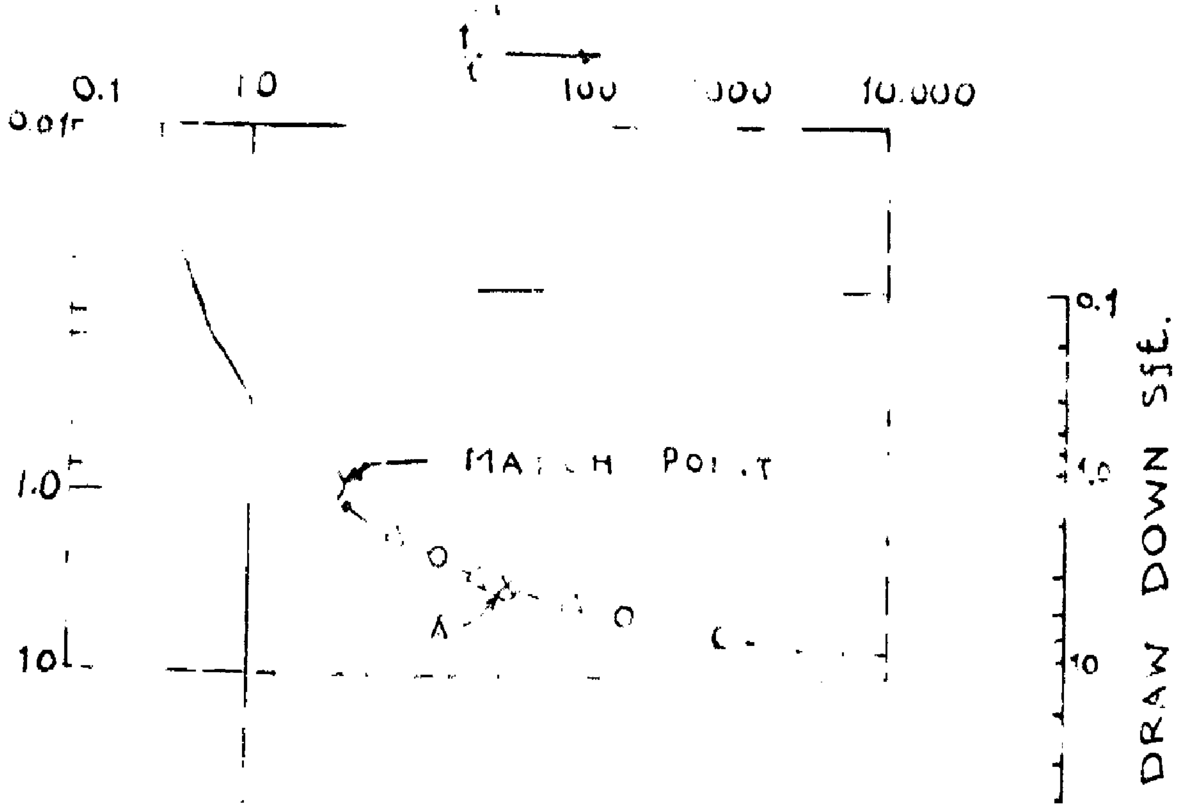


C H A P T E R - VII

GROUND WATER EXPLORATION

7.1 . INTRODUCTION

The subsurface explorations in connection with ground water are done for the collection, compilation and analysis of geohydrological data for the economic utilisation of the ground water resources of the region. Ground-water exploration in any region can have the following objectives:-

(a) Revealing the occurrence and distribution, both laterally and with reference to depths of the various water bearing horizons.

(b) the determination of specific yield, and other hydrological characterestic like Transmissibility, permeability and storage co-efficient of the individual aquifers.

(c) the determination of chemical quality of ground water from individual aquifers as well as cummulative quality.

(d) the study of variation of quality laterally and vertically, and also with reference to time.

(e) The study of problems dealing with the suitability of the quality of ground water from water table zone and deeper aquifers regarding their applicability for irrigation and allied uses depending upon the soil characterestic.

(f) Delimitation of the ground water reservoir and its safe yield.

(g) On the basis of exploration by drilling and testing, to recommend the most suitable areas for ground water development for irrigation and allied uses.

(h) To reveal the knowledge of subsurface geology and paleogeographic conditions.

(i) To reveal the possible sources of recharge and intake of the ground water basins.

(j) The study of rainfall and climatic characterestic and their influence on the occurrence and distribution of ground water as well as fluctuation of water table.

In as much as these above objectives are broad based all efforts are made inspite of some limitations, to collect as much of information as possible to make our knowledge of ground water conditions of any area comprehensive.

7.2. METHODS OF EXPLORATION

The methods of exploration for ground water can be broadly classified in the following four classes:-

(a) Water Divining:- This method is considered more physiological than scentific. There are some persons who claim the supernatural knowledge of being able to indicate ground water by various means like divining rods.

(b) Geophysical Methods:- These methods constitute a form of field investigation in which physical measurements are normally made at the ground surface by using special instruments to secure subsurface information. The physical measurements at the surface are interpreted in terms of the subsurface geological conditions. In these methods exploratory bore holes are not always necessary and may be needed only to provide correlative data. These methods are most suitable for rapid preliminary study of the region. There are four major geophysical methods; Seismic, resistivity, magnetic and gravity.

(c) Photographic Methods:- The methods of interpreting the aerial photograph for the field reconnaissance, delineation of the areas likely to possess water bearing formations and determination of the depth of water table have been gaining popularity recently for a rapid preliminary studies of ground water on a regional basis.

(d) Geological Methods:- These methods include the detailed examination of the Sub-surface strata and ground water by making exploratory drill holes on the chosen sites, taking out the samples of soil and rock for further study, conducting hydrological tests on the drilled hole and testing the quality of the ground water. These methods are more expensive and time consuming but give more accurate results than the geophysical methods. In a systemic regional study of ground water, the preliminary studies should be carried out by the geophysical methods followed by exploratory drilling at sites considered table on the basis of geophysical investigations.

7.3. WATER DIVINING:

Water divining dates back to very ancient times and has always been a matter of controversy. While the protagonists of the various methods of water divining cite numerous instance of their success, others in the opposite group point out that water diviners always take care to locate water at places which any intelligent person would know to contain water. They attribute the instances of success in more difficult cases to 'mere chance'.

It is true that neither the geologist nor the geophysicist can claim hundred percent success in location of sites for water oil, but at least their methods are known, and are based on scientific principle. The methods of water diviners have no known and scientific basis behind them. The proceedure adopted by any water diviner is always shrouded in mystery .

Some of the water diviners claim that when they pass over a region containing ground water either in the form of streams or in depressions, they intuitively feel its presence either as a kind of second sight or as a result of some unconscious or sub-conscious influence of certain occult forces.

Another group of water diviners make use of the 'Divining Rod'. The divining rood consists of a twig of some particular type of tree. The trees commonly used by diviners in India are Neem, Peepul, Peach, Willow etc. It is believed that the twig held by both hands will whirl round when it comes above a subsoil water table. Some diviners claim to feel very great strain in their hands catching the twig as they come across the water table, others pass into a psychical state or rather a hysterical state. At times the twig totally rotates or is completely twisted.

7.4. GEOPHYSICAL METHODS

As pointed out in the preceeding paragraph, geophysical methods play an important role in any modern ground water exploration project. The application of geophysical methods in the field of ground water exploration may be stated as four-fold namely (1) location of productive aquifers (2) determination of the thickness of aquifers(3) estimation of yield (4) Investigation of ground water salinity. Of the above application, the estimation of yield or ground water reserves is not always an amenable to investigation by geophysical methods as it involves many other factors depending on the physical charcteristics of the aquifers.

There are four major geophysical methods used for sub-surface exploration. These are seismic, resistivity, magnetic and gravity method. Of these, the resistivity method is most suitable for ground water investigation and has been used successfully by the Geological Survey of India for locating water in Purana Valley, the Deccan trap area, Mysore and Kutch. In 1949, a party headed by Dr. P.Ermisch carried out a resistivity traverse along the Shergarh Chaba-Phalsund road in the then Jodhpur State with the primary idea of tracing the boundary between fresh and brackish water. The Geological Survey of India is now taking up the geophysical surveys for ground water in Bhilwara district of Rajasthan. The underground water board of the Government of Rajasthan proposes to take up the systematic geophysical surveys of western Rajasthan.

The technique and instruments of these methods are described in the following paragraphs.

7.5. RESISTIVITY METHODS

The electrical resistivity, which is the reciprocal of the electrical conductivity, of any formation varies mainly on the amount of moisture held and the amount of soluble electrolytes present in it. Thus the hard fresh granites and gniesses, being more or less impervious, have a high resistivity- varying from 100 metre ohms and above, whereas the more decomposed and saturated portions of such rocks have usually far lower resistivity- mostly of the order of 10 metre ohms and less. It is, therefore, possible by adopting a suitable system of field measurements to demarcate the more conductive portions of the ground in a given area.

Also as the moisture content of a formation increases, the resistivity goes on diminishing, but when complete saturation is attained, the curve becomes flat and the resistivity becomes constant. Thus by measuring the resistivity at different depths, it is possible to demarcate the zone of saturation.

Theory

A general expression giving the relation between the resistivity p_x of any formation and the resistivity p_1 of its water content may be stated as:

$$p_x = \frac{p_1}{k_t k_s}$$

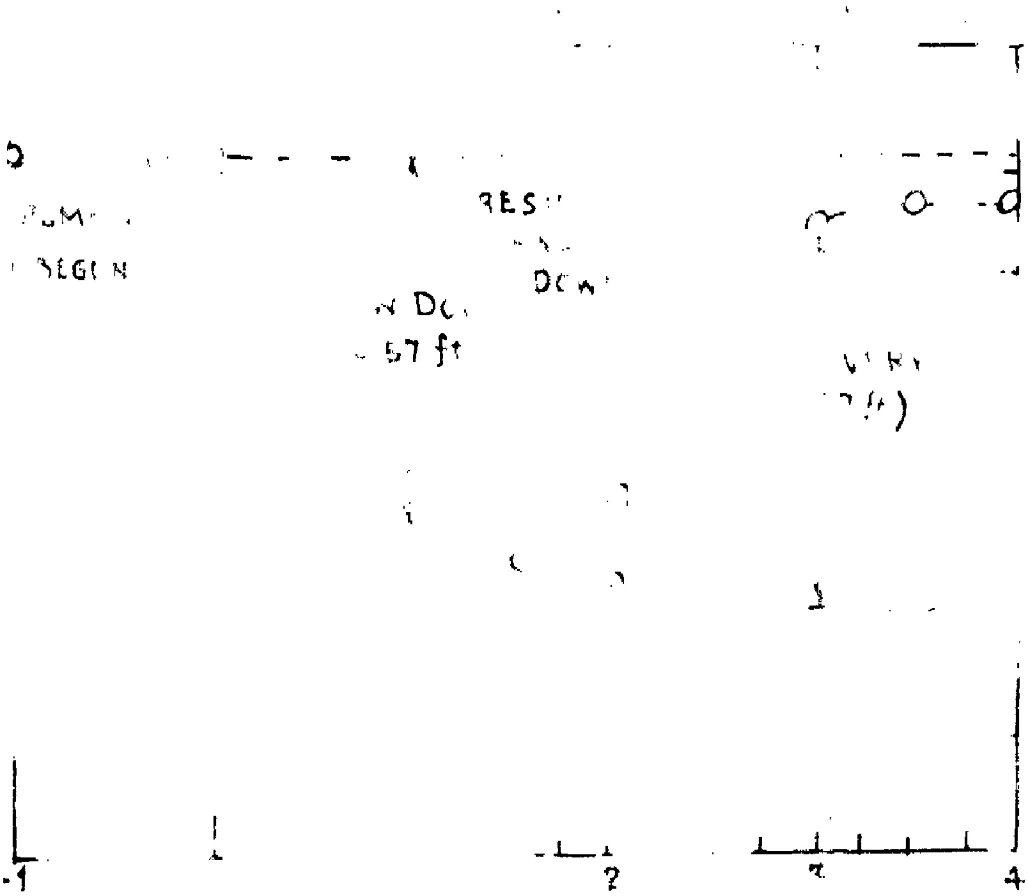
where k_t is a factor depending on the texture of the rock and k_s another factor which expresses the degree of saturation of the rock. In a porous formation, k_s and ρ_1 would be the dominant factors, whereas in a non-porous or compact formation k_t would be the dominant factor. Also in the zone of saturation, k_s will be evidently unity. Maxwell has derived the following expression for the conductivity $\sigma_x = \frac{1}{\rho_x}$ of any formation in terms of the conductivity of of the pore-filling liquid and 2 that of the rock material itself:

$$\sigma_x = \frac{3\sigma_2 + 2\, v_1/v_x(\sigma_1 + \sigma_2)}{3\,\sigma_1 - v_1/v_x\,(\sigma_1 - \sigma_2)}\,\sigma_1$$

where v_1 is the pore volume, and v_x total volume of the material of the formation which is assumed to consist of spherical grains whose distances are large compared to their radii. For highly porous formations, σ_2 would be nearly zero and the above expression would reduce to (in terms of resistivity values)

$$\rho_x \approx \frac{3 - \frac{v_1}{v_x}}{2\,\frac{v_1}{v_x}}\,\rho_1 = \frac{3 - v_1}{2v_1}\,\rho_1$$

if $v_x = 1$. Fig. 7.1 shows the above relation graphically, that is, the ratio of the resistivity of the formation ρ_x to the resistivity of the pore-filling medium ρ_1 against percentage porosity of the formation when the pores are completely filled with liquid. This relation then holds good beneath the water-table, that is, within the zone of saturation. It will thus be clear that by determining the resistivity of



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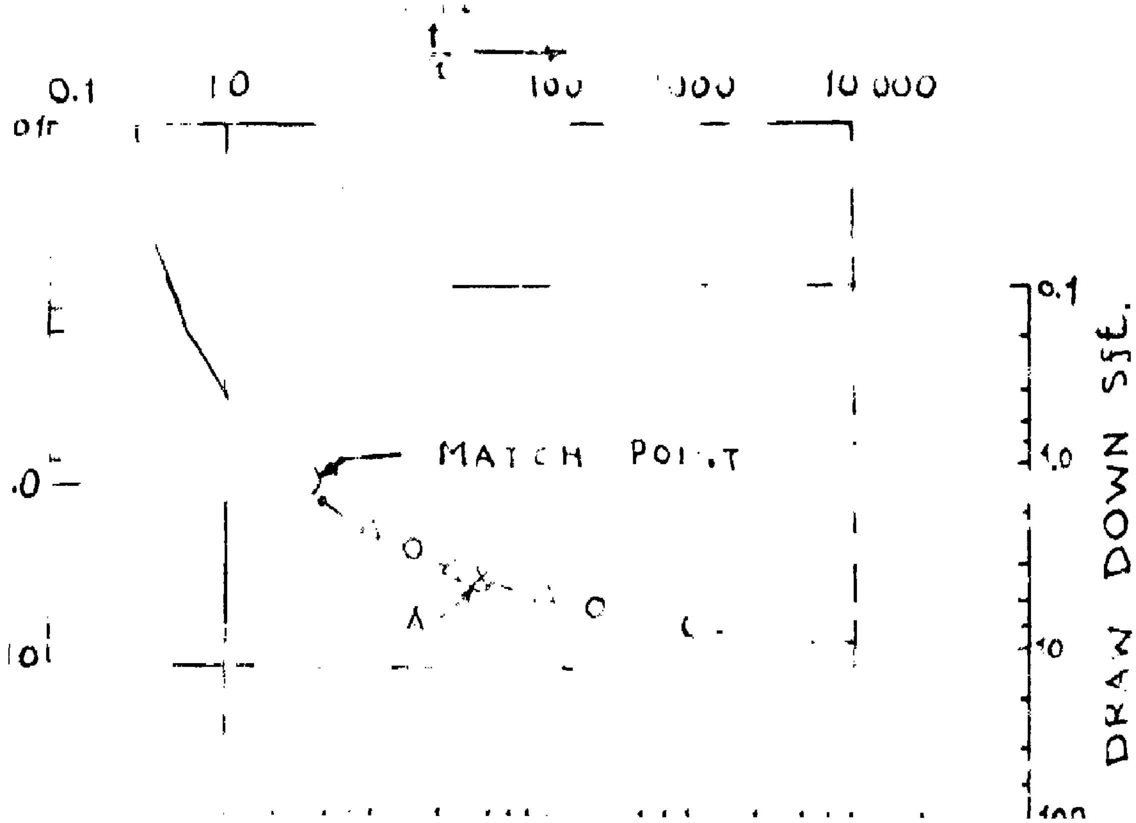
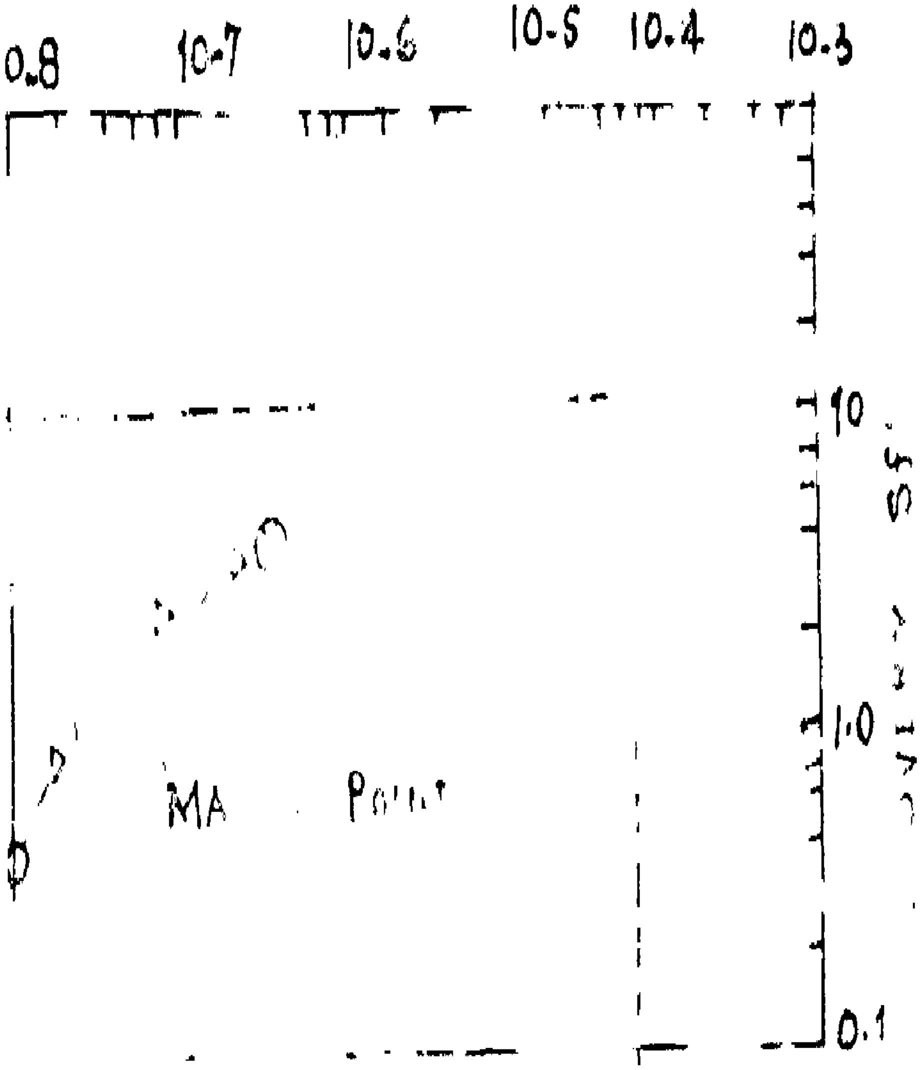


DRAW DOWN TEST D A SUPERPOSED O ..IS TYPE CURVE



0 100

REC

ON RVE

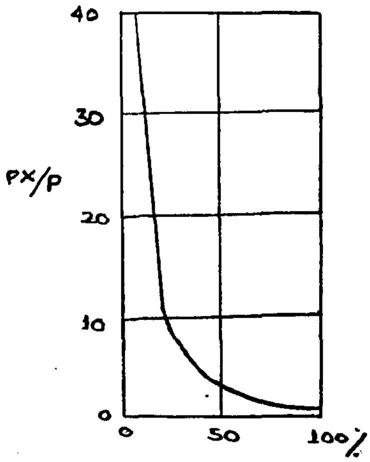


Fig.7.1 Relation between resistance factor $\rho = \rho_x/\rho_1$ and percentual volume v_1 of water in rocks.(after Sundberg)

the zone of saturation by conventional electrical depth probes, and also the actual resistivity of the water, say in wells in the area, we can obtain a measure of the porosity of the medium within the saturation zone. In practice, the ratio ρ_x/ρ_1 which is commonly known as the formation resistivity factor is found to attain as high values as 100 in the case of compact igneous and metamorphic rocks and as low values as 1.5 to 4 for marls, loess, alluvium and sandy soils.

If the formation is assumed to consist of spherical grains in cubic arrangement, the resistivity ρ_x of the porous formation with a pore volume v_1 may be further expressed as

$$\rho_x = \frac{3\rho_1}{v_1}$$

In the case of saline aquifers, the above relation enables us to obtain an idea of the resistivity of aquifers, the water of which may just be used for drinking purposes or for cattle. For human consumption a salt content of 0.25 per cent is considered to be the maximum permissible, while for cattle the maximum salt content would be about 0.7 per cent. The specific resistance of the former is about 180 ohm-cms while for the latter it would be of the order of 65 ohm-cms. Therefore, for a porosity of 40 per cent the resistivity p_x of an aquifer, the water of which could just be used for drinking purposes, would be

$$p_x = \frac{3p1}{v1} = \frac{3 \times 180}{40/100} = 1350 \text{ ohm-cms.}$$

while the limit of the resistivity p_x of an aquifer whose water may just be used for watering stock is by a similar calculation 500 ohm-cms. If the porosity of the aquifer be 60 per cent, the above two values would reduce to 900 and 325 ohm-cm respectively.

A similar relation for a permeable reservoir whose pores are filled with saline solution has been given by Archie as

$$p_x = p_1 \theta^{-m}$$

Where θ is the porosity expressed as a fraction and m, the exponent has a value lying between 1.8 and 2.0 for consolidated sediments and about 1.3 for clean unconsolidated sands.

Instrumentation and Techniques:- According to the usual practice, the electrical resistivity of a portion of ground at a site is measured as follows:-

Four electrodes are set in the ground in a line and at an equal distance apart (Fig.7.2). A set of D batteries and a milliammeter are connected in series with the outer pair of electrodes. They are the current electrodes and consist of sharp pointed metal rods. A potentiometer for measuring voltage is connected between the inner pair of electrodes, which are the potential electrodes. They are porous pots containing a solution of copper sulfate, some of which seeps into the ground and makes a good electrical contact. The circuit through the pot is completed by a copper bar which passes through the lid of the pot and into the solution.

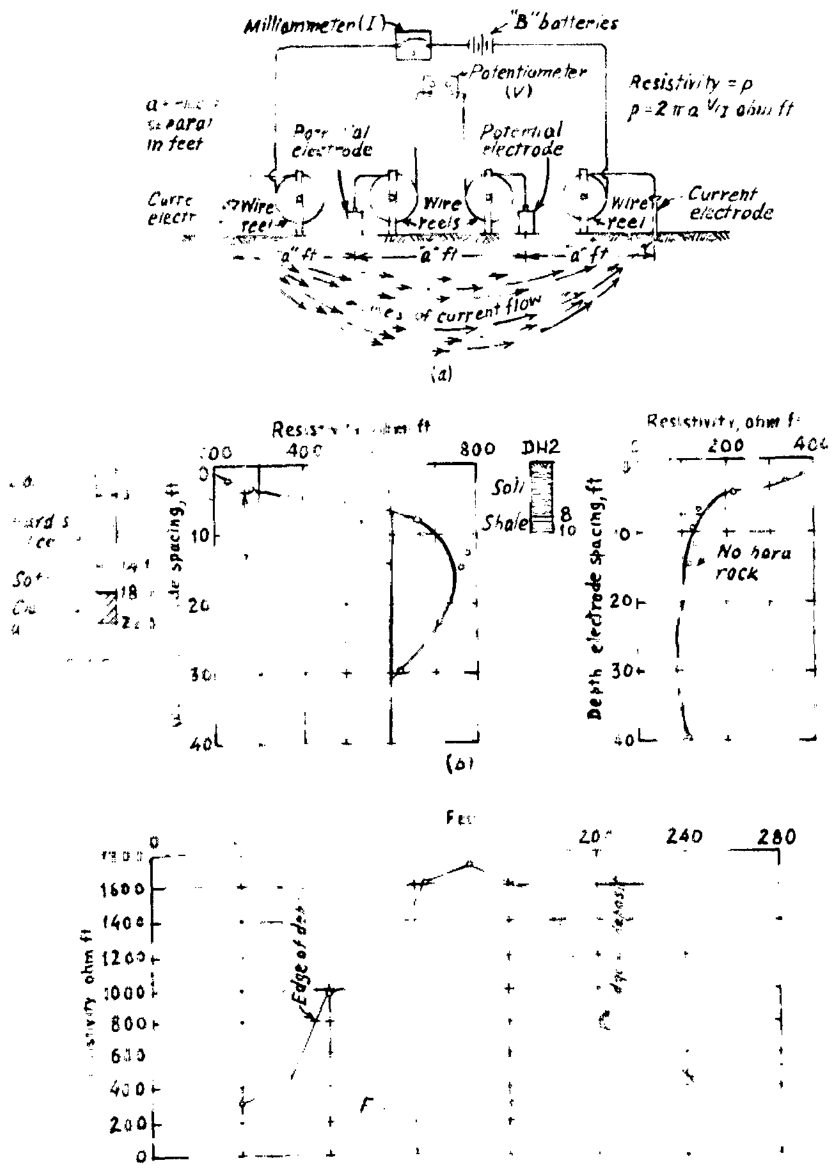


FIG 7.2 Electrical resistivity field method

To determine the resistivity of the ground, the current I that flows from the batteries and through the ground between the current electrodes is measured on the milliammeter. At the same time the voltage V between the potential electrodes is measured on the potentiometer. The equal spacing of electrodes, which is measured in feet, is designated as 'a' From the measured values of I, V, and a, the resistivity of the soil or rock between the current electrodes is found by the formula which states the resistivity $p = 2\pi a(V/I)$. The term $2\pi a$ relates to the volume of material measured, whereas the term V/I is electrical resistance in ohms. The units of resistivity are ohm-foot if 'a' is measured in feet. Ohm-centimeters or ohm-metre are also some times employed.

The resistivity method may be used to make (1) resistivity depth measurements at a selected point or (2) fixed depth resistivity measurements along a traverse line. In method 1, the electrode spacing 'a' is progressively increased to pick up changes in resistivity with depth. As the distance 'a' between the electrodes becomes greater, the current penetrates to a greater depth, related to 'a'. This procedure has been called, figuratively, electrical drilling. On the basis of the field measurements the resistivity depth curves are traced, the resistivity in ohm-foot is plotted on the horizontal axis, and the electrode spacing 'a' in feet is plotted on the vertical or depth axis (Fig. 7.2.).

In method 2, the four electrodes are kept at a constant spacing while they are moved along a line, and resistivity measurements are made at various stations. Lateral changes in resistivity of materials are indicated, in contrast to the vertical changes obtained in method 1. The procedure of method 2 has been called, also figuratively, electrical trenching. Field measurements are shown graphically as resistivity traverses. The stations are plotted on the horizontal axis, and the resistivity, in ohm-feet, is plotted on the vertical axis.

Figure 7.2 shows the resistivity curves traced in search of a high-resistivity siliceous rock. Progressive increase in resistivity until the maximum resistivity is reached and the curve starts to descend shows the presence of the rock (left curve). Conversely, low resistivity shown by the right curve indicates the absence of rock. A traverse traced at a gravel deposit(fig. 7.2) indicates the boundaries of the deposit as the resistivity drops below a certain minimum (about 800 ohm-ft in this case).

Resistivity Surveys in Shergharh Phalsund area of Western Rajasthan.

The surveys were carried out in 1949 by KRUMSEK (17) to determine the depth of water table and the thickness of the water bearing zone and also to differentiate between the ground water sources of fresh and brackish water.

A belt stretching east-west along the Shergarh-Chaba-Phalsund Road was selected with the primary idea of tracing the boundary between fresh and brackish water. It was, later on, found that there was no fresh water at all, everywhere the ground-water being more or less saline a fact which rendered the geophysical survey most difficult. " Electrical soundings" were carried out at the wells within reach; and then a continuous line of soundings, on the average a mile apart, all the way from Shergarh to Phalsund, was taken, often connecting the sounding by "constant separation traverses". The electrical sounding curves follow the same broad pattern and roughly approximate three-layer curves of high-low-high type. The curves indicate that the water-bearing zone is generally thin and under such circumstances the electrical sounding curves lose most of their discriminatory significance. However, they help to distinguish empirically certain "types". For instance, the general character of the curves was fairly constant along the belt between Shergarh and the outskirts of Phalsund, and along this stretch conditions are known to be uniformly unfavourable. Recognition of this type of curve is useful in giving information regarding the inadvisability of sinking wells under certain conditions.

Ermisch was of the opinion that the area has no continuous water-table, and that the little rain-water which seeps in, collects on the top of the rhyolite floor in several depressions forming small basins. Only the presence of small reservoirs, separated from one another, could explain the marked and erratic differences in salinity between neighbouring wells. Cases were revealed in Phalsund area where a thin layer of drinkable water floated on brine.

As it was felt that geophysical investigations were by no means enough for getting sufficient knowledge of the hydrology of this desert area, additional information was collected regarding the level and depth of water in the wells, its temperature and salinity, and the variation of the latter with depth.

7.6. <u>SEISMIC METHOD</u>

The shallow seismic refraction method is used in ground water exploration mainly to determine the depths to particular beds, as for instance, in bedrock problems involving a study of bedrock topography, depth to water-table in an unconsolidated medium or the investigation of structural features which give useful information regarding the presence or disposition of buried aquifers. This method makes use of the difference in the elastic properties or the longitudinal seismic wave velocities of various rock formations. The depths to and the attitude of various beds can be determined by measuring the arrival times at the ground surface of waves generated by blasting explosives near the ground surface and which get critically refracted along the interfaces of subsurface beds that have increasing associated wave speeds with depth.

Instrumentation And Techniques:- A number of seismic wave receivers termed Geophones, or pickups, are set in a line on the ground at measured distances apart (100 ft in Fig.7.3). At the shot point, a charge of a few pounds of a special explosive(usually nitramon) is exploded. Seismic waves sent into theground by the explosion reach the geophones, are picked up by them, amplified, and transmitted to the recording device, or oscillograph(Fig.7.3) The seismic record, or seismogram, thus produced consists of several lines or traces (Fig.7.3), on for each geophone. The shot instant is recorded by a special mark on one trace, and the instance of arrival of the first wave(i.e., the wave energy) at each geophone can be determined from the seismogram. Some of the waves(direct waves) travel close to the ground surface with a velocity V_1 ; others cross the upper layer obliquely and are refracted, after which they travel along the top of the underlying material with a velocity V_2. The quickest way for the latter wave to reach a geophone is to cross the upper layer in both down and up travelling under a certain angle(= critical

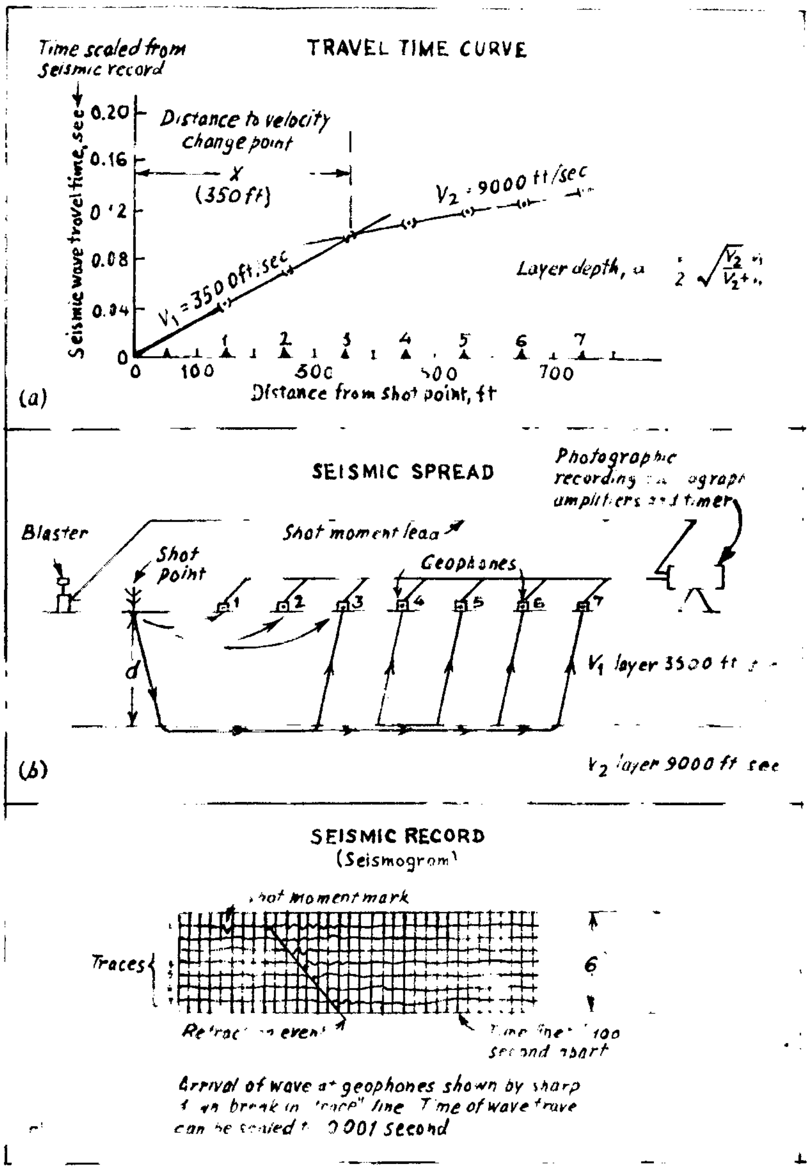


FIG 7 3 Seismic refraction method

angle of grazing incidence") as shown in Fig.7.3b. It should be noted that the laws of refraction of the seismic waves are analogous to those of light refraction, hence a similarity in terminology.

To obtain the travel-time curve (Fig 7.3 a) the distances between the shot point and all geophones are plotted horizontally; the times between the shot instant and the times of arrival of the first waves causing "breaks" in the traces are plotted vertically.

Joining the points thus obtained produced two intersecting straight lines. At all geophones to the left of the point of intersection in that figure, the direct waves arrive first, whereas at the rest of the gwophones the refracted waves arrive first. At the point of intersection itself, both a direct and a refractéd wave arrive simultaneously. Distance 'x' of this point of intersection can be simply scaled. The distance(in feet) from the shot point to any geophone at which direct waves arrive first is divided by the time(in seconds) the direct wave requires to reach that geopone to obtain velocity V_1(in feet per second). The distance between any two geophones usually are equally spaced from 50 to 100 ft. apart; the whole distance covered by the geophones is often made equal to from 3 to 12 times the desired depth of penetration. From measurements of seismic wave speed as described above, it is possible to find the depth to certain types of geological horizons, such as bedrock, at several points in an area. The bed-rock at a damsite, for example, may be the horison which carries seismic waves at a relatively high velocity.

It would be evident that for the successful application of the electrical resistivity method there should be a sufficiently marked contrast in the electrical resistivity characteristics of the various formations under investigation. Similarly a well marked contrast in the longitudinal seismic velocity would be an essential prerequisite for the successful application of the seismic refraction method. In some areas, there may be a good electrical contrast between the formations but a poor seismic velocity contrast, while in other areas the reverse may be the case. The two methods would thus oftentimes mutually complement one another very well and, therefore, can beused in conjunction with one another with great advantage.

7.7 MAGENTIC AND GRAVITY METHODS

The magnetic and the gravity methods are somewhat similar in respect to the field operations but distinctive as to the type ofphysical measurements. In magnetic procedure, a magnetometer is used to measure the vertical component of theearth's magnetic field at closely spaced stations in an area, These measurements are corrected for certain systematic variations. The resulting magnetic values relate to local subsurface conditions. In the gravity method, a gravimeter is used. Measurements are made of the force of gravity at certain field stations and corrected for variations as necessary. The corrected gravity values reflect conditions below the surface.

These two methods are not used in engineering investigations so much as the seismic and resistivity methods. The main reason for this infrequent application is that gravity and magnetic measurements areless easily interpreted in quantitative terms than are cases, however, where either the magnetic or gravity method may be uniquely suited to obtain subsurface information. For example, the magnetometer is an excellent tool for outlining intrusive dikes, and the gravimeter can be used in searching for buried solution channels or caverns.

7.8 PHOTOGRAMMETIC METHODS

These methods are based on the fact that presence of ground water can be corelated with features visible from air:patterns of of topography, vegetation, land use, and drainage, and miscellaneous ground features. In searching for ground water the photo interpreter must identify porous and granular water bearing form-

formations, and must consider location, elevation, and other ground conditions which affect the storage and movement of ground water. He should be able to compare the area being studied with other areas which have already been investigated.

Ground water in deserts can usually be located quickly by means of vegetation indicators which appear in aerial photographs. The ~~quantity~~ quality of water, in particular, its salt content, can sometimes be ascertained by the study of natural vegetation. The depths of ground water in various part of the region can often be estimated from vegetation types and patterns of land forms interpreted from aerial photographs.

A method of systematic study of ground water by photo interpretation developed by Howe involves the following steps:-

(a) Delineation of streams, drainage lines, and surface waters on a photomosaic of the area.

(b) Detailed interpretation of surface materials in the area and delineation of soil types according to physiography and vegetation.

(c) Delineation of landforms and land use patterns and correlation with subsurface water conditions. Interpretation of special ground features, such as flooded gravel pits, ponds, quarries, lakes, ditches, and swamps, which provide clues to ground water conditions.

(d) Delineation of areas likely to possess water-bearing formations.

(e) Review of the literature, including well logs, geologic reports, and other information about the area; field check and low-altitude photography of problem spots.

(f) Preparation of a ground-water map and written report.

7.9 GEOLOGICAL METHODS:

As pointed out in para 6.2, these methods consist of drilling holes on chosen sites to extract samples of rock, soil and water for further studies. The information on quality of the sub-surface material may be obtained not only from the sample but also from the field observations of resistance to advacing the hole. Hydrological tests on the holes cased after drilling give information about the quality and quantity of water.

The methods of constructing these test holes include the following:-

(1) Auger borings.

(2) Wash borings.

(3) Drilling:-

(a) Percussion drilling

(b) Direct rotary drilling

(c) Reverse rotary drilling.

7.10 AUGER BORING

Auger borings often provide the simplest method of soil investigation and sampling. They may be used for any purpose where disturbed samples are satisfactory and are valuable in advancing holes to depths at which undisturbed sampling by thin-walled tubes is required. Depths of auger investigations are, however, limited by the ground-water table and by the amount and maximum size of gravel, cobbles, and boulders as compared with the size of equipment used. Hand-operated post-hole augers 4 to 12 inches in diameter can be used for exploration up to about 20 feet deep. However, with the aid of a tripod, holes up to 80 feet deep have been excavated successfully and economically Machine-driven augers are of three types; Helical augers 3 to 16 inches in diameter; disk augers up to 42 inches in diameter; and bucket augers upt to 48 inches in diameter.

In auger, boring is made by turning the auger the desired distance into the soil, withdrawing it, and removing the soil for examination and sampling. The auger is inserted into the hole again, and the process is repeated. Pipe casing is required in unstable soil in which the borehole fails to stay open, and especially where the boring is extended below the ground-water level. The inside diameter of the casing must be slightly larger than the diameter of the auger used. The casing is driven to a depth not greater than the top of the next sample and is cleaned out by means of the auger. The auger can then be inserted into the boarhole and turned below thebottom of the casing to obtain the sample.

The soil auger can be used both for boring the hole and for bringing up disturbed samples of the soil encountered. It operates b best in somewhat loose, moderately cohesive, moist soil. Holes are usually bored without the addition of water; but in hard, dry soils or in cohesionless sands the introduction of a small amount of water into the hole will aid the drilling and sample extraction. Rock fragments larger than about one-tenth of the diameter of the hole cannot be successfully removed by normal augering methods. Larger sized holds permit examination of the soils in place, and therefore, are preferred for foundation investigations.

7.11 <u>WASH BORINGS</u>

To make bore holes by a simple method known as wash boring (or wash borings or jet holes), a four-legged derrick with a block at the top generally is used. Before washing starts, the hard surface material should be broken up and removed, e.g., to a depth of about 1 ft. with a pick or bull point (iron bar with sharp point). If the washable soft material is hardened at the top or covered with other hard layers, it is first necessary to make a regular bore hole by one of the methods described hereafter. The casing is then driven into the uncovered washable material by repeated blows of a drop hammer. The usual weight of hammer used with a cathead is about 140 to 300 lb, the height of free fall being 2 to 4 ft. With cable hoists, hammers weighing up to 800 lb may be used. The casing encloses a wash pipe, generally 1 in. or more in diameter, with a chopping bit at the end. Thus, the wash pipe in this case is actually what is termed a drill rod. After the casing is driven to a reasonable depth, earth material is washed out from inside the casing. The drive head of the casing is replaced by a T pipe (i.e. a pipe shaped like the letter T). The wash pipe is connected to a swivel (also called a "water swivel"), and the swivel connected to a pump. The wash pipe ejects a jet of water through the bit. The water thus erodes the soil material next to the tip of the casing and returns between the casing and the wash pipe, bringing the broken and eroded soil to the surface as a suspension. The suspension is received in a tub or a sump in the ground under the horizontal portion of the T. (It should be noted that drill mud is applied to borings in the same way, i.e., forcing it under pressure through the wash pipe and having it return between the pipe and the casing). Except, of course, if special drill muds are used, the return water that flows into a sump or "sludge pit" is constantly returned to the hole. The mixture is kept at the correct specific

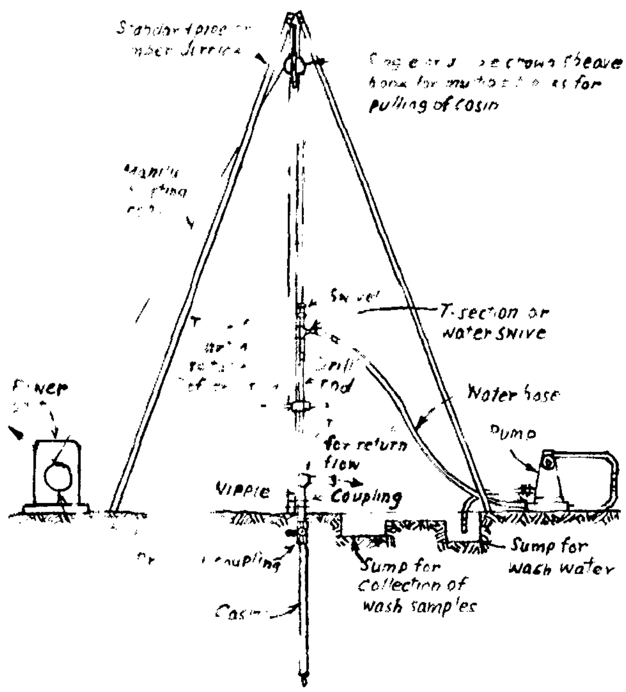


FIG '4 wash boring rig

gravity by occasional additions of water or chemicals. If the drilling work is close to a river or other source of water, it is preferable to pump water directly instead of reusing the water from the sump. To facilitate rapid erosion of the material under the bottom of the bit, the wash pipe is churned up and down and twisted. Hoisting, in this case, may be accomplished by wrapping rope around the water swivel and lifting and dropping the pipe by alternately pulling and loosening the rope warp on the cathead. Hand wrenches are used to twist the pipe.

When the hole is washed out, sampling usually follows. Wash boring, however, may be of value even without subsequent sampling. Such is the case when it is known that rather shallow rock underlies a certain locality and the exact depth of the rock is to be considered in the design.(This application is not its exact depth cannot be determined.) Wash boring with-out sampling also may be useful in the preliminary exploration before expensive, deep, undisturbed sampling starts. The cuttings(or "sludge") returning from the hole will give some, though incomplete, information about the general character of the soil and the sequence of the soil strata. Such identifications have to be regarded with caution, as the wash water tends to wash out the fines from the soil. The returning cuttings thus may indicate that the soil is coarser than it actually is. Similarly, large gravel may be broken into fine chips under the bit and thus not show in the cuttings. However, the presence of such coarse material sometimes can be detected by the action of the bit and by the presence of numerous sharp rock fragments in the cuttings. Often, washing out of soft material such as soft clay or organic silt can be done to a considerable depth, such as 60 ft or 70 ft, by the use of a short length of casing (e.g. 15 ft) at the top of the hole only. Generally, during the washing, the casing should be firmly gripped by a clamp or safety "dog " to prevent its possible loss into the hole. In very soft materials, the casing may sink down several (and sometimes many)feet under its own weight. To remove the casing, it is pulled by upward blow of the drive hammer against the drive head.

A wash boring crew usually consists of a foreman and two helpers. It is the foreman's duty to submit daily progress reports to the engineering office and keep track of the following data: (1) diameter and type of the casing per lineal foot; (2) weight of the hammer, average height of fall, and number of blows required to force the casing through each lineal foot; (3) loss or gain in wash water if any; and (4) his own log of the boring regardless of whether or not there is an engineer or geologist at the site.

7.12 PERCUSSION DRILLING

The percussion method of drilling has been used successfully over a considerable period of time and is particularly suitable to penetrate mixtures of sand, gravel and boulders such as are found commonly in alluvial and glacial deposits. This method can drill larger diameter holes compared to the rotary drilling methods but it is not possible to take out undisturbed core by this method. It is therefore suitable when the primary aim is to make a hole in the ground without obtaining precise data about the nature of the sub-strata.

The drilling rig used for percussion drilling consists of a "Chopping bit" screwed into a "stem" which in turn is attached to a set of " jars" held by a rope or a cable. The chopping bit may be a heavy bar 4 ft. or more long, working on the bottom of the hole. It acts together with the string of tools in a hammering or " percussion" action. The energy requiredfor this action can be provided in several ways.

The method generally used is shown in fig. 7.5 . This figure shows a "walking beam" that moves up and down by means of eccentrically mounted jars driven by a motor. The jars serve as a hammer to drive the sampler after the hole is made or may be used to jerk the bit loose if it sticks at the bottom of the hole.

The hole usually is fully or partly filled with water. The slurry formed at the bottom of the hole is periodically bailed out by means of bailers or sand pumps.

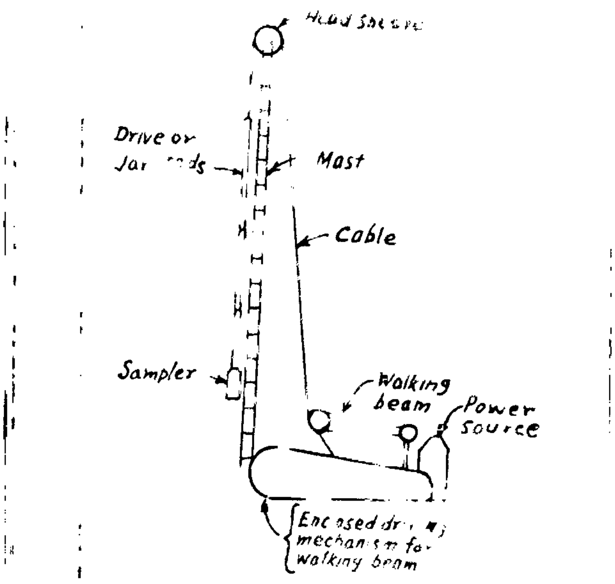


FIG. 7.5 PERCUSSION DRILLING ASSEMBLY

7.13 <u>ROTARY DRILLING OR CORE DRILLING</u>

The objective of the core boring is to obtain samples of a rather hard material, whether rock or hard soil, in the form of a cylindrically shaped core. This is done by a rotational process (40 to 1,000 rpm or more) using the rotary rig. Water, drilling mud, or air is used in core boring. The samplers used generally are termed core barrels. There are single-tube and double tube core barrels (fig. 7.6). In the latter type, the inner tube retains the core and usually does not rotate with the outer tube. The rotating tubes in both types of core barrels have drill bits at their cutting ends. The actual grinding or cutting devices, or "media," may be (1) permanently fixed to the bit, such as cast-set diamonds used in diamond core drilling; (2) fixed to the bit but exchangeable or refaced when worn, such as steel tooth and cutters, tungsten carbide (or "hard metal") inserts, or hand-set diamonds; or (3) fed between the bit and the rock, as chilled shoot (shot drilling).

The core boring process is as follows: (1) the bit makes an annular opening in the rock, (2) the barrel gradually slides down into this opening, (3) the core enclosed in the barrel is separated from the rest of the rock mass as later described, and (4) the barrel is lifted to the ground surface. The measures taken to avoid loss of the core consist of (1) relieving water or air pressure above the sample, for example by a small ball-check value that opens automatically if the pressure increases above a certain limit, and(2) supporting the core from below by a core catcher or core spring. This is a circular, springlike device which pemits the core to mov e upward but, bu spreading out, prevents it from falling out of the barrel.

In drive sampling, the material displaced by the sampler is pushed laterally and may be pressed into the sample. In core boring, the material around a sample is ground up and removed by the circulating wateror drilling fluid. Sometimes the core boring is done in a dry bore hole, and the cuttings are removed by circulating air at high pressure or by using a helical hollow augor. In some types of core barrels, the coarser particles in the cuttings moving up in the drilling fluid tend to fall back because of the decrease in velocity of the fluid. To prevent this, core barrels especially in the case of shot drilling, are provided with special sludge barrels for collecting coarse cuttings. Such a sludge barrel sometimes is termed a "calyx" barrel. Calyx also is used to mean a very large diameter hole (30 in or greater) excavated by shot drilling; also the actual method of shot core boring is interchangeable called " calyx boring".

Single- tube barrels are used in sound rock or in large-diameter holes in all kinds of rock. If the diameter of the hole is small, or if the material to be sampled is soil or fissured or soft rock, the core should be protected from the erosive action of the drill water. In such cases a double-tube barrel is indicated.

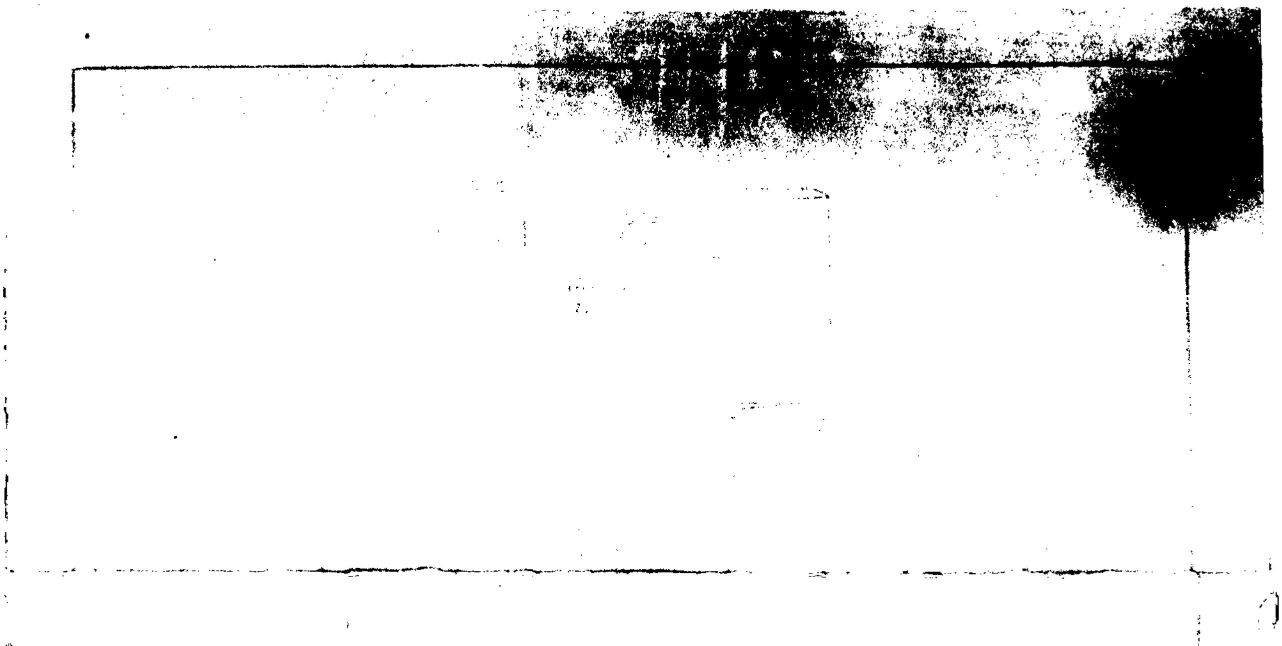


FIG. 7·60 ... Mfg. Co.

The inner tube should be provided with a linger if soil cores are to be obtained. The liner with the soil material is then taken out of the sampler, sealed, and sent to the laboratory.

Diamond and Calyx (or shot) Core Boring:- Two types of diamonds are used for rock boring: black diamonds, or carbons, and gray, yellow, or brownish industrial diamonds known as borts or bort. Carbons are of higher quality and much harder than hortz but cost roughly ten times as much. Diamond bits may be hand or mechanically set. In the latter case they are termed "cast" or "cast-set" bits. In the former case, holes are drilled in the inner and outer edges of the bit, the carbons placed in the holes, and the bit steel is hammered or peened around the carbon. Usually a few carbons are set on the outside of the bit about ⅛ in. or more above the bit face(i.e., its lower edge). These diamonds act as reaming stones during the drilling to widen the hole and thus protect the carbons and steel in the bit face and prevent the cuttings from binding ("freezing") the bit. The bit is screwed into the bottom of the core barrel, which is rotated at various speeds depending upon rock conditions. As the heavy friction heats the bit, cold water is forced through the hollow drill rod to keep it cool and wash the cuttings upward. The success of a diamond-coring operation depends upon the skill of the drill operator in maintaining ~~the~~ his drill speed, his water pressure, and his drill bit pressure as just the right levels for the particular kind of material that is being drilled.

After the core run is completed (i.e. the full length of the core barrel has penetrated the rock), the core is separated from the rest of the rock. In one method the circulating water is shut off and the core is "dry-blocked" or "burned-in"; i.e. the clearance between the barrel and the lower part of the core then is packed with ground materials, and the core may be extracted, though with some damage to its lower part. In some rocks, a rapid increase in rotation speed may be all that is required to break the core loose. In hard cores of large diameters, the barrel is withdrawn and replaced with one having a core retainer and special bit that undercuts the core. Unfortunately, sometimes none of these methods work, and the broken-off core at the bottom of the hole is picked up during the next core run(and usually is severly damaged).

Calyx or Shot Core Borings- In this type of boring, single-tube barrels only are used. Chilled-steel shot is fed into the waste water; it will become partially embedded in the soft steel of the coring bit. To be effective, the shot must be crushed during the operation; sometimes precrushed shot ("calyxite") is used. The cuttings are removed from the bit by circulating water and deposited in the calyx above the barrel proper. The core may be retained by methods similar to those used in connection with diamond drilling. In rock with numerous open fractures, this methods may be unsuccessful as the shot may be lost in the rock openings. Large-diameter holes (36 in. and larger) have been drilled by this method. It also has been used to sink ventilation shafts up to 2,000 ft. in depth for mines. For the extremely large diameter holes (such as 10 ft) the motor operating the bit is placed directly above it, and the entire apparatus follows the bit down the hole by being lowered on cables. The operator in such cases may ride directly on the top of the motor. This large -diameter boring requires specially built equipment; even so, the work is difficult if the rock is broken or the ground-water pressures are very high.

7.14. <u>REVERSE ROTARY DRILLING</u>

In the direct circulation method described in para 7.12 above, water is pumped inside the bore through the drill pipe and comes out through the bore on the outside of the drill pipe. In the reverse circulation method, the process of circulation is reversed, i.e. water is sucked up through the drill pipe by a suction pump and is allowed to flow into the annular space outside the drill pipe. As a matter of fact, the hole is throughout kept method needs a vacuum pump for priming and a suction pump for circulation.

It must be possible to rotate the bit at different speeds so that it can come cut its way through all types of formations, such as, sandstone, hard to soft clays, sand and gravel. In order to make the bit cut effectively and hence, to promote faster drilling, adequate pressure has to be applied to it. To ream certain portions of the hole, where strata are hard the bit has to be moved up and down and also to be taken out of the hole and inspected periodically.

The drilling fluid on the other hand must be able to remove the cuttings from the hole without interrupting the progress of drilling-in other words removing the cuttings and making a hole go on simultaneously. The cuttings are brought to land surface through the drill pipe. The pump must provide sufficient upward velocity to the largest cuttings, or to put it diferently, the upward fluid velocity must exceed the greatest slip of particle be cut. The circulating fluid which always fills thehole upto ground level provides the hydrostatic head to prevent the hole from collapsing. It would not be out of place to point out the few points of difference between the direct and Reverse Rotary System.

Table 7.1

Difference between direct and reverse rotary methods.

Direct Rotary	Reverse Rotary
1. The drilling fluid passes down thedrill pipe and rises with cuttings through the annular space between the bore and drill pipes.	The drilling fluid circulates down the annular space and is brought to ground level with cuttings through the drill pipe.

2. The drilling fluid consists of equajol, bentonite and local clays added to water so that the viscosity is sufficient to bring the cuttings up through the annular space between the bore and drill pipes.	The drilling fluid is clean water except where heavy caving conditions are experienced.
3. Plastering action of the drilling fluid due to the presence of jelly like clays.	No plastering action required except during heavy caving.
4. Diameter of hole not generally exceeding 20 inches.	Diameter of holes usually 27 inches.
5. Drilling to greater depths in thousands of feet possible	Depths below 600 feet rarely attained.

Advantages of Reverse Rotary Method:- In the direct circulation method, there is a tendency of the bore to collapse. In reverse circulation method, there is a pressure on the formation due to superimposed load of water above the spring level, which prevents the hold from collapsing even though no lining mud is used.

In direct circulation bores, lining mud has to be used to prevent the hole from collapsing and this mud has a detrimental effect on water yielding capacity of the water bearing formation.

Thus by the reverse rotary drilling process, it is possible to drill holes to a greater depths at fast speed. The yield of wells bored by this method is also more.

7.15 COMBINATION OF PERCUSSION AND ROTARY RIGS.

As pointed out in the preceeding paragraphs, the fields of application of a percussion rig and a rotary rig are slightly different. Now a days rigs have been designed which are a combination of the two. These rigs can operate as percussion rigs and also reverse rotary rig and thus are able to drill holes in almost all sorts of formations whether hard or soft with casing or without casing pipes.

7.16 EQUIPMENT AND METHOD OF DRILLING USED BY EXPLORATORY TUBE WELLS ORGANISATION IN WESTERN RAJASTHAN

The Exploratory tube wells organisation taking up the investigations for ground water as well as the construction of the productive tube wells is using the following types of drilling rigs:-

(1) Diesel powered Frank Direct Rotary Mud Circulation rigs designed for drilling and constructing water wells down to 1500 ft.

(2) Diesel powered Failing make Direct Rotary Mud circulation rigs capable of drilling and constructing water wells down to 1000 ft.

(3) Mayhu (Senior) make Direct Rotary Mud Circulation Rig capable of drilling pilot holes or slim holes down to 1000 ft.

(4) Star make (72 speed star) Percussion-cum-Direct Rotary Mud Circulation Rig capable of constructing wells down to 1000 ft. Drilling could be shifted to percussion or rotary with the help of this rig, depending on the strata.

(5) Reverse circulation Rigs, Frank and Winter Weiss make capable ofconstructing production wells down to 500 ft. deep.

(6) Star make (71 speed star) Percussion Rigs capable of drilling and constructing down to 500 ft.

The rig units are self contained regarding ancillary equipment like heavy vehicles, welding sets, mobile workshops, compressors, test pumps, water tanks and tractors with dozing attachment.

Selection of Sites- The importance of obtaining maximum information regarding water resources of a virgin area depend largely on the selection anddisposition of the exploratory sites. In view of this reconnaissance survey for the location of sites is normally carried out by the geologist , based mainly on the geologic conditions and also on the result of the geophysical traverses carried out by the geologist. This is followed by final pinpointing of the sites by a high level site selection committee, including also a state representative.

In selecting sites, a few key holes are recommended. Drilling of each well gives a vital data on the future drilling programme of the area.

The following points are taken into consideration by the Committee apart from the geological considerations:-

(1)The demand for lift irrigation and likelihood of any surface irrigation schemes being taken up in the vicinity in the near future.
(2) The elevation of ground to facilitate maximum natural gravity flow of water through channels to the farthest end of the commanded area, if the well proves to be productive.
(3) The desirability of the proposed site to be close to power transmission line for running the productive tube wells economically.
(4) The area should be out of the flood zone.
(5) On the feasibility of heavy machinery reaching the site.

Normally to obtain maximum subsurface geological & hydrological data, a grid pattern, triangular coverage or defined section (say north-south or east-west) is adopted.

The successful productive wells act as the nuclei for future development. Coverage of the area by more wells in future, is done normally by placing the wells radially to the initially proved successful wells. If further development is desired, wells placed perpendicular to the radial lines would yield more detailed information.

Drilling operations.- The initial step in drilling operations is to drill a pilot hole of about six-inch diameter down to a depth of 1000 ft or bed rock, whichever is earlier. The operations normally commence on the key holes in the area which may have to be drilled to the maximum depth of 1500 ft. Depending on the nature of strata XXXXXXXXXXXXXXX obtained from the key holes, depths of drilling at other sites are restricted. During drilling operations field geologists collect and examine strata and frame lithological log of the boreholes. The bed rock encountered is cored by using core assembly to collect geological data.

For percussion drilling, the drilling operations commence with a 16" diameter driving string and taken to a maximum depth recommended for housing. Beyond this depth, the well is normally telescoped to 12" or 10" diameter. The depth of drilling depends on the availability of enough thickness of strata and generally wells are completed within 500'.

Observations wells are drilled close to the main wells are drilled close to the ma main wells whenever detailed studies on hydrological characteristics are desired in an area. The observation holes are not normally gravel packed but adequate care is taken to see that the assembly lowered is more or less indentical with the one lowered in the main production well, except for its smaller diameter. They are developed by air lift method and back washing to establishing hydrological continuity with the main well during tests. The observations well assembly has to be pulled out soon after the necessary observations are made to avoid jamming.

Exploration work done by the Exploratory Tube Wells Organisation.- During the first phase of their operations in the years 1956-[illegible]

Exploratory Tube wells Organisation took up 10 bore holes in the Distri of Jaisalmer, Barmer, Bikaner, Churu, Jodhpur and Sikar. During the second phase in years 1959-61, they put in another 12 bore holes in the Districts of Barmer and Jaisalmer.

Since then, they have taken up the work on an extensive scale in Jalore District where they have put in as many as 37 bore holes. Besides they have also taken up a few bore holes each in the Districts of Nagour, Johdpur and Sri Ganganagar.

The methods of hydrological tests conducted on these wells have been described in paras 7.18 to 7.22. The summarised record, of the bore holes drilled in Jalore District and during the first and second projects is given in Appendix 7.1 and Appendix 7.2 respectively. The detailed report of bore hole logs and hydrogoical tests carried on some typical wells is enclosed as Appendix 7.3. This also gives the details of electircal logging of a few bore holes.

7.17 <u>OPERATIONS AND EQUIPMENT OF RAJASTHAN UNDERGROUND WATER BOARD:-</u>

The Rajasthan Underground Water Board undertakes the the following works:-

(1) Sinking of tubewells.

(2) Deeper Boring in existing dry wells.

(3) Deepening of wells by rock drilling and blasting.

Apart from this, occasionally the rock excavation work is also undertaken for canal cutting and broadening of highways. Sometimes the works of pumping and dewatering of wells are also undertaken.

The Board has 6 heavy dut direct rotary drilling rigs for undertaking the work of sinking of tubewells. For construction of tubewells in Rajasthan, drilling depth varies from 300 to 1,000 feet and drilling is required to be carried out in alluvium and rock formations. The tubewells are constructed with slotted tubes and are packed with gravel and developed. Other types of strainers are not used since they are not only expensive, but the discharge of the tubewell is also reduced. Besides this, there is possibility of the fine slots of the strainers getting chocked due to existence of fine sand and cutting of the rock. Therefore, the slotted tubes are pre-dominantly used in the State for better performance and life of the tubewell.

Rajasthan has a large number of dug wells, about 5 lakhs in number. Many of the dug wells are either in disused State or their yields are inadequate for the requirement of drinking and irrigation, due to either excessive pumping of the well or the chocking of the water sources. To tackle this problem, Rajasthan Underground Water Board undertakes the work of boring in open wells and deepening of wells by rock drilling and blasting, according to the condition of the formation of the wells. Normally, if soft rock or alluvium formation exists, in the bottom of the well, boring is undertaken with percussion drilling rigs available with the Board. The depth of boring varies from 50 feet to 150 feet., or more according to the condition of the strata encountered during the course of boring. On completion of the boring, slotted tubes and plain pipes are lowered and are packed around with gravel and developed.. In some wells, of course, if the formation is strong enough to stand without any danger of its being caving in of the bore hole, the pipes and slotted tubes are not inserted and only a small piece of pipe is lowered on the top to protect from accumulation of silt. This system is found to be very much effective for augmenting the water supply in the disused or partially used wells and thereby the cultivators are benefitted very much.

There are a large number of wells where the formation is very hard and, therefore, in such cases the work of deepening cess of rock drilling and blasting in hard impervious formation, a larger area of crevices and joints of percolation are not only opened, but it also increases the storage capacity of the well. This work is not possible to be undertaken by the cultivators with their indigenous tools. As such this work is undertaken by the Board for the cultivators with the help of air compressors and other pneumatic tools. With this process the drilling of anumber of holes and blasting in one well is completed within an hour's time.

The procedure adopted is to drill a number of holes depending upon the dimensions and strata at the bottom of the well by means of pneumatic rock drills. The drilled holes are later charged with high, water proff explosives and blasted by means of a dynamo condensor exploder. The debris, after the blast, is removed by the well owners,. Dewatering before the blast is also carried out by the well-owner, but if the quantity of water in the well is much, the dewatering is also done by pneumatic sump pumps for which the cultivator has to pay extra.

Ordinarily the deepening of the wells is carried out upto 10 feet depth, but in exceptional case the wells are sometimes deepened to a depth of even 50 feet or more.

For deepening of wells by rock drilling and blasting, units have been allotted for each district of the State and at present 40 such units are under operation throughout the State. The Supervisors and the Unit Incharges keep constant touch with the Panchayat Samitis and Zila Parishads authorities, who are supposed to send consolidated demand of work in their areas. In all the cases the deposits are required to be made in advance at the Head Office at Jodhpur.

The foregoing works are undertaken by the Board by charging fixed rates, calculated on the basis of "No Loss No Profit". For construction of tubewell, complete in all respects, Rs. 75 per foot, for boring with drilling rigs in open wells Rs. 38 per foot and for deepening of wells by rock drilling and blasting, Rs. 52 per foot, are charged. Subsidy to the extent of 25 per cent for the wells which are mainly used for agricultural purpose is provided. Thus, the rate or deepening the agricultural wells is 25 per cent less than the rate charged or deepening the non-agricultural wells.

7.18 <u>LOGGING OF BORE HOLES</u>:-

The term "logging" in its broad sense means recording of earth crust material along a single direction, commonly along a vertical line starting at the ground surface. The log of a bore hole may be made in written form or plotted graphically to scale. The character of a log depends on the materials of the bore hole, on the method of drilling and finally on the purpose for which bore hole is being drilled.

For rock material, besides the name of rock in each stratum and the elevations of the top and bottom of each stratum, the following information should be included in the log: (1) color, fabric, texture (such as finegrained), type of cementation (such as calcite-cement, clay-cement, etc.), weathered or not. (2) the presence of joints, fractures, or seams and whether they are open or closed or filled with other material and their dip; (3) amount of core recovered and the average lengths of the cores; (4) location of the drill hole. (5) elevation of either the ground surface or collar (top) of the casing, carefully indicating which of the two is given; (6) angle from vertical and the bearing of the hole (the compass direction in which an angle hole is driven); (7) in rotary drilling, speed of penetration of the bit (e.g., 1 ft in 10 min) and the number of rpm during this period; and

(8) unusual occurrences during the boring (e.g. loss of core).

Logs of the typical bore hills drilled in the districts of western Rajasthan by the Exploratory Tube wells organisation along with the data of other hydrogolical and aquifer performance thests are given in Appendix 7.3.

7.19 INDIRECT LOGGING METHODS:-

In the indrect methods, no samples are taken out of the bore holes,. The two methods generally used are:-

(1) Electrical logging.

(2) Radioactive logging.

Electrical Logging:- An electric log is a record of resistance of apparent resistivity and spontaneous potential of the formations penetrated by a drill hole. Resistance and resistivity are determined by sending an electric current into the well and measuring the potential drop-for resistance between the point of current emission in the hole and a point on the land surface; for apparent resistivity, between two points at a fixed separation and at some distance from the point of current emission in the drilled hole or between a point in the bore hole some distance from the point of current emission and a point at the land surface. The spontaneous potential is recorded as the difference in electric potential between the formations traversed by the hole and a point on the land surface.

The variations in the resistivity are responsive primarily to the fluid content of the formation and variations in spontaneous potential are responsible primarily to changes in the permeability of the strata. Studying these two characteristics of the formation, it is possible to make broad conclusions concerning the lithological characters of the formations, their thickness, permeability, fluid content and chemical characteristics of the contained fluid.

The equipment used in making these measurements consists of an electrode or system of electrodes which is lowered into the hole; a single or multiconductor cable spooled on a winch which raises or lowers the ~~in~~ electrode system; a measuring sheave which records the depth of the electrode system, electrical measuring instruments and a source of electromotive force on the land surface connected to the electrode system by the cable; and a plotting mechanism which records measured values on film or paper.

The Exploratory Tube wells organisation has used this method of logging in some of their holes. The electrical log of some of the bore holes are given in Appendix 7.3. The prococedure adopted by the Exploratory tube Wells Organisation is described in the following paragraphs:

Following the pilot hole drilling operations, the hole is thourongbly cleaned free from cuttings and then electrically logged using mud as the medium by filling the pilot hole with drilling mud to its brim during logging operations. The spontaneous potential and resistivity curves are recorded automatically as the electrode passes through the bore hole to the maximum depth. The electric log curves indicate the effective ~~pm~~ porosity of water bearing zones (resistivity curves) of also the quality of water (spontaneous potential curves) relative to the mud.

These, when studied in conjunction with the detailed lithological log, enable the drilling Engineer to take a decision whether the well has to be abondoned due to in sufficient and poor water bearing strata or whether it has to be converted into a productive well. A productive well is a well yielding more than 20,000 IGPH at a depression of 20'.

The resistivity kit forming an ancilliary equipment to be logging unit is also used to determine the porosity of the formation samples collected during drilling operations. These samples so examined give a rough idea of the porosity of sediments to be screened in the well. Similarly the resistivity Kit can be used for determining the chloride concentration of the formation water collected by means of a quality test on a particular zone. This also sometimes substitutes the detailed chemical examination of the sample.

Radioactive Logging:- One of the two methods of radioactivity logging, namely, neutron logging, has much in common with the neutron scattering method as used for the determination of the moisture content in soils. In the neutron logging (Fig. 7.7) an an inonization chamber filled with an inert gas is lowered into the bore hole. There is a source of neutrons at the bottom of the ionization chamber (crosshatched in the figure). This source is formed by combining beryllium nine, Be^9, with helium four, He^4. The fast neutrons leaving the chamber bombard the walls of the bore hole and, thus, release rays that ionize the gas in the ionization chamber. The electic current generated is amplified, and its voltage, which is proportional to the intensity of the rays, measured. An automatic recorder traces the log by plotting these measured values as horizontal ordinates from a vertical base line representing the hole. In a formation containing a considerable amount of fluid (such as gas, oil, or water) and thus porous, the hydrogen reduces the velcity of the neutrons so that only a small percentage of neutrons actually bombards the formation. Thus the recorded curve recedes to the left of the vertical base, line, indicating a low -ray value. Conversely, if the formation is very tight and thus contains

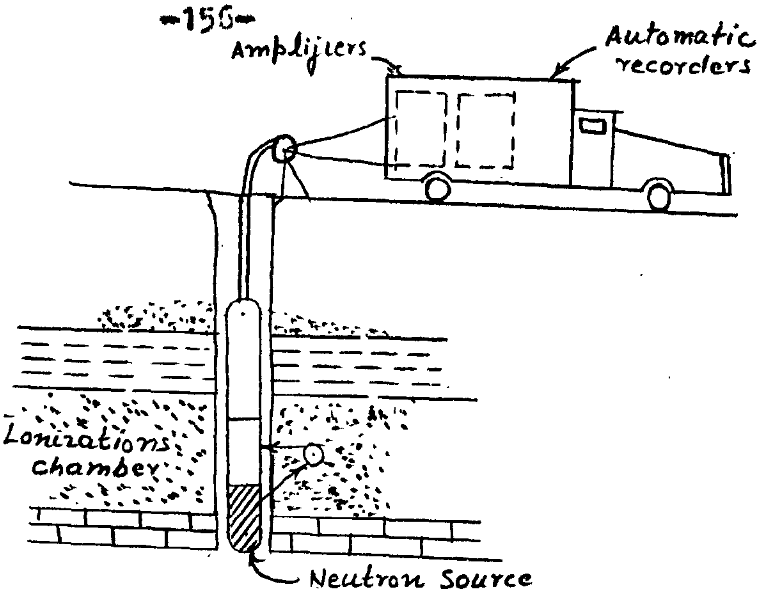


FIG. 7.7 RADIO ACTIVE LOGGING

little fluid, the neutron bombardment is almost unimpeded and the considerable number of rays emitted cause the recorded curve to extend to the right.

Besides locating saturated zones in limestones and sandstones, the neutron logs give some indication of the classifications of the formations. Sand, limestone, dolomite, anhydrite, salt, and coal are low in radio-activity, whereas, shales, bentonite, and volcanicash have the highest values of radioactivity encountered.

The other method of radioactivity logging is the γ-ray method. Both methods require special equipment which in both cases is essentially the same, although there is no source of neutrons at the bottom of the ionization chamber in the γ-ray method. All rocks contain measurable quantities of radioactive materials which release γ-rays. (These are primary γ-rays, whereas the γ-rays in the neutron logging are secondary.) When the γ-rays strike the gas in the ionization chamber, it ionizes. The subsequent phenomena are the same as in the neutron logging. It appears that the results of the γ-ray logging down to a depth of 70 ft. are affected by cosmic rays. Hence, the method is not applicable in civil engineering unless foundation data are required at depths greater than 70 ft.

7.20 Hydrological Tests on Wells:- The hydrological tests are necessary on the wells for the successful development of the well and making an estimate of the ground water resources of the region. The discharge data from the pumping tests can be mused to estimate the specific yield, transmissibility, permeability and storage co-efficient of the aquifers tapped by the well. The methods for computing these have been described in chapter VI. For the storage co-efficient, it is necessary to observe the draw down in the unpumped OBSERVATION WELLS situated around the main well. The other propeties can be calculated from observations on a single well.

7.21 Equipment for Pumping Test:- The choice of pumping equipment should be based on information obtained during the drilling and development stages and the pump should be capable of lifting a greater quantity than is required for permanent abstraction. Well characteristics can be determined rapidly by a recharge test.

The standard of measurement of water levels should be as high as possible. Both direct reading, manually-operated and self-recording, mechanically-operated instruments are used. The former include steel tapes and electrical-contact measuring instruments, which depend on the closing of an electrical circuit on contact with water, both single and double-electrode methods being used. Recently, a direct-reading steel tape, incorporating a measuring device based on an electro-chemical principle, has been developed. Continuous measurements as small as 0.01 foot can be recorded on the automatic water level recorder. The use of a pressure gauge to record depth of water level is discouraged because of the degree of accuracy of measurement of water levels required in the subsequent analysis of draw-down data.

Measurement of water levels by manually - operated measuring devices is made difficult by the presence of pumping equipment in small diameter wells. This may be overcome by lowering a measuring tube, about one inch in diameter and perforated below water level, into the well. In some wells, water cascades down the well from above the pumping water level, producing intermittent shorting between the electrodes. This can be prevented by shielding the electrodes, or by measuring inside a tube. An air-lift is used occasionally where development of a well in unconsolidated strata is necessary water level measurements should then be made inside a measuring tube.

Discharge can be measured either by weir tank, by orifice plate, by Venturi meter or by direct-reading and integrating water-meters. The weir tank has many advantages where both a direct-reading automatic weir-recorder and a hook-gauge are installed, for example, changes in yield can be instantaneously noted. The integrating water-meter is useful for recording total abstraction, but there is an unavoidable time lag in determining quantitative changes of rate. All instruments for recording discharge and for measuring water levels require careful calibration before and after the test. The discharge water should be piped to some point where recirculation cannot take place, for example, to where an impermeable bed overlies the producing aquifer. The well should be left idle for a few days before the test commences, but when this is impossible, a careful analysis of the trend of water level should be undertaken and adjustments made for incomplete recovery.

7.22 Step Draw Down and Aquifer Performance Tests- The Exploratory Tube Wells Organisation is carrying out these two tests in order to determine the specific capacity, co-efficient of transmissibility and field permeability. The organisation has been doing work more for locating production wells rather than for carrying out a systematic study of the ground water conditions. As such no observations wells were sunk around the main wells in most of the cases. It is therefore not possible to determine the Co-efficient of storage.

Only in one case of tube wells near Dabla in the Lathi series of the Jaisalmer district, water level has been recorded in observations tube wells. Based on these observations, Vijayraghwan (52) has calculated the storage co-efficient and the total ground water storage for the region. The results are described in para 9.10.

Step Draw Down Tests:- After allowing the well to recouperate to static conditions the step draw down test is conducted. The pumping is carried out after regulating the discharge at each x stage for a specified period and fluctuations of water level are measured and recorded. The object of the step draw down test is to determine the specific capacity of the well. The object of the discharge is stepped up in stages at intervals of one hour or more and measurement of the water level fluctuations and the corresponding draw-down at the end of each stage for the particular discharge are recorded. The discharge measurements are made by use of manometer and keeping an orifice plate of known diameter at the end of discharge pipe (of a particular dia - say 8" or 6") and by reference to tables.

The data obtained is used to determine the specific capacities. By plotting the discharge and draw down values on a graph paper it will be possible to determine what will be the draw down for a particular discharge and vice versa for a specified pumping period. From a step draw down test it is also possible to determine the optimum discharge for the particular well and also the critical velocity i.e. beyond which there is the tendency for disturbing of the equilibrium resulting in steep fluctuations of water levels i.e. excessive draw downs as well as sand flow, which will be detirmental to the well.

Another factor which can be determined is the discharge for 20 feet of draw down. A successful well is expected to yield about 20,000 Imperial gallons per hour for 20 feet of depression. To confirm the same as well as determine the hydrological constants an aquifer performance that is then conducted after the well is allowed to recuperate to normal static conditions.

Aquifer performance test:- One importat criterion to be considered before this test is that, the development of the well is complete and that the aquifers k have be under normal conditions. Prior to the test the well is allowed to reduperate for atleast 24 hours. After static a conditions are reached, an aquifer performance test (or final pump test) is conducted. The discharge to be maintained for this test is determined from the data of step draw down test already collected.

Prior to the aquifer performance test the static level is recorded. Thereafter pumping is carried out keeping a constant discharge for a specified period i.e. still the draw down increment per hours is not more than 0x .01 feet. The water level measurements are carried out at regular intervals (x one minute intervals, followed by 2 minutes, 5 minutes, 10 minutes, 15 minutes, 30 minutes, 60 minutes and 120 minutes in stages) using a steel tape or an electric sounder and measurements are carried out with reference to the top of the casing or any other known measuring point. The pumping may be carried even for 24 hours or more. The formation water xxxp sample is collected for chemical analysis (complete) before stoppage of pumping. After stoppage are carried out till static conditions are reached. The intervals of water level measurements during recuperation period are usually the same as for pumping period.

Analysis of hydrological data:- The data collected during the aquifer performance test corresponds to two periods namely draw dow n and recovery periods. Both the draw down and recovery data can be used according to convenience for computation of Hydrological constants like Transmissibility and permeability.

In practise, the draw down data is used for calculating the specific yield (i.e. gallons per minutes/ft draw down). The draw down observed before the close of pumping is used for claculating the same.

From the recovery data the residual draw down is obtained which is plotted against t/t' (t - time in minutes since pumping started and t' - time in minutes since pumping stopped) on a semi log paper and from the slope of the straight line plot the residual draw down over one log cycle (S) is obtained which is used in the formula $T = \frac{264\ Q}{S}$ where T - Co-efficient of transmissibility expressed in litres per day per meter Q - discharge in liters per minute and s - residual draw down over one log cycle. This is the non equibilirum formula modified by Jacab and described in details para 6.10. The permeability value is then obtained by using the formula $p = \frac{T}{\text{thickness}}$ where T - transmissibility, P - permeability expressed in litres per day per sq. meter. , and thickness - effective thickness of aquifer.

The computation of S value or storage co-efficient is done by drilling a number of observation holes around the main well or pumped well (preferrably in a straight line or radial pattern) and tapping the same aquifers as in the main well and in hydrological continuity with the same. During aquifer performance test, pumping is carried out at the main well and water level fluctuations both during pumping and recovery period (i.e. after pumping) are recorded at the main and observation wells. The draw down or recovery data as the case may be are used in computations of S and T values. There are two methods in vogue. One is the Theiss type curve solution or graphic method and the other (2) Jacobs straight line approximation method. These methods are described in details in para 6.8 to 6.10.

7.23 Quality Tests on Aquifers:- The quality tests are required to confirm the inferences independently drawn from the electrical logs, especially in the marginal cases. Besides they are essential when the pressure heads of the aquifers have to be judged individually in artesian basins. This sometimes helps to take a final decision regarding the confined aquifers to be screened in a well along with the unconfined aquifers. For this purpose, the drill stem-tests are conducted even on aquifers as deep as 900 ft. below ground level. Water is lifted through the drill pipe by means of a compressor, using generally a one inch air time. The individual zones are separated from the others by packers, either indegenous or imported. The water samples thus collected are analysed in the mobile field laboratory units to save time by taking on the spot decisions.

APPENDIX 9.1

DETAILS OF TUBE WELL DRILLED IN JALORE DIST.BY EXPLORATORY TUBE WELLS ORGANISATION

S.No.	Location	Depth Drilled in ft.	Zone Tapped	Housing Details	S.W.L in ft.	Draw-down in ft.	Yield in IGPH	QUALITY Chloride content(ppm)	 Total Dissolved salts.
1.	Saran	720	90-110 210-230 252-322 341-349 359-376 388-408 430-470 484-495	14"-90'	17.06	11.50	15,300	2720	4930
2.	Ahore	189	60-80 90-156	12"-59'	25.98	19.38	8,000	50	305
3.	Lola	136	79-120	14"-26' 12"-79'	24.12	27.09	6,400	255	940
4.	Hun	343	83-129 164-262 267-285	14"x25'6" 12"-25'6" 65'6"	25.30	25.58	6,000	300	1130
5.	Mogalwa	678	95-156 178-190 220-259	14"-95'	36.85	21.48	26,800	570	1960
6.	Rathuoga	508	300-450	14"-100'	12.45	29.95	7,300	1730	4010
7.	Degaor	259	58-99	10"-60'2"	17.52	19.52	13,020	730	1900
8.	Bhogal	140	-	ABANDONED -					
9.	Jujani	709	204-230 352-317 433-462 537-578 591-606 643-698	10"-110'	78.72	21.70	10,800	2990	4660
10.	Tikki	321	36-46 84-159	14"-83'	22.95	26.05	19,000	50	300

11. Mithri	299	90-110 112-233	12"-90'	39.90	30.70	8,950	1135	2920
12. Un.	270	35-70 85-100 116-136 181-232	12"-85'	21.46	22.77	8,000	127	495
13. Arnai	730 '	202-242 313-344 402-442 452-462 501-522 581-593	12"-144'	76.77	19.32	3,000	3900	7674
14. Toshin Ka Bouri	125'	60-68 68-125	14"-60' 12"-60'-68' 10"-68'-78'	38.00	18.00	3,000	5120	18484
15. Maspura	233	77-210	14"-77'	-	-	-	1910	5360
16. Padarli	186	40-50 55-60 65-70 75-80 101-144	14"-101'	14.35	29.75	3,950	3030	7440
17. Ghona	144		- ABANDONED -					
18. Bokna	150		- ABANDONED -		17.50	20,000	40	300
19. Sanpura	337	25-56	8"	16.20	16.00	18,000		
20. Dadhal	716	82-92	14"-70'	12.59	22.83	28,930	115	690
21. Dagora	624	70-140 179-211 230-260	14"-70'	8.60	13.04 14.90	36,550 62,040	395	17000
22. Tibra	417	70-135 211-255	14"-55'	17.15	20.66	11,200	105	900
23. Golia	409	75-135	14"-75'	17.00	23.09	29,450	120	1080
24. Koswara	527	145-160 171-184 195-205 217-240 253-270	14"-80'	14.24	23.54	21,050	180	690

25. Panchanva	191	35-45 65-145	14"-45'	17.74	39.15	2,500	160	820
26. Garh	229	80-107 123-136 106-195	14"-90'	33.93	30.82	5,350	100	570
27. Kura	255	232-266 311-353 413-454 520-583 606-725	12"-185'	87.38	55.10	11,500	320	1020
28. Surana	301	61-126	14"-61'	14.58	21.05	33,300	60	550
29. Santa	225	30-79 101-134	8"	11.85	16.10	14,000	355	1010
30. Navarkheda	282	82-140	8"	16.75	35.54	7,000	40	360
31. Elana	514	22-48 78-100 140-152	8"	18.60	20.60	16,200	375	1470
32. Dudi I	198	-	ABANDONED -					
33. Dudi II	245	-	ABANDONED -					
34. Bokra	417	19-69 313-370	8"	16.80	12.67	14,000	630	2284
35. Poharpura	255	30-40 70-80 100-140	12"-70'	-	20.78	4,950	40	350
36. Bhihnal	150	81-141	14"-80'					
37. Sovari	691	-	ABANDONED -					

APPENDIX 7.2

EXPLORATORY TUBE WELL ORGANISATION HISTORY OF TUBE WELLS

FIRST PROJECT 1956-58

S.No.	Name of site	Distt.	Depth Drilled	Range of Granuar Zone	Lithlogy sand stone	Age (Geological) Jurassic Lathi	Zones tapped	Dep-tof Pro-duct-ion well	SWL BGL	Yield IGPH	Dr-dn do-wn	Ty-pe	Re-m...
1.	Chandhan	Jaisalmer	984	106-226 292-312 350-390 410-470 548-580 592-638 700-886 844-948			106-226 292-312 350-390 410-470 548-580 592-638 700-886 844-949	995	118.37	50640	19.44	API	
2.	Jaisalmer	Jaisalmer	1000'	-	-	-do-	-	-	-	-	-	-	Abo... -cd
3.	Sunargoan	Bikaner	606	-	-	Pertiary	-	-	-	-	-	-	ade...
4.	Kolayat	Bikaner	1000	-	-	"	-	-	-	-	-	-	-to
5.	Phalana	Bikaner	741.8	-	-	"	-	-	-	-	-	-	twel of
6.	Khara	Jodhpur	496.5	-	-	"	-	-	-	-	-	-	-(
7.	Ratangarh	Churu	213	-	-	"	-	-	-	-	-	-	-(
8.	Botia	Barmer	288(777)	258-331 337-378	Sand-Stone	Creraceous Barmer	-	-	-	-	-	FBT	-(
9.	Dholia	Jaisalmer	98	-	-	Vindhyans	-	-	-	-	-	-	Poor ... lity ...
10.	Sikar	Sikar	441	74-100 190-210 266-270 280-292 374-384	Sand	Older Alluvium	73.8-94.8 190.8-208.8 269.6-287.2 366.9-384.4	338.4	84.6	3500	18.02	FYT	nity. rock ... shall... depth

Abandoned l... district

SECOND PROJECT-1959-61

11.Esonla	Barmer	833	374-394 422-464 483-583	Sand stone	Cretaceous	374-393 422-464 483-583	592	301.65	11000	16.71	APT	
12.Bhotia	"	272	376-438 445-460 520-576 620-660	"	"	247-292 301-461	492	231.60	10000	13.87	APT	
13.Shed	"	803	-	-	Tertiary	-	-	-	-	-	-	Abondoned sin no granuler s were made
14.Googa	"	921	410-430 450-470 545-565	Sand stone	"	410-430 450-470 545-565	-	267.00	-	-	DST	Abondoned Hig silvor water
15.Borioda	"	1500	601-618 702-723	-	"	601-618 702-723	-	-	-	-	"	-do-
16.Bisukalan	"	957	643-664 685-766 786-796	Sand stone	Lathi	643-664 685-766 786-796	806	212.13	1620	57.87	APT	-do- low dischar
17.Shed Gadra	"	802	620-640	"	Tertiary	-	-	-	-	-	DST	-do- Saline wate
18.Bandra	"	1007	-	-	"	-	-	-	-	-	-	-do- since no gr ler zone were met
19.Devikot	Jaisalmer	452	380-400	Sand stone	Lathi	-	-	-	-	-	PYT	-do-
20.Jaisalmer	"	1257	325-350 407-426 516-568 620-640	"	Jaisalmer	-	-	-	-	-	DST	-do-highly saline
21.Fatehgarh	"	984	331-341 432-466 558-572 609-690	"	Lathi	346-368 388-447 468-509 547-586 625-687	662	308.57	201000	10.27	APT	-
22.Dabla	"	722	564-654	"	"	555-653	658	239.40	20000	21.00	Apt	-

APPENDIX 7.3 (A)

DETAILS OF BORE HOLE AT CHAKNALI RAMPURA

Location:- The exploratory bore hole at Chaknalirampura C.M.P. is located in Ganganagar District. The bore hole is located near the south eastern side of the village pond and 565' away due N° 87°E of C.M.P. staff quarter. The ground level at bore hole is 560.62 ft. above mean sea level.

History of Drilling and Testing operations:- The pilot hole drilling at site was started on 24.1.61 and was stopped on 28.1.61 at a depth of 623'-10".

The bore hole was electrically logged on 22.3.61. Preliminary quality test were conducted on 4.3.61 and 5.3.61 on the following zones.

(1) 150 - 252

(2) 333 - 350

(3) 414 - 437

The test well was constructed to ascertain the hydrological characteristics of the aquifer.

The well was developed by compressor for 4½ hours by turbine pump for 4½ hours.

The step draw down and Aequifer performance tests were conducted on 23.11.61 and 26.11.61 respectively.

The tube well was abandoned due to highly saline quality of formation water.

Geological Data Formation Samplings:- Representative formation samples were collected at regular intervals of 10 and 15 ft. from the drill tubings. The samples were washed free of drilling mud and preserved after drying.

Lithological Logs:- The following is the lithological log prepared after an examination of the drill cuttings and observation of drilling phenomena.

Lithology	Depth range (in ft)	Thickness in ft.
Top soil, clay, ferruginous	0-18	18
Sandstone, greyish, very fine to fine grained composed of quartz & Mica.	18-252	234
Clay, dirty yellowish and grey.	252-333	81
Sandstone mostly medium grained compact and composed of subangular to angular grains of quartz.	333-350	17
Clay, dirty yellow, sticky	350-414	64
Sandstone, Coarse to very coarse and occasionally fine, grains composed of quartz.	414-472	58
Clay, sticky, dirty greyish yellow	472-597	125
Sandstone, reddish, fine to medium grained and compact.	597-624-10"	26' 10"

Electrical logging:- The exploratory bore hole at Chakandi Rampura(Daj) drilled by exploratory tube wells organisation, Government of India, was logged between 0.9.30-11.30 hours on 22.3.61 to a depth of 506 ft. below ground level by Shri N.Choudhuri, Senior Technical Assistant, Geological survey of India.

Resistivity of the drilling mud was 4.2 meter at 30° C.

A traced copy of the E.Log is being submitted as there are several base changes in the original log.

Depth.	Description
0.25	Very low resistivity impervious bed.
25- 200	Moderately resistivi bed, it may be due to the present of sandstone.
200- 325	Very low resistive impervious bed.
325-355	Moderately resistive bed. It may be due to the presence of sand stone.

355-440 Very low resistive impervious bed.

440-465 Moderately resistive bed. It may be due to the presence of sand stone.

465-595 Very low resistivity impervious bed.

The quality of water and the porosity of the moderately resistive beds cannot be determined as the S.P. log is absent.

Gravel shrouding was carried out using gravel of the grade 1/8" to ¼" . A total of 1100 cft. of gravel was added before and during development. The well was developed for 4 hours and 30 minutes by compressor and 4 hors and 30 minutes by turbine pump. A‾ ohn stone(15 H.P.)Turbine pump was installed for conducting tests.

Step draw down test:- The step draw down test was conducted on 23rd Nov.1961. All water level measurements were carried out(by means of steel tape)with reference to measuring point, top of 10 housing pipe 1' -10" above ground level.

The result are tabulated below, 6" discharge pipe with 3" Orifice was used.

Date	Hours	Depth to water in ft.b.m.p	Discharge in USGPH	Remarks
23.11.61	14.15	142.80	-	Static water level.
	14.16	-	-	Pump started
	14.23	163.70		Manometer reading 5"
	14.29	164.50	4560	
	14.33	165.00		
	14.36	166.02		
	14.39	168.50		R.P.M. 1200
	14.42	169.26		Discharge fluctuating
	14.45	168.16		-do-
	14.48	167.70		-do-
	14.51	168.53		-do-
	14.54.	167.55		-do-
	15.00	-		
	15.01			
	15.04	168.24	4740	Discharge stopped up water sample collected
	15.14	168.54	4740	Manometer reading 5½"
	15.23			Pump locking
	15.45	168.05	4740	Pump shut off

On the basis of the step draw down data the specific capacity was calculated.

Discharge U.S.G.P. PM/ft	Draw down in ft.	Specific Capacity USGP Pm/ft.
76	24.75	3.07
79	26.05	3.03

The average specific capacity come to 3 USG P.M/ft.

Aquifer performance tests- An aquifer performance test was conducted on 26.11.61 between 08.31 hrs. and 14.30 hours. Water level reading were measured with tape and fluctuations were recorded during pumping period and recovery period. The results are tabulated below.

Hydrolocial data:-

After a careful study of the lithological log the following zones were tested for quality.

Zones 414 - 437 ft b.g.l
333- 350 ft.b.g.l.
150 - 252 ft.b.g.l.

The tests were conducted by air lift method.

Zone 414 -437 ft. b.g.l:

The following assembly was lowered

4" Drill pipes		0 - 394 ft.
4"	slotted pipe	394 -414 ft.
1"	air line - 10 length.S	

Compressor started - 13..15 hours on 4 March 1951.

Compressor stopped 15.05 hrs. -do-

A sample of formation water was collected at the end of the hour.

Zone 333-350 ft. b.g.l.

The following assembly was lowered

Drill pipe		0 - 322 ft.
4"	slotted pipe	322 . 342 ft.

10 lengths of 1" dia air line.

Compressor was ran for two hours at the end of which a sample of formation water was collected.

Zone 150-252 ft. b.g.l.

The following assembly was lowered

Drill pipes	0.- 207 ft.
4" dia slotted pipe	207 - 227 ft.
1" dia air line 10 longhts.	"
Compressor started -	00.00 hrs. on 5th March 1961
Compressor stopped -	03.15 hrs. -do-

A sample of formation water was collected at the end of the hours for partial chemical analysis.

In order to determine the hydrological characteristics of the first aquifer a test well was constructed after reaming the pilot hole to 27½ diameter to a depth of 262 ft. b.g.l. The following test well assembly was lowered.

Above ground level	- 10" dia blank	1' -10"
Below " "	- 10" dia "	0-170' -0"
-do-	- 10" dia slotted (1/16) slot	170-250'-7"
-do-	- 10" dia blank with	plug 250'-7"-255'-7"

Cement plugging was done between 2.59'-7" and 26' 7" below the assembly to seal off the lower zones yielding water of inferior quality.

Date	Hour	Depth to water in ft.	discharge USGH Ph	Remarks.
26.11.61	0.8.25	142.00.	-	Static water level
	0.8.31	-	-	Pump started.
	08.40	163.40	4560	Manometer reading 5"
	08.44	165.08	-	-

08.47	163.79	4560	
08.51	163.60		
08.54	163.30		
08.57	163.63		
09.01	162.80		
09.04	162.30		
09.07	162.59		
09.11	163.20		
09.14	162.80		
09.17	172.80		
09.20	163.09		
09.23	164.10		
09.26	163.80		
09.30	163.77		
09.35	164.03		Water sample collected
09.40	163.36		
09.45	163.21		
09.50	163.48		
09.55	163.54		
10.00	163.39		
10.05			Discharge adju sted.
...	...	...	...
10.10	163.47	4560	
10.15	4		Discharge adjusted.
10.20	164.88	4560	
10.30	164.75		
10.45	164.76		
11.00	165.47		
11.15	164.93		

	11.40		
	12.00	165.36	
	12.30	164.42	
	13.30	163.91	
	14.30	164.56	
	14.30		
Recovery data			Pump shut off
	14.32	137.60	
	1435	143.60	
	14.38	143.70	
	14.41	143.58	
	14.44	143.56	
	14.46	103.51	
	14.49	143.47	
	14.51	143.46	
	14.53	143.49	
	14.55	143.47	
	14.57	143.44	
	14.54	143.57	
	15.03	143.33	
	15.04	143.56	
20.11.61	15.07	143.35	
	15.10	143.57	
	15.12	143.49	
	15.13	143.43	
	15.15	143.38	
	15.17	143.48	
	15.19	143.38	
	15.21	143.46	
	15.23	143.43	

	15.25	143.40
	15.28	143.39
	15.30	143.34
	15.35	143.28
	15.40	143.31
	15.45	143.32
	15.50	143.31
	16.00	143.24
	16.10	143.24
	16.20	143.31
	16.30	143.28
	16.45	143.34
	17.00	143.39
	17.15	143.29
	17.30	143.37
	18.00	143.26
	18.30	143.2[illegible]
	19.00	143.22
	19.30	143.19
	20.00	143.18
	22.00	143.17
	24.00	143.07
27.11.61	04.00	143.02
	08.00	142.91
	12.00	142.88
	16.00	142.85
	20.00	142.83
28.11.61	04.00	142.82
	08.00	142.81
	10.00	142.80

Recuperation readings discontinued.

Computation of transmissibility:- The T Value could not be determined as the residual draw down value do not confirm to a straight line on plotting on semi log sheet against t/t'.

Chemical Data

From the bore hole at chaknali Rampura three formation water samples were collected for partial chemical analysis during preliminary tests. Besides one sample of formation water was collected for partial analysis during S.D.T. The results are tabulated below

S.No.	Particulars.	Samples from Zone		
		240-252'	335-350'	424.457'
1.	Chlorides in P.P.M	700	909	4100
2.	Carbonates in P.P.M	20	-	-
3.	Bicarbonates. "	316	252	170
4.	Sulphates. "	88	80	320
5.	Temp. Hardness."	270	160	170
6.	Perm.Hardness. "	-	-	830
7.	Total dissolved solids. "	1530	725	8170
8.	P.H.	8.2	7.4	7.8

APPENDIX-7.3 (B)

DETAILS OF BORE HOLE AT BHAINSWARA

Location :- The bore hole is located in Jalore District Rajasthan and is situated towards the north of Jawai river and due 45°N of Bhainswara Village.

History of Operation:- The pilot hole drilling at UN was started on 28-1-1965 and stopped at a depth of 82.30 metres below ground level on the strength of the formation cuttings. The reaming was started on 31-1-65 and completion 1.2.65 upto a depth of 73.63 metres below ground level.

The production well assembly was lowered on 2nd February, 1965 and development of the well was carried out from 3rd Feb. to 5th February, 1965.

Geologicalxx log

Formation sampling:- Drilling cut out "T pipe were allowed to settledown in the simple catchers and representative samples were collected at regular intervals of 3.05 metres, 3.35 metres and 3.96 metres or whenever a change of formation offered. The samples were washed, dried up and collected in properly labelled sample box.

Lithological Log:- The Lithological Log based on the examination of the dril cutting is given below:-

Lithology	Depth range in metres.	Thick in metres.
Top soil, grey with sand coarse grained	0-3.05	3.05
Gravel with sand, composing of quartz pink and white with granite pieces.	3.05-6.1	3.05
Gravel with little sand compositing pieces of gneisses quartz rhyolite and granite.	6.1-10.67	4.57
...nded to ...	10.67-14.02	3.35

1.	2.	3.
Sand, coarse grained with pink, white & grey quartz .	17.37-30.78	13.41
Sand, same as above with white clay, sticky towards top and bottom, middle sections more sandy.	30.78-40.84	10.06
Sand, clayey, sticky white	40.84-50.90	10.06
Sand coarsed grained, sub-angular ~~grains~~ grains of quartz equi-angular, clayey towards top and with gatherred granite pieces.	50.90-60.96	10.06
Sand with gathered granite	60.96-71.02	10.06
Granite gathered with pink felspar & white quartz.	71.02-82.3	11.28

Hydrological Data:- The bore hole was converted into a production well and the following Assembly was lowered after reaming the bore hole upto a depth of 71.63 metres with 349/370 mm R.R. bit.

After reaming of the well, the following assembly was lowered:-

305 mm dia Housing	0.34 metres above ground level.
" " "	0 to 10.36 metres Below " "
" " slotted pipe	10.36 to 21.17 metres " " "
" " Housing	21.17 to 25.46 " " " "
305 X 203 mm dia Housing	25.46 to 25.77 " " " "
203 mm dia slotted pipe	25.77 to 30.34 " " " "
" " " Blank pipe	30.34 to 35.52 " " " "
" " " Slotted pipe	35.52 to 41.05 " " " "
" " " Blank Pipe	41.05 to 51.71 " " " "
" " " Slotted pipe	51.71 to 67.23 " " " "
" " " Bail Plug	67.23 to 68.45 " " " "

The Assembly was throughly washed with clean water. The well was developed by turbine pump.

Step Draw Down Test:- A step drawdown test was conducted on 12th February, 1965 bitween T.O. 30 hrs. to 13.9 hrs. An eight inch diameter pipe (discharge) and 102 mm dia orifice plabe were used for 203 mm measuring the discharge. All 102 mm measurements are with reference to a point 0.64 metres above ground level.

Summarised results of the step drawdown test are tebulated below:-

Stage	Discharge G.P.M.	Drawdown in metres.	Sp.capacity G.P.M/M.	R.P.M.
I	528.95 LPM	5.25 metre	101 LPM/M	1000
II	681.31 LPM	8.14 metre	84 " "	1050
III	828.99 LPM	10.95 metres	76 " "	1200

Aquifer Performance test:- An aquirfer performance was conducted on 13th February, 1965 betwwen ~~ax~~09.58 hrs. to 9.50 hrs. (14th February, 1965) keeping a constant discharge of 606 LPM. A 203 mm diametre with 102 mm pipe orifice plate was used for measuring the discharge while electric sounder was used for measuring water level. All measurements are with respect to a point 0.64 metres above ground letel.

Summarised result of the aquifer performance test is as follows:-

Static water level	7.19 metres b.m.p.
Draw down	6.94 metres (22.8 ft)
Discharge	606 LPM (8000 IGPH)
Duration of pumping	7.20 minits
Co-efficient of transmittibility	9,16,800 LPM
Field permeability	25,080 LPM/metres.

C H A P T E R - VIII

QUALITY OF GROUND WATER IN WESTERN RAJASTHAN

8.1 IMPORTANCE OF QUALITY OF WATER

The quality of water, especially the concentrations of the different salts present in water is very important to determine whether it would be suitable for irrigation and domestic and industrial use. The fertility of soil depends to a largexxx extent on the concentration of salt in irrigation water. Certain crops are more sensitive to salinity in Arrigation water. Suitable methods for leaching of salts from the fields may be necessary where irrigation water with a high salt content is applied over a prolonged period. Water for domestic use should be colourless, free from objectionable odours and xxxxx tastes and should not xxxxxx contain excessive salts and other poisonous metals. Water for industrial use should be such that it does not cause foaming or scaling of boilers.

8.2 CHEMICAL COMPOSITION OF GROUND WATER

The composition of ground water ranges in salinity from pure rain water to high mineralised wasters such as connate brines. It is an aqueous solution, generally composed of bicarbonates, sulphates and chlorides of the alkali earths and alkali metals. Siliceous ground waters do occur but are not common.

Waters of atmospheric origin (meteoric waters) contain carbon dioxide and small amounts of dissolved substances derived from the atmosphere. In percolating through the soil, they gather soluble constituents, both organic, and inorganic, and additional carbon dioxide from humus and otherorganic matter. Ground water charged with carbon dioxide is powerful weathering agent. It reacts with certain minerals, forming new compounds such as carbonates, bicarbonates, sulphates of sodium, potassium, calcium and magnesium, soluble alkali silicates and free silica in true solution or in colloidal form. Aluminium, iron and silica remain mostly in the insoluble residue.The rates of decomposition of the minerals depend on their physical and chemical properties. Sodium and potassium are leached out rapidly, calcium and magnesium comparatively slower.

A second group of ground waters are cannate waters containning substances which were present in solution at the time of deposition of the sediments (e.g.Houston artesian basin and some other coastal sedimentary areas in U.S.A.)

Thirdly, physical and chemical changes can also change the composition of ground waters percolating through the soils and rocks. Concentration of dissolved solids in ground waters may take place by evaporation and transpiration. Base exchange, adsorption, oxidation of suplhides, reduction of sulphates and mixing with cannate waters can also change their quality. Base exchange softens ground water when it comes in contact with materials releasing sodium in exchange for calcium and magnesium in the water. The bases and acids which result from the hydrolysis of the salts of weak acides and strong bases or viceversa are readily adsorbed without substitution. Consequently, the bases formed from alkali and alkali-earth carbonates, silicates and and phosphates are adsorbed to form silicates, thereby increasing considerably the concentration of acid radicals. On the other hand, the silicate and phosphate anions of the alkali silicates and phosphates are partly removed by soils, chiefly by reactions with $Fe(OH)_3$ and $Al(OH)_3$, which lead to the formation of insoluble compounds. The reduction of sulphate in ground waters is attributed to the presence of organic matter and sulphate-reducing bacteria.

It follows from the above discussion that the following factors influence relative ground water salinity:-

(1) The net balance between annual evaporation, precipitation and run off.

(2) The rate of local rock weathering or solution with resultant formation in the soil of water soluble salts from the decomposition products.

(3) The rate at which salts are transported into the region by streams, winds and rains from outside sources and deposited in soil.

(4) The permeability of and hydraulic gradient in the water bearing rocks.

(5) The balance between the rate of ground water circulation and the rate of salt accumulation in the ground water body from infiltrating water.

8.3 METHODS OF ANALYSIS

In cases of partial analysis, the water samples collected from representative wells and bore holes are analysed for determining pH, conductivity or specific conductance, hardness and contents of carbonates, bicarbonates, chlorides, calcium, magnesium, sodium and potassium. In cases of detailed analysis, besides the above, the total dissolved salts are determined and the contents of silica, boron and nitrate are also determined.

The methods generally used for determining these properties are described below:-

The pH value of the water samples are determined by pH metre which gives direct reading using C.G.C.R.I's Glass electrodes.

The specific conductance is determined with the help of constant cell of known resistivity. It also gives the direct reading on separate panel in mhos (reciprocal of resistance) which is converted for convenience to micro-mhos per centimetre.

The sodium and potassium contents of water samples are determined separately using Flame Photometer. The direct Galvanometer readings are recorded for different water samples for sodium and Potassium separately and the values are obtained from ppm. readings graph, which has already been prepared with standard sodium and potassium solutions. In case if the galvanospot is not recorded in the scale, dilution was made with its due consideration if calculations.

The calcium and magnesium are determined simultaneously using standared solution of EDTA - (Sodium Salt) and Erichrome-Black-T an an indicator. The calcium content is, then, separately determined using EDTA (Sodium Salt) and muroxide as an indicator. The difference of above titrations indicated the content of Magnesium.

EDTA (Sodium Salt) is previously standardised calcium chloride $\frac{N}{100}$ solution separately using Erichromo Black T and Muroxide and indicators separately.

Standard solution of Silver nitrate is used to determine soluble chloride contents of water samples using Potassium Chromate as an indicator.

The sulphate content is determined volumetrically using EDTS (Sodium Salt) and Erichrome Black- T as an indicator. The procedure is carried out simultaneously but separately along with titration from the determination of calcium and magnesium. Excess of measured quantity of Barium Chloride solution is added and remaining unutilised Barium chloride was determined using the same solution of EDTA. Measured quantity of Magnesium chloride was added just before the end point to refine the change of colour at the point

Standared solution of sulphoric acid was used for the determination of carbonate and Bicarbonate contents of water samples using Phenolphatholine and Methyl Orange as indicators simultaneously but one after the other.

Total dissolved solids is determined from the residue obtained by evaporating a known quantity of water and dehydrating at 180° C for one hour.

Silica content is determined from the total solids by moistening with HCl and dehydration and treatment of insoluble residue with HF.

Boron is estimated calorimetrically with alchoholic solution of curcumion and oxalic acid.

Nitrate content is estimated by phenol- disulphonic acid method.

8.4 INTERPRETATION OF WATER ANALYSIS RESULTS

Interpretation of chemical analysis data of water is necessary to assess the suitability of water for any particular purpose. Water for irrigation purposes should satisfy the needs of the soil and the crops. For domestic purposes, the quality should meet the physiological needs. For generation of power, the quality of water should not allow wastage of heat by formation of scales and corrosion of metal parts. The significance of the different ingredients in water furnishes the basis for studying the quality of water.

Classification of Water According to U.S.Salinity Laboratory:- In 1954, the U.S. salinity laboratory proposed a classification incorporating the important features of the earlier work on the subject along with the further advances based on the effects of concentration of total salts, sodium, boron and carbonate and bicarbonate in soils by irrigation waters. They have been termed as:

(a) Salinity hazard.

(b) Sodium hazard.

(c) Boron hazard.

(d) Bicarbonate hazard.

Water for irrigation has been rated as good, medium and bad on the basis of specifications indicated below:-

(a) Salinity Hazard:- It depends on the total salt or conductivity rating. The electrical conductivity of the solution depends on the total concentration of salts in the solution.

Waters have been classified under the following categories according to the salt concentration or electrical conductivity:-

Class.	Grade.
Good	Nos. 1-0-250 EC X 10^6 = 0-2.5 m.e./l.
	2-250-750EC X 10^6= 2.5-7.5 m.e./l.
Medium	3-750-2250-EC X 10^6=7.5-22.5 m.e./l.
Bad	4-2250-4000 EC X 10^6= 22.5-40.0 m.e./l
Very bad	5-Over 4000 EC x 10^6= Over 40.0 m.e./l

(EC=Electrical conductivity.

me/l = milli-equivalent/litre).

(b) Sodium Hazard:- The use of water of high salinity for irrigation purposes ultimately deteriorates the soils. This deterioration is particularly dependent upon the proportion of sodium ions to the total cations in water. This factor is expressed by the following ratios, defined by the equations

$$SSP = \frac{\text{Soluble Sodium Concentration (meq per litre) X 100}}{\text{Total Cation concentration (meq per litre)}}$$

SAR = Sodium

$$SAR = \frac{Sodium}{\left(\frac{Calcium + Magnesium}{2}\right)^{\frac{1}{2}}}$$

$$ESP = \frac{\text{Exchangeable Sodium (meq per 100 gm soil) X100}}{\text{Cation Exchange Capacity (meq/100 gm soil)}}$$

$$= \frac{100(-0.0126+0.01475\ SAR)}{1+(-0.0126+0.01475\ SAR)}$$

Where SSP is soluble Sodium Percentage, SAR is Sodium Adsorption Ratio and ESP is Exchangeable Sodium Percentage.

The ESP ratio suggests the fate of the soil when treated with water of a specific nature. If the soil is irrigated with water that gives rise to an ESP ratio higher than 15, the soil degenerated into a saline-alkali soil. Extensive application of gypsum may counteract the high ESP of the soil. The dosage of gypsum required for preventing deterioration in different types of soils and under different conditions of land use has to be worked out.

The SAR is related to the relative activity of sodium ions in the exchange reaction with soil when it is continuously leached with water.

Waters have been classified under the following categories according to SAR:-

Quality		
Good value	. .	Upto 10 - low sodium water.
Medium.	. .	Between 10 to 18 - medium quality water.
Bad	. .	Between 18 to 26 - high sodium water.
Very Bad	. .	Above 26 - very high sodium water.

(c) Boron hazard:- Small amounts of boron in irrigation water may prove injurious to some crops. The degree of injury depends on the selective absorption capacity of the different types of plants. Quality rating of water to boron has been developed by Scofield (1936) and modified by Wilcox (1948). The relation between boron and the suitability of water for irrigation is shown below:-

Permissible limits of several classes of irrigation water boron.

Classes of Water. (Rating Grade).	Sensitive crops (p.p.m)	Semi-tolerant crops (p.p.m)	Tolerant crops (p.p.m.)
Excellent . .	below 0.33	below 0.67	below 1.00
Good . .	0.33 to 0.67	0.67 to 1.33	1.00 to 2.00
Permissible . .	0.67 to 1.00	1.33 to 2.00	2.00 to 3.00

Taken from Wilcox (1948).

(d) Bicarbonate hazard:- Bicarbonate concentration of water has been suggested as an additional criterion for irrigation water. If the water contains a high concentration of bicarbonate ions, as the soil solution becomes more concentrated, there is a tendency for calcium and magnesium to be precipitated as carbonates. As a consequence, relative proportion of sodium increases and gets fixed in the soil. The convenient way of expressing value of the water in terms of the "Residual Sodium Carbonate" concentration is as follows:-

Residual sodium Carbonate = $(CO_2+HCO_3)-(Ca+Mg)$ where the ionic constituents are expressed as milli-equivalents per litre.

Water have been rated on the value obtained as follows:

Rating	Water containing
Good	Less than 1.25 m.e./ℓ., safe for irrigation purpose.
Medium	between 1.25-2.5 m.e./ℓ., marginal for irrigation purpose.

Bad	more than 2.5 m.e./ℓ.	not suitable for irrigation purpose.

Classification of Water According to Enderson:- In 1955 Enderson in his book 'water well handbook' has given a classification based on the total soluble salts (T.S.S.) in water. Water having more the 7000 ppm. of soluble salt has considered unfit for irrigation. Below this value of TSS, water was divided into five classes as under below:-

S.No.	Class	Range of T.S.S. in ppm.
1.	Class I (C_1)	Upto 180
2.	Class II (C_2)	180 to 500
3.	Class III (C_3)	500 to 1500
4.	Class IV (C_4)	1500 to 3200
5.	Class V (C_5)	3200 to 7000

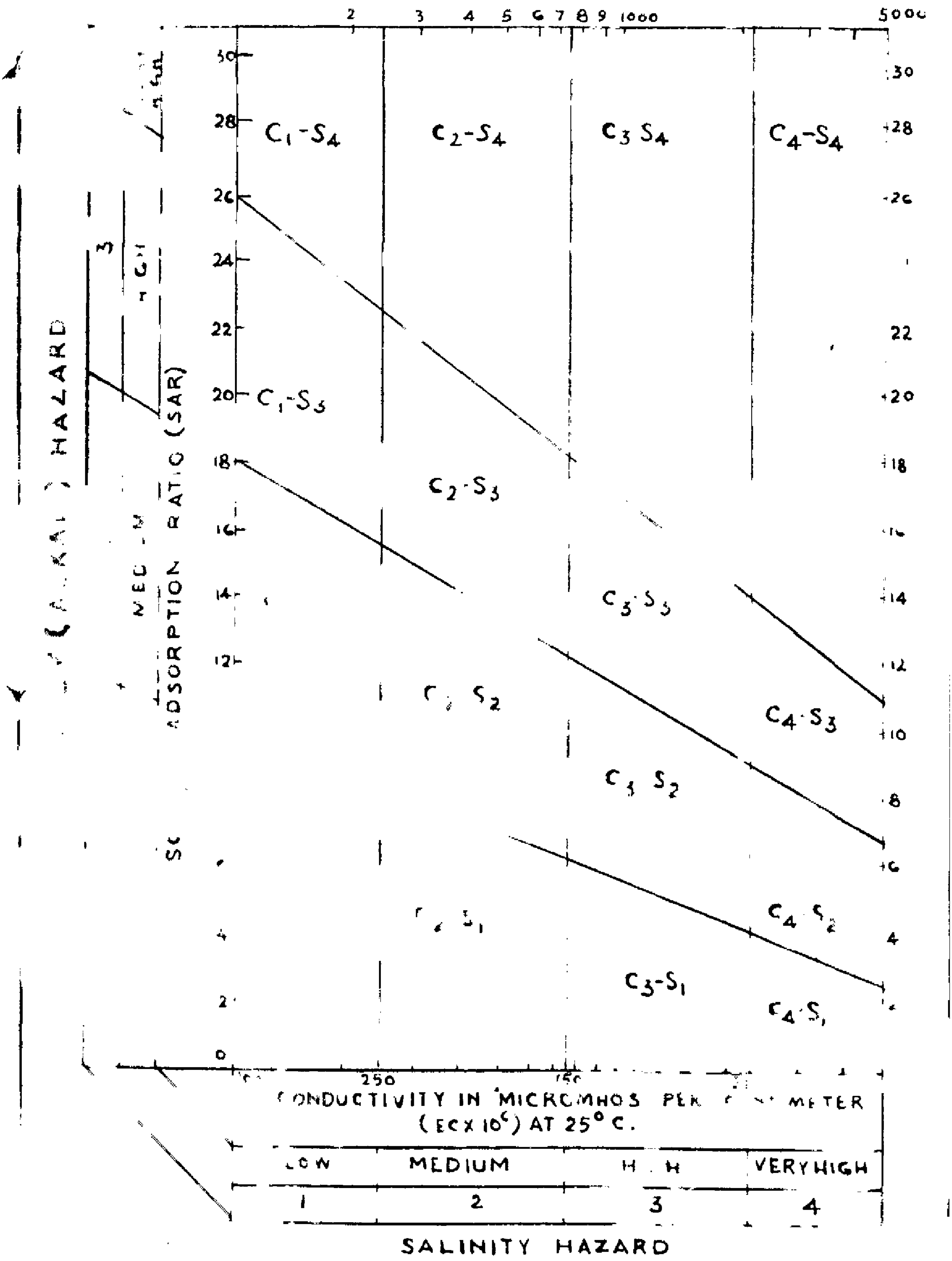
Classification of water due to Richards:- This classification is based on the SAR and the conductivity of the solution. It is further based on the assumption that the water will be used under average conditions of soil texture, drainage, infilteration rate, quantity of water used, salt tolerance of crops and climate.

The classification is shown diagrammatically in figure. 8.1 The interpretation of this diagram is as under:-

Low Salinity Water (C_1) :- This can be used for irrigation with most of the crops and soils, with little likelihood of developing the soil salinity.

Medium Salinity Water(C_2):- This can be used for plants having moderate salt tolerance with special practices for salinity control and if moderate amount of leaching occurs.

High Salinity Water (C_3) :- This cannot be used on soil with restricted drainage. Special management for salinity control even



CLASSIFICATION OF WATER ACCORDING TO RICHARDS

PLATE 8·1

with adequate drainage may be required and plants with good salt tolerance should be selected.

Very High Salinity Water (C_4):- Not suitable for irrigation unless very special circumstances of soil being permeable, drainage being adequate and irrigation water is applied in excess to provide considerable leaching and very salt tolerant crops are selected.

The classification of water with respect to SAR is primarily based on the effect of exchangeable sodium on the physical conditions of the soil.

Low Sodium Water (S_1):- This can be used for irrigation on almost all soils with least danger of development of harmful levels of exchangeable sodium.

Medium Sodium Water(S_2):- This will present an appreciable sodium hazard in fine textured soils having high cation- exchange capacity especially under low leaching capacity, unless gypsum is added to soil. This water can be used on coarse textured or organic soils with good permeability.

High Sodium Water(S_3) :- It may produce harmful levels of exchangeable sodium in most soils and will require special soil management good drainage, high leaching and organic matter additions. Gypsiferous soils may not develop Harmful levels of exchangeable sodium for such waters.

Very High Sodium Water (S_4) :- This water is generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity, where the solution of calcium from the soils or use of gypsum or other amendment may make the use of these waters feasible.

Classification According to Kanwar:- Kanwar has classified water according to salinity and sodium hazard in the form of a triangular diagram which is reproduced as figur 8.2. The water is devided in four classes as follows:-

Class I - Water suitable for irrigation even for sensitive crops.

Class II- Water suitable for irrigation for tolerant crops.

Class III-Water suitable for irrigation for semi-tolerant crops.

Class IV -Water unsuitable for irrigation.

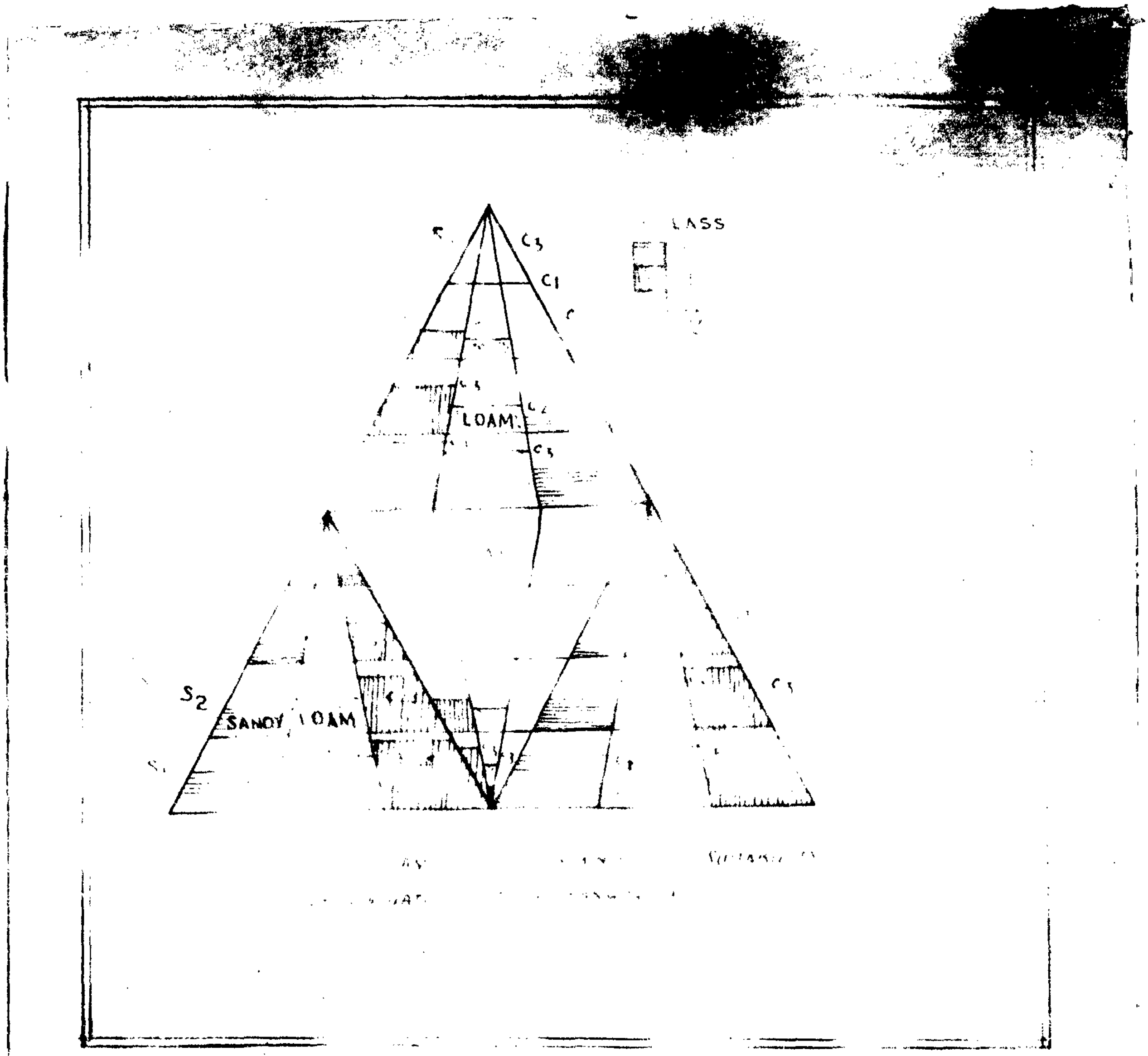


PLATE 8·2

8.4 GENERAL CHEMICAL CHARACTER OF WATER IN WESTERN RAJASTHAN

In general, the ground water of the region is characterised by moderate to high salinity, which is a common phenomenon in the arid and semi-arid regions of the world. Common salt and sodium sulphate are the usual constituents of ground water in this region. This salt is brought to the ground water by leaching from the soils by infiltrating waters which percolate down to the zone of saturation.

The problem of salinity of the surface and ground water has been discussed in details by Auden (2). According to him much of the rainfall penetrates into the dunes and sand plains and fails to be removed as run-off. The exceptionally low humidity, high temperatures and strong evaporation in Western Rajasthan result in the concentration of dissolved salts and the widespread precipition thereof as pan and other deposits. Abundant deposits of gypsum occur as pans only a few feet below the sands of north East Jodhpur and Bikaner. Salt lakes also occur, e.g. at Pachpadra, Sambhar and Didwana.

The origin of these salt deposits, which include the carbonate, bicarbonate and sulphate of sodium, in addition to the usual chloride, is not full understood. La Touche has given the following explanations:-

> The rain water flowing from the hills is evaporated long before it reaches the sea, owing to the porous nature of the sand and the dryness of the atmosphere, and the salt it contains, which would under ordinary conditions be carried by river into the sea, and help swell the amount of salt already there, is deposited amongst the sand grains, and in process of time has thoroughly impregnated the soil with salt.

Holland and Christie found it difficult to regard this mode of origin as satisfactory, remarking that there are neither inflowing large revers, nor traces of ancient rock salt, nor saline springs, and that the catchment areas and granites, quartsitites and schists, are not likely to yield large concentrations of salt during the short periods of scanty precipitation. They carried out experiments in 1908 to determine the quantity of salt carried by the prevailing hot-weather south-west and SSW winds, which indicated that over a front of 300 Km (186 miles) about 130,000 tons of salt could be transported into Rajasthan each hot weather from the Runn of Cutch (1909). They concluded that wind alone is sufficient to account for the large accumulations of salt in the region, and considered that the low-lying Runn of Cutch, which is subject to periodical tidal inundation and has extensive salt flats, would be the provenance of the Rajasthan salt.

Godbole (20) considers this theory of salt deposit as improbable because of the following facts:-

(1) If the salt is wind blown, we cannot account for the fact that some neighbouring lakes have different salt content. Some lakes in the reason even contain fresh water.

(2) If the salt is wind bolown, we should have appriciable deposits of salt dust on the western slopes of Aravallis since the winds are not gales bolowing all the 24 hours of the day and hence if the salt travels as far as Sambhar lake, a part of it must definitely be deposited in the way.

According to Godbole, all these salt deposits are the result of precipitation of dryed up lagoons containing sea water having large quantities of salts. As already mentioned in para 2.2, during the Jurassic period, an arm of sea had extended in western Rajasthan from south-west.

How-ever, so far no theory has been conclusively proved. Accepting that wind-blown salt, precipitated salt and also solutions carried by river, are factors in explaining the origin of the Rajasthan salt, it is clear that conditions for concentration will be optimum in area of internal and interrupted drainage, where there is a strong in draught of hot dry winds.

As already stated in Chapter-I, the climate of Western Rajasthan is subject to great variations with alternating wet and dry cycles and with extremes of range in rainfall. This factor is very important in determining the salinity of ground water and its annual variation depending of the climate cycles. The average annual evaporation in the region is generally much higher than the average annual precipitation, Thus in years of normal or below normal rainfall, infilteration may be small or negligible, evaporation is higher and surface run off is low, Consequently those soluble salts which have been formed by the weathering of local rock or which have been transported in the region by by streams, winds and rains tend to a accumulate in the soil. In subsequent years of higher rainfall, a part of the accumulated salts in the soil may be dissolved and carried out of the region by surface run off. How-ever, at the same time considerable amounts of salts are leached from the soil by infilterating waters which percolate down into the zone of saturation.

The salinity of the ground water in the region also varies annually depending on the climatic cycle. Waters which may be serviceable during wet cycles, when there is more flushing of the water sources, and greater increments are added to isolated masses of ground water, away from the drainage lines, may become too saline from safe use in irrigation during the alternating dry cycle.

A detailed systematic study of the periodic variations in salinity of ground water in the region has not been taken up so far. Taylor (46) made a study for the Pali region and the result are discussed in the following paragraphs.

8.5 DISCUSSION OF THE INVESTIGATION FOR QUALITY OF WATER CARRIED OUT IN THE REGION:

In his introductory report on the ground water resources of Western Rajasthan, Audon (2) has given the results of partial chemical analysisof water from Western Jodhpur and Bikaner area. These are reproduced as appendix 8.5 & 8.6.

Taylor (46) carried out partial chemical analysis of water samples taken out from 370 representative wells in Pali region during November 1951 to April 1952. In the monsoon season of 1952, the rainfall was considerably above normal.The effect of infiltration from this rainfallon the chemical quality of ground water were also studied. The summarised result of these studies are reproduced as Appendix 8.1.

Basu (5) during 1955-56 analysed water samples from exploratory test wells and tube wells in connection with the investigation for ground water resources of Western Rajasthan. They also analysed water samples from a few open wells. The results of these tests are reproduced as Appendix 8.2.

The Under Ground Water Board collected samples from representative wells in Jalore region in the period from November, 1955 to January, 1966. These samples were analysed for partial chemical analysis in their laboratory situated at Jodhpur. The abstract of the results, showing the average value of different ionic constituents along with their range are reproduced in Appendix 8.3.

Chatterji and Mondal (9) carried out a systematic survey for quality of ground water in Siwana development block of Barmer District in 1963. They classified the region of the block according to the classification of ground water given by Enderson. In Siwana region, high saline water containing upto 10,000 ppm. total dessolved salts are used for irrigation and water containing upto 12000 p.p.m. are used for live stock drinking. On this basis they have added two more classes C_6 & C_7 in their classification. The result of the analysis is reproduced as Appendix 8.4.

A brief description of the quality of ground water based on the information collected from the above sources is given below.

In the Siwana development block, about 35.8% of the total area of the block is suitable for ground water exploitation. Of this nearly 75% has waters of C_2 to C_4 type according to Enderson classification. The well water at Botia near Barmer shows that the chlorides and the total dissolved salts content are 88.5 and 2200 p.p.m.

According to Taylor, the following are the safe limits for the quality of water to be used in irrigation:-

Chlorides	355 p.p.m.
Sulphates	480 p.p.m.
Total solids	2000 p.p.m.

Although the quality of water in Barmer is not suitable according to these or other standards acceptable normally in other areas, the desert conditions must be considered while considering the acceptibility of the water. As pointed out earlier, in Siwana development block in Barmer, waters having total soluble salts upto 10,000 p.p.m. has been used for irrigation.

The quality of water around Jaisalmer is tolerable. The quality of water near Chandan is fairly good.

In Jalore region, the character of ground water in the different water bearing zones differs greately in total concentration of dissolved salts and in relative abundance of various constituents. The high salinity of younger and older Alluvium , as seen in Appendix 8.3, is due to efflorescences of salts particularly located in the northern part of Jalore District and along river Khari. Otherwise, in general, ground water from alluvial formations indicates low to medium mineral concentration. Ground water is comparatively less saline along stream courses, indicating that soluble salts accummulated during the rock weathering are being washed off by the water recharging these basings. Ground water away from these stream courses shows a gradual tendency of increasing salinity.

In Pali region there is a moderate to high concentration of dissolved salts. Cholorides probably largely as, sodium chloride, - is the most common and abundant of the anion constituents present. On an average the chloride concentration exceeds 1000 parts per million so that most well waters of the region have a perceptibly to strongly salty taste. Carbonates are generally absent or are present only as traces in most of the well waters of the region. Bicarnonates, however, are on the average the second most abundant of the anionic constituents. They are generally present in concentration ranging between about 400 and 900 parts per million. Sulphates which are the third most abundant of the anions, are generally present in slightly less concentration than bicarbonates. The pH values of most of the well waters lie between limits of 7.3 and 8.3 indicating that slight alkalinity generally prevails in the ground water.

In order to study the seasonal changes in salinity of Pali region, in November 1952 some 65 of the wells which were sampled e earlier in November, 1951 to April 1952 were sampled again. The comparative analytical data on these wells, given in Appendix 8.1 is summarised in the table given below:-

Summary of changes in bicarbonate, chloride and sulphate content between November 1951- April 1952 and November 1952 in 65 wells of the Pali Region.

	Bicarbonate (HCO_3)	Chloride (Cl)	Sulphate (SO_4)
Average net change; plus (+) is increase. xxxxxxx, minus(-)is decrease, in parts per million.	+13	-168	-174
No.of wells showing increase ..	37	29	15
No.of wells shoeing xxxxxxxx decrease	28	36	39
No. of wells showing no change ..	0	0	11
Maximum increase in ppm ..	658	2,114	630
Average increase, in ppm ..	125	252	123
Maximum decrease in ppm. ..	667	2,090	2,000
Minimum decrease in ppm ..	2	2	20
Average dicrease in ppm ..	137	507	289

The precipitation from the monsoon in 1952 was considerably above normal and the changes in mineral concentration of ground water are due to the effects of leaching of soil and infiltoration of this rain water.

In a few instances such as in as in wells 1 and 2 infiltration brought above increases amounting to more than 2000 parts e per million in the total salinity of the ground water and in many sampled wells increases of several hundred parts per million were registered. On the other hand salinity decreases of comparable magnitude were measured in slightly more than half of the wells sampled.

These differences fromplace to place in the Pāli region emphasise the local nature of changes in ionic concentration of dissolved solids in the ground water caused by infiltration. Where salts were available in the soil zone for dissolution by infiltrating water, increases in the local salinity resulted but where such salts were not available, the infiltrating water tended to dilute the ground water and to decrease the salinity. The table of Appendix-8.4 also indicates that the net increases or discreases in bicarbonates, chlorides and sulphates are not uniform from well to well. In many cases increases in one anion are marked by decreases in the other two anions in the same sampled well and vice versa. For example well 19 registered a decrease of 667 p.p.m. in bicarbonates while showing increases of 276 p.p.m. in chlorides and 630 p.p.m. in sulphates. An increase of 175 p.p.m. in bicarbonates was measured in well 162 while at the same time the chlorides and sulphates decreased by 14 and 60 ppm. respectively. Such data suggest that chlorides and sulphates were available in the soil in the soil for dissolution in the vicinity of well 19 but that bicarbonates were lacking. In the vicinity of well 162 an opposite condition apparently prevailed. Where decreases in all three anions occured such as to well 271 a lack of available salt in the soil for dissolution is indicated. Conversely where increases were measured in all three anions such as in well 103, the soil apparently contained salts of the three anions available for dissolution by infiltrating water.

Owing to the relatively low permeability of the rocks of the Pali region, ground water circulation is generally slow. Thus the salts dissolved in the ground water are only gradually returned to the surface in areas of ground water discharge along the principal ephemeral streams of the region. As a consequence of the balance between the rate of salt accumulation and the rate of ground water circulation and discharge, the net salinity of the ground water remains generally high. How-ever, marked changes in salinity may occur from year to year as a result of shifts in the balance between the rate of salt accumulation and the rate of ground water circulation. A lower salinity which generally characterises the water of the southeastern part of the Pali region is attributed to a more active ground water circulation resulting from higher water table gradients which prevail in this area. Consequently the balance between the rate of salt accumulation and ground water circulation favours a lower salinity.

The quality of water from the open wells around Dholia, Nokha, Kolayat and Palana is satisfactory. The chloride content varies from 100 to 200 p.p.m. and dissolved solid content from 510 to 960 p.p.m.; but to the immediate south of the above area extremely poor quality of water has been found at Khara. The chloride and dissolved solid were 200 and 4800 p.p.m. respectively.

The quality of water in the Ratangarh area is also not satisfactory. Water sample from an open well at Naua, two miles south west of Ratangarh borehole, shows 900 p.p.m. of chlorides and 3000 p.p.m. of dissolved solids.

The quality of water in the Sikar area is excellent, the chlochlorides and dissolved solid contents being 23 and 375 p.p.m. only.

APPENDIX C.2-PARTIAL CHEMICAL ANALYSES OF WATER FROM SELECTED WELLS IN THE P[illegible] REGION SHOWING CHANGES IN SALINITY OF THE GROUND WATER BETWEEN NOVEMBER 1951-APRIL-1952 AND NOVEMBER 1952.

(Analyses by B.N.Sen, Assistant Chemist G.S.I)

Parts per Million.

Well no.***	Bicarbonate(HCO3)			Chloride (Cl)			Sulphate(SO4)		
	Nov.51** to April.52	** Nov.52	Net* change.	Nov.51 to Apr.52	Nov.52	Net* change	Nov.51 to Apr.52	Nov.1952	Net* change
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
1.	275	475	+200	597	1683	+1086	150	540	+390
2.	3278	3450	+172	2991	4105	+2114	Tr	Tr	0
3.	1375	1125	-250	701	704	+ 3	40	60	+ 40
6.	332	325	- 7	1500	4848	+ 652	410	220	-190
7.	527	450	- 77	4470	4664	+ 194	1130	960	-170
10.	412	425	+ 13	690	1122	+ 432	270	340	+ 70
12.	229	250	+ 21	980	769	- 211	280	240	- 40
13.	573	625	+ 52	1752	1748	- 4	600	560	- 40
15.	550	675	+125	153	182	+ 29	120	40	- 80
17.	343	300	- 43	10	25	+ 16	Tr	Tr	0
18.	492	550	+ 58	821	838	+ 17	1300	1280	- 20
19.	2017	1350	-667	1303	1579	+276	290	920	+630
20.	458	475	+ 17	82	274	+ 192	Tr.	Tr.	+ 40
28.	641	550	- 91	1807	1670	- 137	580	420	-160
32.	171	275	+104	10	39	+ 20	Tr.	Tr.	0
35.	561	625	+ 64	1210	1344	+ 134	260	340	+ 80
41	630	675	+ 45	914	861	- 53	220	200	- 20
43.	641	650	+ 9	1051	1161	[illegible]	330	360	+ 30
46.	710	700	- 10	1276	482	- 794	40	Tr	- 40
47.	550	525	- 25	668	639	- 29	170	140	- 30
54.	745	675	- 70	306	261	- 45	Tr.	Tr.	0
62.	573	500	- 73	4968	3442	-1526	4600	2960	-1640

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
63.	550	450	- 100	1814	1004	- 810	1120	300	- 820
65.	848	650	- 198	49	130	+ 81	160	220	+ 60
66.	733	350	- 383	4217	2127	-2090	3660	1560	-2000
67.	389	450	+ 61	175	274	+ 99	Tr.	Tr.	0
68.	492	1100	+ 608	220	404	+ 184	100	60	- 40
101.	368	360	- 16	105	169	+ 64	Tr.	Tr.	0
102	733	925	+ 192	2870	2831	- 49	520	360	- 160
103	504	775	+ 271	1470	2270	+ 800	240	320	+ 80
105	1673	1075	- 598	840	391	- 459	Tr.	Tr.	0
106	710	700	- 110	330	326	- 4	50	60	+ 10
108	515	475	- 40	145	143	- 2	Tr.	Tr.	0
111	805	860	+ 55	565	508	- 57	200	160	- 40
138	412	480	+ 38	868	952	+ 87	40	60	+ 20
130	515	525	+ 10	940	274	- 66	120	60	- 60
140	515	500	- 15	1080	1070	- 10	280	240	- 40
154	490	500	+ 10	1675	1683	+ 8	540	320	- 220
158	710	700	- 10	2215	1983	- 232	780	720	- 60
160	470	600	- 130	550	479	- 81	160	100	- 60
162	550	725	+ 175	1240	1226	- 14	280	220	- 60
166	425	500	+ 75	1190	1670	+ 460	340	400	+ 60
169	481	475	- 6	680	691	+ 11	200	220	+ 20
176	653	700	+ 47	3730	3732	+ 2	1480	1400	- 80
178	538	500	- 38	2230	913	-1317	700	200	- 500
179	538	625	+ 87	2280	978	-1302	660	460	- 200
180	527	525	- 2	4060	3588	- 472	2360	2000	- 360
182	733	800	+ 67	2055	1866	- 189	640	600	- 40
221	538	550	+ 12	712	469	- 243	240	140	- 100
246	401	425	+ 24	[illegible]	[illegible]	-1037	1260	960	- 300

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
263	596	850	+ 254	1427	221	-1206	2200	260	-1940
264	378	475	+ 97	402	[illegible]	[illegible]	340	280	- 60
265	320	300	- 20	36	52	+ 16	Tr.	Tr.	0
271	492	450	- 42	3574	1879	-1695	600	380	- 220
276	458	625	+ 167	524	900	+ 376	400	700	+ 300
277	297	350	+ 53	36	39	+ 3	Tr.	Tr.	0
279	653	350	+ 305	537	417	- 120	160	140	- 20
289	320	325	+ 5	12	13	+ 1	Tr.	Tr.	0
290	827	325	- 2	744	835	+ 91	480	520	+ 40
296	356	375	+ 20	451	352	- 99	460	260	- 200
299	251	375	+ 124	3562	2061	-1502	1380	1100	- 280
301	859	1100	+ 241	2342	1709	- 633	1780	1280	- 500
373	332	675	+ 343	428	339	- 149	140	40	- 100
374	1077	500	- 577	2769	1944	- 825	980	[illegible]	- 260
380	492	1150	+ 658	2745	3353	+ 408	680	560	- 120

* Net Change: Plus(+) indicates net increase and minus(-) indicates net decrease, in parts per million, between the two periods of sampling.

**Dates when samples were taken are given in the attached list.

***Well number corresponds to that given in Appendix 1 & 2.

APPENDIX 8.1-Contd.

Dates of sampling for comparative analysis shown in the foregoing table.

Well No.	Nov. 51 to Apr. 52.	November 1952	Well No.	November 51 to Apr. 1952	November 1952
1.	Nov. 21, 1951	Nov. 19, 1952	108	Jan. 3, 1952	Nov. 27, 1952
2	21	19	111	4	27
3	21	19	138	9	27
6	22	19	139	9	28
7	27	21	140	9	28
10	28	19	154	21	28
12	28	20	156	21	28
13	20	29	160	22	28
16	29	20	162	22	28
17	29	24	166	23	28
18	29	23	169	30	28
19	29	23	176	31	28
20	30	20	178	Feb. 2, 1952	28
28	Dec. 3, 1951	23	179	2	28
32	3	23	180	2	28
36	3	23	182	2	28
			221	Mar. 5, 1952	28
41	4	23	246	14	24
43	5	23	253	15	27
46	6	23	264	18	27
47	5	27	268	19	27
54	12	27	271	21	24
62	13	24	276	22	29
63	13	24	277	22	29
66	13	24	279	22	29
66	13	24	289	24	25
67	14	27	290	24	25
93	21	20	296	24	25
101	Jan. 2, 1952	27	299	25	25
102	2	27	301	25	25
103	2	27	373	Apr. 12, 1952	21
105	3	27	374	12	21
106	3	27	380	15	19

APPENDIX 8.2

Results of Complete Analysis of two water samples from Rajasthan.

Sample No.	Date of collect-tion.	pH	Hardness as CaCO3 (total)	N.C.	SO_3	K_2O_2	Fe	Ca	Mg	Na	K	CO3	HCO3 SO4 Cl NO3 B	Dissolved solids	Sp. conductance (micromhos at 77°.)
				CONSTITUENTS IN PARTS PER MILLION											
1.	16.12.67	7.9	18	Nil	18	Trace	0.07	47	17	341	Nil		3561773731-1	1070	1760
2.	6.8.67	8.3	116		-	-	Nil	29	14	157		tra-ce	40530 70 1-0.8	804	828

Source of sample:

(1) Cumulative water sample from B.H.1.

(2) Cumulative water sample from B.H.8.

APPENDIX 8.2 Contd.

Results of Partial Chemical Analysis of a few Water samples from Rajasthan.

Sample No.	Date of collection	Constituents in parts per million					Conductance (Micromhos.)
		pH	Cl	CO_3	HCO_3	Hardness as $CaCO_3$	
1.	7.3.57	7.3	865	Nil	738	360	3640
2.	8.4.57	7.6	743	"	411	220	3570
3.	22.3.57	7.6	1306	"	338	336	5020
4.	21.1.57	8.1	10	"	291	216	430
5.	28.1.57	8.4	995	Trace	176	670	4670
6.	27.11.56	8.6	528	"	456	156	2700
7.	28.4.57	7.7	400	Nil	380	170	2080
8.	1.3.57	8.2	114	Trace	146	320	883
9.	21.12.56	8.2	228	"	665	395	1620
10.	6.12.56	8.2	488	"	775	500	2830
11.	12.1.57	7.4	86	Nil	278	250	1080
12.	4.2.57	8.3	202	Trace	327	470	1680
13.	18.2.57	7.8	164	Nil	387	180	1190
14.	16.4.57	7.6	867	"	436	440	3340
15.	31.7.57L.	7.8	23	"	339	192	626
16.	1.8.57	7.6	10	"	608	192	806
17.	4.8.57	7.8	83	"	339	144	816
18.	6.8.57	8.3	72	Trace	411	116	914

APPENDIX 8.3
IONIC COMPASITION OF WATER SAMPLES FROM JALORE REGION.

Water Bearing formation.	No. of well sample.	pH	Specific conductance in micromphos.	T.D.S. p.p.m.	EQUIVALENT PER MILLION. Na+	K+	Ca++	Mg++	Cl-	So4	Hco3	Co3	Total hardness p.p.m.	S.A.R.	R.S.(
Yonger alluvium	27	8.26 7.15-8.8	4940 452-23000	3730 380-22600	28.0 1.52-76.11	1.21 .10-5.14	10.39 1.13-125.4	10.36 1.82-77.80	40.71 3.98-106.6	2.63 1.20-7.10	7.62 4.7-20.68	0.76 .31-2.39	10.40 120-10160	11.71 1.31-73	4.30 1.57-12.4(
Older alluvium	81	8.91 7.8-9.1	3772.1 698-10420	2662.6 532-8240	24.4 2.44-130-93	1.21 64-10-23	3.19 .32-16.09	6.70 1.09-18.73	30.19 2.13-87.54	2.79 .20-8.78	7.27 3.46-15.12	1.06 .36-2.23	495.876 .87-1240	14.80 1.43-83-55	4.23 .09-1(
Undifferentiated clay formations	28	8.25 7.2-9.2	2457.2 737-7390	1699 452-7674	2.68 2.87-200.70	17.74 .04-200-70	3.17 .40-14.65	3.04 p33-14.64	20.53 1.69-110.60	2.21 .40-5.60	6.64 3.90-13.02	p74 .31-2.13	332.2 44.146	17.71 71.90-72.85	5.95 .2-1(38
Malani valcanics	2	8.45 8.2-8.7	2345 1180-3510	1948 836-3010	11.96 5.65-18.27	.79 .45-1.13	2.70 .76-4.64	4.13 2.20-6.7	13.62 5.47-21.77	.98 .4-1.92	4.30 3.35-5.25	.625 .57-.67	357.5 148-567	6.15 4.64-7.67	2.97 2.97-2.97
Jalore granite.	69	8.28 8.2-9.2	3162.49 1040-12299	2238.31 676-7440	21.58 2.52-108.73	4.22 .03-96.14	3.03 1.0-22.25	5.36 1.69-21.12	20.29 4.80-130-48	2.61 1.24-11.60	6.84 4.65-13.67	0.74 .52-1.82	418.02 158-2080	10.91 3.62-38.88	4.18 2.59-12.75

....

APPENDIX 8.4

CLASSIFICATION OF GROUND WATER

S.No.	Class	Range of T.S.S. in p.p.m	Percentage of total area of ground water exploitation.
1.	Class I (C1)	Upto 180	Nil
2.	Class II (C2)	180 to 500	14.69
3.	Class III (C3)	500 to 1500	35.94
4.	Class IV (C4)	1500 to 3200	25.80
5.	Class V (C5)	3200 to 7000	18.10
6.	Class VI (C6)	7000 to10000	5.34
7.	Class VII (C7)	Above 10000	0.12

APPENDIX-8.5

Analyses of waters from Western Jodhpur (Geological Survey of India) parts per million.

	Phalsund no.1	Phalsund No.2	Shorgarh Well No.1	Shorgarh Well No.2	No.1 Shointra Road side well.	Shointra well No.2 inside Village.	Tana well road side	Chhaba No.1
Lime (CaO)	404	425	368	372	338	295	357	608
Magnesia (MgO)	233	200	65	59	7	Nil	Nil	263
Chlorine (Cl)	580	900	720	460	500	600	535	3800
Sulphuric anhydride (SO_3)	919	785	410	313	101	111	174	1211
Total dissolved solids.	2576	2892	2144	1684	1472	1396	1624	8296

APPENDIX

Bikaner Water Analyses (I.C.I (India) Ltd.) parts per million.

	Bikaner	Hanumangarh.	Surpura	Ratangarh new well.	Ratangarh old well.	Churu new well.	Churu old well.	Gudsar	Suratgarh
Lime (CaO)	171	106	219	78	71	42	40	51	46
Magnesia (MgO)	98	51	121	74	88	82	136	414	16
Carbonate (CO_3)	104	160	111	171	167	403	403	107	56
Chlorine (Cl)	731	66	871	337	371	503	746	429	20
Sulphuric anhydride (SO_3)	345	36	104	49	506	319	436	10	4
Nitrate (NO_3)	10	3	9	66	117	10	41	23	..
Total dissolved solids.	2129	429	1926	991	1123	2101	2717	309	136

APPENDIX 8.6

Water bearing formation.	No. of wells sampled.	Parts per million* Bicarbonate (HCO3) Max.	Min.	Median	Average	Chloride (Cl) Max.	Min.	Median	Average	Sulphate (SO4) Max.	Min	Median	Average.
Younger alluvium	15	940	229	447	494	8353	1200	1500	2372	4720	Trace	410	912
Older alluvium	151	2406	137	538	642	14013	10	1752	2252	4600	Trace	390	678
Vindhyan limestone	17	550	332	425	442	2625	340	805	1077	620	40	280	234
Malani volcanics	8	3278	297	768	1071	2891	171	701	1108	2320	Trace	480	775
Jalore granite	88	2704	229	561	628	8784	10	1122	1666	8200	Trace	360	721
Aravalli slates	62	1214	309	827	641	7150	25	914	1364	2360	Trace	200	350

*Based on analysis of samples taken from wells during the period extending from November 1951 to April 1952.

CHAPTER - IX
ESTIMATION OF GROUND WATER RESOURCES OF WESTERN RAJASTHAN

9.1 THE GROUND WATER INVENTORY

The ultimate goal of quantitative hydrological measurements is to determine the additions of water to the ground water reservoirs from all sources (ground water increment) and discharge of every kind from the ground water body (ground water decrement). The balancing of one against the other is called the GROUND WATER INVENTORY.

As was pointed out in para 3.6, the main problem in regard to any ground water development is to know the recharge of the ground water from all surface and sub-surface sources. The total storage capacity of the ground water reservoir, which can be estimated from the average specific yield (or storage co-efficient for confined aquifer) and area and depth of the aquifer, does not give an idea of the yield from the under-ground reservoir in continued pumping over years. It is the recharge of the annual change of storage ~~of storage~~ of ground water which gives an idea of the maximum yield that can be utilised from the reservoir.

To compute the change that has occured in the amount of ground water in a catchment area during a specified period, it is necessary to determine the precipitation that has occured in the catchment during the period and estimate the loss which this precipitation has suffered due to evaporation and transpiration. The difference between the precipation and the estimated loss gives the total run off, a part of which has entered into the sub-soil and the rest has moved along the bed of the rivers in the catchment as registered by the river gages as the "observed run off". The difference between the total run off and the observed run off represents the quantity of water that has entered into the sub-soil and increased the amount of ground water during the period specified.

The essential difficulty lies in making an appropriate estimate of the loss due to evaporation and transpiration. The loss suffered by any particular precipitation depends on a number of factors, namely, the state of soil, temperature of the soil, temperature and humidity of air, velocity of the wind and the amount of sunshine.

9.2 FACTORS INVOLVED IN GROUND WATER INVENTORY

The factors which may be measured and used in ground water inventory are as follows:-

Ground Water Increment:

1. Rainfall penetration to the water table.
2. Natural influent seepage from streams, lakes and ponds.
3. Artificial influent seepage from irrigation, reservoirs, spreading operations, including feeding water down wells.
4. Inflow of free or confined ground water from outside the area investigated.

Ground Water Decrement:

1. Effluent seepage and spring flow of free ground water and discharge by surface flow, evaporation and transpiration, or a artificial removal by drainage works.
2. Effluent seepage and spring discharge of confined water along faults or leakage from the lower portions of aquifers holding confined water.
3. Artificial discharge by pumping.
4. Subsurface discharge of free or confined water from under-neath the area.

Only certain of the above mentioned factors may be important different ways. In the natural state, before artificial draft on ground water ~~water~~ has been made by pumping or drainage, equilibrium is generally established between ground-water increment and decrement. If subsurface inflow and outflow beneath the area under investigation are small, influent and effluent seepage are equal. Lowering of the water table by pumping reduces and may completely cut off effluent seepage and therefore the available water may be measured either by influent seepage or by the original effluent seepage.

If the supply is not overpumped, a second equilibrium is reached which is registered by a stationary water level after a considerable period of pumping. The quantity of water that can be pumped without a continued lowering of the water level, therefore, may measure the quantity of water available. Also, as previously stated, a stationary water level in a pumping confined water well indicates equilibrium between extraction and supply.

It must not be concluded that a considerable lowering of the water table is serious or is detrimental to the water supply. Just as a surface reservoir must be drawn down in order to catch and preserve flood flow, so the surface-reservoir level (water table) must be lowered sufficiently to prevent loss by effluent seepage. A decrease in the area of effluent seepage increases the area of influent seepage (absorptive area) and in turn increases the rate of ground water recharge. A depleted reservoir at the end of the dry season or cycle of dry years is necessary if the water is to be salvaged in the following wet season or cycle.

A well tapping confined currents of water diverts water escaping from the conduit below the well, which, under natural conditions, often supports a high water table in swamp areas, and lowering of the water table may reclaim the swamp land. Extreme over-pumping any salvage water locked up in clays. Of course, unreasonable lowering of the water table or depletion artesian aquifers may increase the cost of pumping and make ground water unavailable to those who are not financially able to sink deep wells or to pump from the greater depths.

9.3 WATER BALANCE EQUATION

It is rather difficult to evaluate correctly the factors involved in the inventory described in the preceeding paragraph. A more convenient way of estimating the ground water recharge is by the use of water balance eqation covering the period of a year.

If P denotes the precipitation during a particular period (say a year), R the observed runoff during the same period, E the loss due to evapporation and transpirationduring the period and W_1 and W_2 the ground water contents at the beginning and the end of the period (all quantities being expressed in inches of water spread over the area covered by the catchment) then the water balance equation can be expressed in the from

$$W_1 + P = R + E + W_2$$

or,

$$W_2 - W_1 = P-(R + E).$$

Now P is a quantity which can be fairly accurately determined for any catchment provided there are well distributed rain gauges over the catchment. R can also be determined fairly accurately (although not so accurately as P) from the river gauge readings. E is not so easy to determine, but using experimental data for evaporation and transpitation, we could form and estimate, although rough, for E. The evaporation varies from season to season and from soil to soil and the same soil evaporates at different rates depending upon the distance between the surface of the soil and saturated level of moisture below the soil surface.

The underground water content will consist of two parts, namely, the stored ground water below the water table, which we denote by G, and the soil moisture between the water table and the ground surface, which we denote by S, both being measured in inches of water. If G_1, S_1 and G_2, S_2 be the values of these quantities at the beginning and the end of the period then the condition $S_2 = S_1$ will be approximately satisfied if the beginning and the end of the periods are both dry epochs, and the state of the ground is very nearly the same. Under these conditions, $G_2 - G_1$ will be a measure of the increase in the stored ground water.

It will be clear from these equations that observations of rainfall, run-off and evaporation and transpiration losses can never give the absolute value of the stored ground water, due to precipitation in a specified period. This increase will lead to a rise in the water table. If we have a few wells in the catchment, and if we note the levels of water in the wells in the beginning and the end of the period will represent the increase in the stored ground water, ΔG. If the whole of this increase has been drawn up by lifting or pumping, the level of water in the wells at the end will be the same as in the beginning.

The methods to determine the various factors involved in the water balance equation are described in the following paragraphs.

9.4 <u>MEAN PRECIPITATIONS OF THE BASIN</u>

If the area under consideration is fairly large, the rainfall records of the raingauge stations located in and around the area are collected. The methods used for determining the magnitude of rainfall in different parts of the region can be either of the following:-

(A) Thiessen Polygon Method:- In this method, adjacent stations are joined by straight lines, thus dividing the entire area in a series of triangles. Perpendicular bisectors are erected on each of these lines, thereby forming a series of polygons each containing one and only one rainfall station. The entire area within any polygon is generally nearer to the rainfall station contained therein than to any other and it is therefore assumed that the rainfall recorded at that station should apply to that area.

(B) Isohytal Method:- In this method, the rainfall records of the stations are marked on the area. Then by judgement, isohytals or contours of equal rainfall are drawn. The area between these adjacent contours is assumed to be receiving the mean rainfall between the two contours.

9.5 SURFACE RUNOFF FROM THE BASIN

The surface run off can be measured fairly accurately if gauge discharge observations are taken on all important streams of the region under consideration. However, in order to arrive at the mean monthly or yearly run off from an area, it is necessary to have reliable gauge discharge observations over a prolonged period. In most parts of Rajasthan the gauging of the rivers has been started only recently and as such the observed run off data can not be taken as reliable.

When no run off records are available, emperical formulas for estimating the surface run off from the available rainfall records are used. A great judgement is, however, needed in using these formulas to choose the most appropriate values of the various co-efficients involved.

The methods can be generally divided in two classes:-

(A) The proportional methods.

(B) The Rational methods.

(A) The Proportional Methods:- The proportional methods is the one which was adopted in the early nineties of the last century and is meant to express the run-off as a certain percentage of rainfall; the ratio depending on the magnitude of rainfall and catchment characteristics i.e., shape, slope, vegetable cover, land use, etc. This method is purely empirical and has no logic behind it. For any particular catchment area, this method may give reasonably correct values of run-off in normal years but there will be wide variations between actuals and calculated values in dry and wet years. The run off rainfall ratio will vary with the rainfall and from one catchment to the other with the same rainfall. The work of Sir Alexander Binnie and Messrs. Strange Barlow, Parker and Inglis deserves mention in this connection.

The methods due to Inglis and Strange are described below:-

(i) Inglis Formulas:- A detailed study of rainfall and runoff was made by M/s. Inglis & De Souza for catchments in ghats and plains of the Bombay State, India. They gave the following formulae for the computation of runoff:-

<u>For Ghats:-</u>

$$R = 0.85\ P$$

Where P is total rainfall in inches

& R is run off in inches.

<u>For Plains:-</u>

$$R = \frac{(P - 7)}{100} \times P$$

Where R is runoff in inches

P is total rainfall in inches

This formula is not of wide application and should be restricted to catchments where conditions similar to those prevailing in Bombay area are not with.

(ii) Strange's Table:- Strange divided the catchments into three categories; bad, average and good. He gave a table showing the annual run off depending on on different magnitudes of total monsoon rainfall and the type of catchment. His table is reproduced as table No.9.1 He, however, did not explain the basis on which the figures in his table were arrived at.

(B) The Rational Methods:- The rational method of determining the annual or seasonal run-off from the corresponding rainfall takes into account the principal factors which are responsible for a part of the rainfall being lost to run-off. These factors are evaporation and transpiration which in turn are governed mainly by the mean temperature. Sunshine, clouds, wind velocity and humidity have some effect, but these generally follow the temperature cycle and can, therefore, be represented by temperature. The shape of the catchment, the slope and vegetable cover will have an effect on the seasonal distribution of run-off but not on the aggregate run-off. The existence of glaciers may be a factor of considerable importance and will need special consideration.

Amongst the first to study run off as a residual of rainfall after deduction of losses was Vermeule. His formula is as below:-

$$R = P - (11 + 0.29 P)(0.035 T_A - 0.65)$$

where R = Annual runoff

P = Annual precipitation

T_A = Mean annual temperature.

In the formulae given by Vermeule, it would be seen that for $T = 75^{\circ}$ the limiting value of rainfall for Vermeule formula which would produce no run-off ~~xxxxxx~~ comes to 30". This is obviously not the case as rainfall is below 30" in most parts of India and thus this formula would give no runoff. The formula can thus be of local applicati n only. ~~The formula can thus be of local application only.~~

The formula applicable to conditions in India is due to Khosla (28). By his formula the total evaporation and transpiration losses can be calculated. Deducting this from the precipitation an estimation of total run off (surface as well as ground water) can be made. This formula has been discussed in details in the following paragraphs.

9.6 <u>EVAPORATION AND TRANSPIRATION LOSSES</u>:

Vapour losses from the soil zone occur in two ways:- (i) by the evapo-ration of water at the soil surface and (ii) by transpira-tion from the leaf surface of water which has been absorbed by the plants and translocated to the leaves. The combined loss resulting from the theseprocesses is known as EVAPOTRANSPIRATION.

Where the water table is near the ground, surface evaporation from the soil is almost equal to evaporation from free water surface, whereas with water levels at greater depths below the surface, evapo-ration from soil decreases until it becomes negligible where moisture no longer reaches the surface by capillary action.

The process involved in the loss of water from plants is as fol ows. There is continuous movement of water from the soil into roots, up stems and out of leaves of the plant. Onl a very small por-tion of water absorbed by the roots is retained in the plants. An amount of heat equal to the latent heat of water is required to vaporise the water in the leaves. Hence if heat is not available, transpiration ceases; and conversely as available heat increases, transpiration increases. The majority of heat used for transpiration comes directly from the sun as radiant energy.

As pointed out in para 9.5 (B) evaporation and transpiration losses are governed mainly by the mean temperature, Several emperical formulae have been evolved for calculating these losses. Some of these are described below:-

(A) Lowry Johnson Formula:- The formula assumes a straight line relationship between the evapotranspiration losses and the "effective heat". The relationship is

$$U = 0.8 + 0.156\ F$$

where U = evapotranspiration losses in acre ft. per acre.

F = effective heat in thousands of degree days.

(B) Thornthwaites formula:- Thornthwaite (1948) determined the monthly water balance by evolving the concept of 'potential evapotranspiration' and using the mathematical equation for the potential evapotranspiration.

$$e = 1.6 \left(\frac{10t}{I}\right)^a$$

Where

e = potential evapotranspiration

t = mean monthly temperature

I = constant

a = constant

'I' and 'a' are defined by the following equations:

$$I = \sum i = \sum \left(\frac{t}{5}\right)^{1.514} = \text{sum of the monthly heat indices}$$

$$a = 0.000000675 I^3 - 0.0000771\ I^2 + 0.01792\ I + 0.49239.$$

These values of 'e' are corrected by the latitude factor for day time hours for each month.

(C) Blaney Criddle Formula:- Blaney and Criddle developed a simplified formula using temperature and day-time hours for the arid western portion of the United States. Their formula has been used extensively by the U.S.Soil conservation Service and considerable data has been collected to determine the values of the co-efficients to be used for various crops.

Their formula is

$$U = K\frac{tp}{100} = KF$$

Where the following quantities must be determined for the same period:

U = consumptive use (evapotranspiration losses) of crop in inches for given time period.

F = Sum of the consumptive use factors for the period (sum of the products of mean temperature and precent of annual day time hours) = $\frac{tp}{100}$

K = empirical coefficient (annual, irrigation season or growing season)

t = mean temperature in degrees Farhenheit.

p = percentage of day time hours of the year occuring during the period.

For monthly calculations, the small letters are frequently used for clarity as follows:-

f = monthly consumptive use factors = $\frac{t \times p}{100}$

k = monthly coefficient.

u = kf = monthly consumptive use, inches.

The consumptive use of water by a particular crop in some areas being known, an estimate of the use by the same crop in some other area may be made by the application of the formula U= KF.

The formula of most universal application and by far most suitable for Indian conditions is that evolved by Khosla and is discussed in details in the following paragraphs.

9.7 KHOSLA'S FORMULA FOR CALCULATING LOSSES

Khosla evolved a formula which he first presented in the United Nations Scientific Confrence on the Conception and Utilisation of Resources at Lake Success New York in 1949. It was presented in the form of his paper 'Appraisal of Water Resources'. Analysis and Utilisation of Data (Forecasting water yield, Flood run off, flood frequency, power potential).

Khosla has tried to evolve a formula of, more or less, general application. After a study of available data of rainfall, temperatures and run off in the U.S.A., India and elsewhere, and w with the background of the concept of run-off as a residual of rainfall after deduction of "evaporation loss" it has been possible to evolve a new formula, which (with due regard to the unit of period to be taken for calculations) appears to be of universal application. The fundamental basis of this formula is that temperature can be taken to be a complete measure of all the various factors which are responsible for the loss of rainfall to Run-off. These variables are evaporation, transpiration, sunshine, clouds and wind velocity.

Notations

P = Rainfall (precipitation) in inches.

P_m = Monthly rainfall in inches.

P_A = Annual rainfall in inches.

P_{10} = 10 days rainfall in inches.

R = Run-off in inches.

R_m = Monthly run off in inches.

R_A = Annual run-off in inches.

R_{10} = 10 days run off in inches.

L = Loss in inches.

L_m = Monthly loss in inches.

L_A = Annual loss in inches.

L_{10} = 10 days loss in inches.

T = Mean temperature in degree F.

T_m = Mean monthly temperature in degree F.

T_A = Mean annual temperature in degree F.

T_{10} = 10 days mean temperature in degree F.

1. Formula based on period of one month

$$L_m = \frac{T_m - 32}{9.5} \quad \text{where } T_m > 40^\circ \text{ F.}$$

for $T_m < 40^\circ$ F. the loss (L_m) may provisionally be assumed as

T_m	=	40°	30°	20°	10°	0° F.
L_m	=	0.84	0.70	0.60	0.50	0.40 inches.

The corresponding monthly rainfall (P_m) run-off (R_m) relationship will be

$$R_m = P_m - L_m \quad \text{and} \quad R_A = \Sigma R_m$$

The monthly loss against temperature is given in Table 9.3

2. Formula taking the year as a unit.

$$R_A = P_A - X\, T_A$$ where X is a constant for given catchment.

These formulae will oply in all cases where the rainfall is more or less well distributed over the period in question. But in areas where the rainfall is very low or it comes in occasional cloud bursts, the loss may have to be calculated on a ten- day or fifteen-day basis instead of the monthly or annual bases.

In the case of annual run-off the departure of the calculated from the actual may be due to a change in the seasonal distribution, the rainfall occuring at the close of one year so that the partial effect of it is felt during the following year, or due to inadequacy of rainfall and temperatures stations and run-off data. The same will apply to monthly departure but taken over the year as a whole these departures will decrease. Similarly the departures in the annual analysis of individual years will diminish or disappear if a number of years are dealt with collectively provided the data is satisfactory and adequate. The greater the number of years taken, the closer will be the agreement. Glacier fed streams will need special treatment.

The losses calculated by Khosla's formula for temperatures ranging from 1 to 100° F are given in Table 9.3

9.8 LIMITATIONS OF KHOSLAS FORMULA

The Khoslas formulas was discussed in the proceedings of the Symposium of Ground Water in 1955, when Banerjee (3) pointed out that the monthly runoff given by Khosla's formula does not tally with the actual monthly run off although the annual run-off coincides. He pointed out that all empirical formulas are based on the principle of "curve-fitting". If an empirical formula had been obtained so as to fit in with a particular curve agreeing with observed results, its use is limited to that curve only. It does not apply to any other type of curves. For instance, if we plot the value of $P_A - R_A$ of a particular catchment against T_A (T_A being $> 40°$ F) of that catchment for a number of years, we get a curve to which a straight line passing through the origin makes a fairly good fit. Since this is found to be so for a number of catchments, the empirical formula.

$$P_A - R_A = x\ T_A$$

(where x is a constant for a particular catchment) is justified. It has become possible to fit a straight line in this case because the range of $P_A - R_A$ is small and so also of T_A. A better fit is obtained if we fit the curve

$$P_A - R_A = X\ T_A + y\ T_A^2 .$$

If, on other hand, we plot for any particular catchment the values of $P_m - R_m$ against T_m ($T_m > 40^{\circ}$ F) using data for a number of years for each of the months separately, we get different curves for the different months, and it is impossible to get a single straight line curve

$$P_m - R_m = \frac{1}{9.5}\ (T_m - 32)$$

to fit them all. Indeed, this straight line does not make a good fit with any of the monthly curves. The values for different catchments given by Khosla of the calculated monthly run off from this formula and the actual run off differ so widely from month to month as to show to any one that the curve is a misfit. For instance, in Kosi catchment (1947), calculated run-off in July is 13.76 inches and actual 4.23 inches. In Mahanadi (1932), the calculated and actual run off values are respectively 14.63 and 4.23 inches in July and 5.72 and 8.46 inches in October.

Assuming that this formula is approximately correct, the annual curve has approximately the form

$$\Sigma P_m - \Sigma R_m = \frac{1}{9.5}\ (\Sigma T_m - 12 \times 32)$$

or, since $\Sigma P_m = P_A$, $\Sigma R_m = R_A$ and $\Sigma T_m = 12\ T_A$, we get

$$P_A - R_A = \frac{12}{9.5}\ (T_A - 32)$$

If this is identical with $P_A - R_A = x\ T_A$, we must have

$$x\,T_A = \frac{12}{9.5}\,(T_A - 32)$$

Or,

$$x = \frac{12}{9.5}\left(1 - \frac{32}{T_A}\right)$$

If $T_A = 50^\circ$ F. $x = 0.46$ and if $T_A = 75^\circ$ F $x = 0.75$.

In his Table III, for American and British Catchments where $T_{A\,m}$ is very nearly 50° F, Khosla finds x to vary from 0.41 to 0.57. For Indian catchments. where the mean annual temperature is higher, x will have a higher value, of the order of 0.7 to 0.8.

This process of summing up involves a good deal of "smoothing" and all that we get is that while the monthly curves are misfits, the annual curve obtained from them makes a fairly good fit, provided the annual rainfall is not less than 25 inches or the area is not arid or semiarid.

Dhir pointed out that no where has such a claim was made that Khosla's formula gave comparable results on a monthly basis. The formulas was intended for finding out annual run off and not monthly run off. Dhir (14) explained in his paper presented at the same symposium that the results obtained by the application of Khosla's formula are not comparable with actualy monthly run off values for the reason that the formula takes into account only evapo-transpiration losses, but does not consider the ground water factors of infilteration and regeneration. If therefore, a comparison on monthly basis is required, it is necessary to introduce the factors of infilteration and regeneration in the equations. They also suggested the statistical equations for introducting these factors.

9.9 ESTIMATION OF GROUND WATER RESOURCES OF WESTERN RAJASTHAN BY KHOSLAS FORMULA

Khosla's formula based on periods of one month has been applied to calculated the annual ground water recharge of the region. The formula taking the year as a unit can not be applied in absence of any reliable value of co-efficient 'K' to be used in the formula.

Dhruv Narayna (16) has calculated surface and ground water potentials of Luni basin, taking Khoslas, Blaney-Criddle and Thornth Waite formulas for calculating the evapotranspiration losses. The losses, calculated by Thornth waites and Khosla's formulas were nearly equal.

To calculate the ground water potential, such rain gauge stations, in and around the catchment have been selected whose average monthly rainfall as well as average monthly temperature records are available.

Taking these rainguage stations, Theissen polygon has been constructed to get the area of influence of each rainguage station.

For each rainguage station, the monthly evapotranspiration losses have been calculated by Khosla's formula and subtracting this form the total precipitation, the total run off(both surface and ground water) has been arrived at. These calculations have been done in Table 9.9

As seen from the table, no surplus water balance exists in the effective areas of Jodhpur, Barmer, Pachpadra, Sriganganagar and Bikaner. The records of Jaisalmer and other stations in east and north are not available, but since the precipitation there is even less, it is evident that no surplus water balance will be available in that area.

The surplus run off is contributed by the effective Zones of the stations Ajmer, Udaipur and Sikar. The total annual water potential from these stations is calculated in the table given below.

Estimate of Total Water Potential

S.No. Station	Area of influence of the station. Sq.Mile	Mcft.	Depth of run off (Inches)	Total run off (mcft).
1. Sikar	4720	1,31,800	0.30	3,300
2. Ajmer	4960	1,30,400	2.45	27,800
3. Udaipur	1630	45,450	5.26	19,800

In the report of water Assessment and Utilisation Committee (45) the surface water potential of different river basin have been calculated using the Strange's table as the basis of calculation.

The only river valley in Western Rajasthan is the Luni river valley. For computing the total surface run off from this valley the whole catchment area has been divided into 24 sub-areas and each has been classified as good, average and bad according to Strange classification. The calculation are given in Table 9.5. The total surface run off from the Luni basin is 28,300 mcft.

Substracting the surface run off from the total run off calculated above in Table along the ground water potential of the region works out to 22600 mcft. or 0.52 M.Acre ft.

9.10 DISCUSSION OF THE RESULT ARRIVED AT BY KHOSLA'S FORMULA

As pointed out in earlier chapters also, so far no systematic study for the quantitave estimation of ground water resource has been undertaken by any organisation. In absence of the required data, the method using the Water Balance Equation, which is the most accurate and reliable method can not be employed.

An assessment of total ground water reserves of any region can be made by knowing the water table depth, total depth of aquifers and the storage co-efficient of the aquifer (or the specific yield in case of unconfined aquifers). However, this will serve only to give an idea of the total capacity of the ground water reservoir and not the annual recharge potential. As was pointed out in paras 4.5 and 4.6, the annual recharge of the ground water reservoirs is very much less in proportion to the storage capacity. To start with we can drain larger quantities of water by pumping from ground water reservoirs but ultimately, the net annual discharge can not be greater than the net available recharge.

However, even the data for calculating storage co-efficient or specific yield are not available. The step draw down and aquifer performance test carried out on a single well (described in para 7.22) give data to calculate the co-efficient of permeability, co-efficient of transmissionlity, optimum discharge from the well and critical velocity etc. But unless observations on one or two observation wells located around the main well are taken, it is not possible to calculated the storq e co-efficient. Since so far the drilling has been done only for development of production wells, no where the observation wells have been dug.

In the Lathi Basin of Jaisalmer district, which is an imporatant water bearing strata, two additional tube wells were constructed in the vicinity of the existing tube well at Dabla for ensuring a steady water supply to Jaisalmer town. Vijayraghwan (92) have utilised the data from the observations on those wells to calculate the storage co-efficient for Lathi Basin. Multiplying the storage co-efficient thus got by the average thickness of granular Sone

Basin gives the total ground water storage of the region. The values got by them are as follows:-

Co-efficient of storage = 1.504 x 10-4

Average depth of bore hole below static water level
= 650 ft.

Percentage of saturated granular Zone = 70%

Hence depth of saturated granular Zone
below static water level = 455 ft.

Area covered by the Lathi formation =580 sq.miles.

Hence the total ground water storage=580 X 640 X455 X
1.504 X 10-4 =16640 acre ft.
= 783.5 mcft.

However, as pointed out earlier, no referenc has been made in their paper of the available recharge potential.

The Lathi series is a very promising aquifer for developing production wells. As reported by Mahavir Prasad (34), the water table in the area is about 120 ft. to 220 ft. below ground level. The discharge sustained over long duration pumping of the productive well constructed at Chandan by the Exploratory Tube Wells Organisation during their first phase of operations was 46,000 I.G.P.H. at a steady draw down of 18 ft.

On the basis of Khosla's formula, the ground water recharge potential of the area is nil. This apparently means that probably Khosla's formula is not applicable in the region. But it should also be kept in view that at present, the number of tube wells in the region is very limited. It is very likely that when tube wells are developed in the area in a large scale and when sustained pumping is carried over a number of years, the ground water reservoir may get gradually depleted resulting in the gradual lowering of the

Till such records are available for a period of at least 20-25 years, it is not possible to correctly judge the validity of Khosla's formulae.

Another similar case in western Rajasthan is the exceptional success of the tube wells in BORUNDA VILLAGE (Long 73° 49' E Lat 26° -23' N) in Jodhpur District. There are three tube wells in the village, each of which is reported to give a discharge of about 75000 I.G.P.H. Two of these wells are privately owned but the third is owned by a co-operative society and is being used to supply water for drinking purposes and irrigation.

The village is situated in the lime stone formation about 50 miles east of Jodhpur. The exceptionally good yield from these wells could be due to some special structural feature of the lime stone formation.

Such local exceptions can not be explained on the basis of Khosla's formula which gives the general regional picture of the ground water recharge potential.

STRANGE'S TABLE OF TOTAL MONSOON RAINFALL AND ESTIMATED RUNOFF.

TABLE 9.1

Total monsoon rainfall.	Good catchment. Percentage of runoff to rainfall.	Good catchment. Depth of runoff due to rainfall in inches.	Average catchment. Percentage of runoff to rainfall.	Average catchment. Depth of runoff due to rainfall in inches.	Percentage of runoff to rainfall.	Depth of runoff due to rainfall in inches.
1.0	0.1	0.001	0.1	0.001	0.05	0.0005
2.0	0.2	0.004	0.15	0.003	0.1	0.002
3.0	0.4	0.012	0.3	0.009	0.2	0.006
4.0	0.7	0.28	0.5	0.021	0.3	0.014
5.0	1.0	0.050	0.7	0.037	0.5	0.025
6.0	1.5	0.090	1.1	0.067	0.7	0.045
7.0	2.1	0.147	1.5	0.110	1.0	0.073
8.0	2.8	0.224	2.1	0.168	1.4	0.112
9.0	3.5	0.315	2.6	0.236	1.7	0.157
10.0	4.3	0.430	3.2	0.322	2.1	0.215
11.0	5.2	0.572	3.9	0.429	2.6	0.286
12.0	6.2	0.744	4.6	0.552	3.1	0.372
13.0	7.2	0.936	5.4	0.702	3.6	0.468
14.0	8.3	1.162	6.2	0.871	4.1	0.581
15.0	9.4	1.410	7.0	1.057	4.7	0.705
16.0	10.5	1.680	7.8	1.260	5.2	0.840
17.0	11.6	1.972	8.7	1.479	5.8	0.986
18.0	12.8	2.304	9.6	1.728	6.4	1.152
19.0	13.9	2.641	104	1.980	6.9	1.320
20.0	15.0	3.000	11.25	2.250	7.5	1.500
21.0	16.1	3.381	12.0	2.535	8.0	1.690
22.0	17.3	3.806	12.9	2.854	8.6	1.903
23.0	18.4	4.232	13.8	3.174	9.2	2.116
24.0	19.5	4.680	14.6	3.510	9.7	2.340
25.0	20.6	5.150	15.4	3.862	10.3	2.575
26.0	21.8	5.668	16.3	4.251	10.9	2.834
27.0	22.9	6.183	17.1	4.647	11.4	3.001
28.0	24.0	6.720	18.0	5.040	12.0	3.360
29.0	25.1	7.279	18.8	5.459	12.5	3.630
30.0	26.2	7.890	19.7	5.917	13.1	3.945
31.0	27.4	8.494	20.5	6.370	13.7	4.247
32.0	28.5	9.120	21.3	6.840	14.2	4.560
33.0	29.6	9.768	22.2	7.326	14.8	4.848
34.0	30.8	10.472	23.1	7.854	15.4	5.236
35.0	31.9	11.165	23.9	8.373	16.0	5.582
36.0	33.0	11.880	24.7	8.910	16.5	5.940
37.0	34.1	12.617	25.5	9.462	17.0	6.308
38.0	35.3	13.414	26.4	10.060	17.6	6.707
39.0	36.4	14.196	27.3	10.647	18.2	7.098
40.0	37.5	15.000	28.1	11.250	18.7	7.500
41.00	38.6	15.826	28.9	11.869	19.3	7.913
42.0	39.8	16.716	29.8	12.537	19.9	8.358
43.0	40.9	17.587	30.6	13.190	20.4	8.793
44.0	42.0	18.480	31.5	13.860	21.0	9.240
45.0	43.1	19.395	32.3	14.546	21.5	9.697
46.0	44.3	20.378	33.2	15.283	22.1	10.190
47.0	45.4	21.338	34.0	16.003	22.7	10.669
48.0	46.5	22.320	34.8	16.740	23.2	11.160
49.0	47.6	23.324	35.7	17.493	23.8	11.662
50.0	48.8	24.400	36.6	18.300	24.4	12.200

TABLE 9.2

COMPUTATIONS OF SURFACE WATER POTENTIAL OF LUNI BASIN.

S.No.	Brief description of the valley.	Catchment area in sq.miles.	Nature of catchment area.	Rainfall in inches.	Total available yield in Mcft.
1.	Jojri river upto Bisalpur tank.	512	Bad	14	690
2.	Jojri downstream of Bisalpur tank & upto its confluence with Luni.	88	Bad	14	119
3.	Luni river upto Jaswant sagar	1510	Bad	16	2473
4.	Luni river downstream of Jaswant Sagar upto its junction with Jojri river.	239	Bad	14	322
5.	Raipur Luni river below Raipur Luni site upto Chopra bund.	236	Bad	15	418
6.	Raipur luni river upto Raipur Luni site.	145	Average	18	582
7.	Sukli river upto Sardar-samand tank.	144	Good	18	771
8.	Sukli & Ghuiya rivers upto their junction with Bandi river.	+448	Average	18	1310
		+429	bad	10	2810
9.	Luni upto Junction with Bandi river.	179	Bad	14	242
10.	Khari river upto Hemawas tank	474	Mean of Average & Good.	18	1585
11.	Bandi river downstream of Hemawas tank upto Bandi Nehra site.	192	-do-	18	1021
		+434	Average	17	1491
12.	Sukri river below Bankli bund upto junction with luni.	93	Average	24	750
		+428	Bad	15	701
13.	Sukri river upto Bankli bund	144	Average	19	662
		+512	Bad	10	1010
14.	Mithri river upto vanishing	80	Average	20	418
		+424	Mean of Average & Bad	17	1217
15.	Jawai river upto Jawai Dam	304	Good	24	3306
16.	Jawai downstream of Jawai Dam upto its junction with Khari.	92	Good	23	904
		+970	Bad	13	1308
17.	Khari upto Saina	520	Average	18	2087
18.	Khari below Saina upto its junction with Jawai.	448	Bad	16	734
19.	Luni river upto Nakora site.	966	Bad	12	835
20.	Luni upto Chitalwana site	1360	-Bad	10	682
21.	Bandi upto its vanishing point.	198	Bad	14	267
22.	Bandi river upto Bandi Sandra site.	166	Average	20	868
23.	Sukri upto confluence with Luni.	461	Bad	12	398
24.	River Sagi upto Sagi inundation site.	366	Bad	12	316
		12932			25303

TABLE 9.3

LOSSES CALCULATED FOR VARIOUS TEMPERATURES BY KHOSLA'S FORMULA

$$L_m = \frac{T_m - 32}{9.5}$$

Temperature degrees F.	Losses in inches.	Temperature Degrees F.	Losses in inches.	Temperatures Degrees F.	Losses in inches.
1	0.41	41	0.95	81	5.16
2	0.42	42	1.05	82	5.26
3	0.43	43	1.16	83	5.37
4	0.44	44	1.26	84	5.47
5	0.45	45	1.37	85	5.58
6	0.46	46	1.47	86	5.68
7	0.47	47	1.58	87	5.79
8	0.48	48	1.68	88	5.90
9	0.49	49	1.79	89	6.00
10	0.50	50	1.89	90	6.11
11	0.51	51	2.00	91	6.21
12	0.52	52	2.11	92	6.32
13	0.53	53	2.21	93	6.42
14	0.54	54	2.32	94	6.53
15	0.55	55	2.42	95	6.63
16	0.56	56	2.53	96	6.74
17	0.57	57	2.63	97	6.84
18	0.58	58	2.74	98	6.95
19	0.59	59	2.84	99	7.05
20	0.60	60	2.95	100	7.16
21	0.61	61	3.05		
22	0.62	62	3.16		
23	0.63	63	3.26		
24	0.64	64	3.37		
25	0.65	65	3.47		
26	0.66	66	3.58		
27	0.67	67	3.68		
28	0.68	68	3.89		
29	0.69	69	3.89		
30	0.70	70	4.00		
31	0.71	71	4.11		
32	0.73	72	4.21		
33	0.74	73	4.32		
34	0.76	74	4.42		
35	0.77	75	4.53		
36	0.78	76	4.63		
37	0.80	77	4.74		
38	0.81	78	4.84		
39	0.83	79	4.95		
40	0.84	80	5.05		

(i) For T_m 40°F.

$$\text{Loss} = \frac{T-32}{9.5}$$

(ii) Loss at 40° F = 0.84

Loss at 30° F = 0.70

Loss between 30°F and 40° F varies as a straight line.

(iii) Loss at 30° = 0.70
20° = 0.60
10° = 0.50
0° = 0.40

i.e., .01 for each degree F.

TABLE 9.4

CALCULATION OF TOTAL RUN OFF FROM RAINGAUGE STATIONS IN WESTERN RAJASTHAN.

S.No.	Station	Jan.	Feb.	March.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1.	JODHPUR												
	Mean temperature in oF	62.4	66.6	76.0	85.1	92.4	92.9	88.5	84.4	84.5	80.5	71.5	64.8
	Precipitation in inches	0.15	0.24	0.11	0.13	0.41	1.42	3.97	4.88	2.40	0.32	0.11	0.1[illegible]
	Losses in inches	3.20	3.64	4.63	5.59	6.36	6.41	5.96	5.51	5.52	5.10	4.16	3.4[illegible]
	Total run off in inches	-	-	-	-	-	-	-	-	-	-	-	-
2.	BARMER												
	Mean temperature in oF	63.2	68.5	77.2	87.3	93.2	91.9	87.7	84.7	85.5	83.7	75.1	61.8
	Precipitation in inches	0.10	0.14	0.12	0.06	0.37	0.97	3.52	3.41	1.46	0.10	0.06	0.0[illegible]
	Losses in inches	3.28	3.84	4.76	5.92	6.44	6.31	5.87	5.54	5.63	5.44	4.54	3.1[illegible]
	Total runoff in inches	-	-	-	-	-	-	-	-	-	-	-	-
3.	AJMER												
	Mean temperature in oF	59.2	63.5	73.9	84.4	91.5	91.1	85.0	81.8	82.2	78.0	68.1	61.0
	Precipitation in inches	0.25	0.26	0.23	0.15	0.64	2.43	6.40	6.75	2.51	0.38	0.19	0.2[illegible]
	Losses in inches	2.86	3.31	4.41	5.51	6.26	6.22	5.58	5.24	5.28	4.84	3.80	3.0[illegible]
	Total runoff in inches	-	-	-	-	-	-	-	-	-	-	-	-
4.	UDAIPUR.												
	Mean temperature in oF	61.6	65.0	74.7	84.4	90.6	88.4	82.5	79.6	79.4	72.7	69.8	63.4
	Precipitation in inches	0.21	0.14	0.10	0.11	0.72	3.04	8.55	7.03	3.85	0.57	0.11	0.1[illegible]
	Losses in inches	3.11	3.47	4.49	5.51	6.17	5.94	5.31	5.01	4.99	4.28	3.98	3.3[illegible]
	Total runoff in inches	-	-	-	-	-	-	-	-	-	-	-	-
5.	PACHPADRA												
	Mean temperature in oF	61.1	65.0	76.2	86.9	92.9	93.7	89.5	86.0	82.1	82.1	82.8	63.9
	Precipitation in inches	0.16	0.15	0.12	0.05	0.44	1.15	3.36	3.48	2.01	0.19	0.04	0.0[illegible]
	Losses in inches	3.06	3.47	4.65	5.78	6.41	6.50	6.05	5.68	5.27	5.27	4.30	3.3[illegible]
	Total runoff in inches	-	-	-	-	-	-	-	-	-	-	-	-

S.No.	Station	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
6.	SRIGANGANAGAR.												
	Mean temperature in oF	52.5	50.7	62.6	78.7	91.4	94.1	92.3	90.1	87.1	77.4	66.1	56.0
	Precipitation in inches	0.26	0.44	0.21	0.20	0.24	1.22	2.60	2.78	0.27	0.06	-	0.21
	Losses in inches	2.16	2.01	3.22	4.91	6.25	6.54	6.35	6.12	5.80	4.78	3.60	2.61
	Total runoff in inches	-	-	-	-	-	-	-	-	-	-	-	-
7.	BIKANER												
	Mean temperature in oF	59.3	63.2	75.6	86.4	94.5	96.0	92.0	88.9	88.1	83.1	71.7	62.0
	Precipitation in inches	0.27	0.27	0.23	0.19	0.59	1.21	3.34	3.60	1.21	0.21	0.05	0.20
	Losses in inches	2.87	3.39	4.59	8.72	6.58	6.72	6.32	5.99	5.91	5.38	4.18	3.16
	Total runoff in inches	-	-	-	-	-	-	-	-	-	-	-	-
8.	SIKAR												
	Mean temperature in oF	58.7	61.[illegible]	72.7	84.2	94.0	94.2	88.3	84.3	83.5	78.6	66.3	58.3
	Precipitation in inches	0.36	0.33	0.30	0.11	0.64	1.84	4.99	5.80	1.83	0.24	0.14	0.27
	Losses in inches	2.81	3.06	4.28	5.49	6.53	6.55	5.93	5.50	5.42	4.00	3.61	2.77
	Total runoff in inches.	-	-	-	-	-	-	-	0.30	-	-	-	-

CHAPTER-X

CONCLUSION AND RECOMMENDATIONS FOR FUTURE EXPLORATION.

10.1 PRESENT DEVELOPMENT OF GROUND WATER IN THE REGION:

The present utilisation of ground water in the region is rather scanty. The utilisation is mainly through shallow large diameter dug wells. In most cases wells were not dug more than about 10 to 20 ft. below the water table. The wells are sunk manually, using simple tools, in unconsolidated alluvium or soft rock. Blasting powder is used to break ground where hard rock is encountered. The dug wells for small scale irrigation are limited to the alluvial plains of river Luni and its tributaries.

Recently some tube wells have been constructed in Jaisalmer, Barmer, Jalore and Sikar Districts in the region. In Jaisalmer District the few deep tube wells have been constructed around Chandan , Batia and Dabla in the Lathi formation. In Barmer, the tube wells are limited to area around Batia in sand stone formation In Jalore Distt. a good number of tube wells have have been constructed in the Tehsils of Bhinmal, Ahore and Jalore. In Sikar District only two production tube wells have been constructed one near Sikar and other near Palsana village. Most of these tube wells have been constructed by the Exploratory Tube Wells organisation and then handed over to either Rajasthan Public Health Engineering Department or the Rajasthan Under Ground Water Board for operation and maintenance. The Under Ground Water Board has also done the work of deepening of a number of existing wells by rock drilling and blasting, thereby improving their yield.

10.2 AREAS SUITABLE FOR FUTURE GROUND WATER DEVELOPMENT

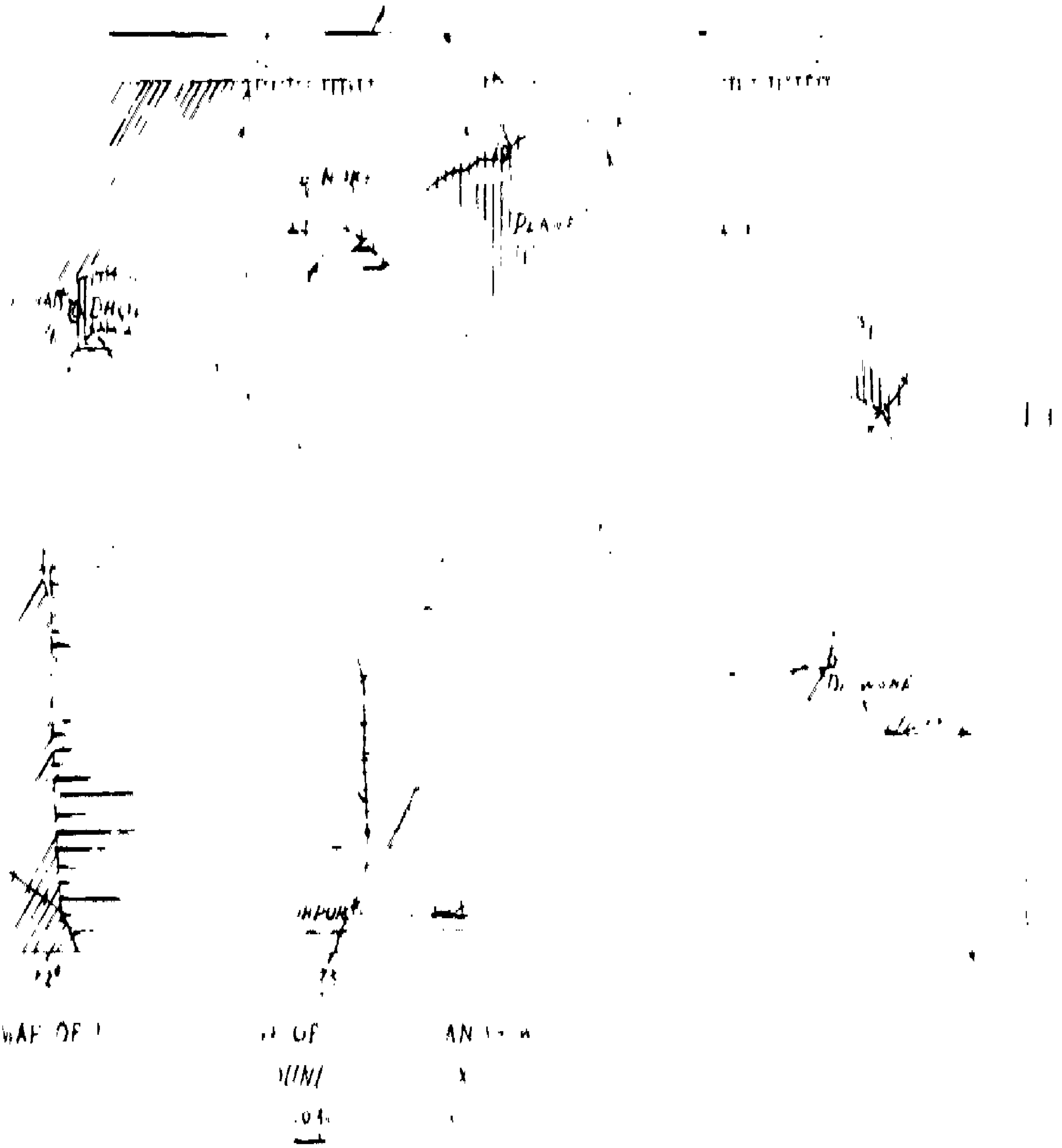
As pointed out in para 1.2, the Western Rajasthan region is characterised by extensive areas of wind-blown sand and only about 7% of the total area is covered by out crops of consolidated geological formations. The magnitude and extent of ground water movement, storage etc. in the sandy alluvial tract is not yet known. Also as seen from Table 9.4, the loss due to evaporation is a strong factor here.

The factors limiting the development of ground water in the region are the depth of water table beyond the economic pumping range, the poor quality of water making it unsuitable for irrigation and the low yield of the wells.

The water bearing properties and the depth of water table in different lithological formations have been discussed in details in para 2.5. On the basis of this certain areas can be straight away excluded from programme of future development.

The Granite and metamorphic rocks of the foundation contain only small quantities of water along the joints, The Vindhyan sand stones, which occupy a considerable area, have low porosities but do hold, in places, fair quantity of water along prominent joint planes. The mesozoic and cenozoic formations, variously consolidated, are likely to contain water not only along joints but in the body of the rock. However, most of the ground water is retained solely in the wind blown sands and alluvium, especially where these rest on crystallines.

There is no evidence for assuming that an "underground lake" with centripetal drainage, exists in this part of Rajasthan. The ground water body, or zone of saturation, is considered to rest as a saddle across the inferred watershed striking east west just north of Jodhpur city. In some areas there is probably no continuous Zone of saturation, and the ground water occurs only as isolated patches resting in hollows in the basement, with varying degrees of



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The true ground water basins lie outside the area under consideration in the Gangetic and Punjab regions, and towards Multan. These basins are virtually cut off from western Rajasthan either by rock barriers or by contrary hydraulic gradients.

On the basis of the data available upto the field season of 1956-57, Basu (5) has prepared a map of the arid zone of Rajasthan showing the areas suitable for future ground water exploration. This map is reproduced as plate 10.1 They have divided the area in three zones:-

1. Area where future exploration is recommended.

2. Area not considered suitable for future exploration as indicated by surface geological information.

3. Area not considered suitable for future exploration as indicated by exploratory drilling.

Results of subsequent exploratory drilling in the zone (2) have also shown that the area is not suitable for ground water development..

However, the area of Jalore District, especially that covered by the Tehsils of Bhinmal, Ahore, not included in this map, has also been found quite suitable for future development as a result of the extensive boring done by the Exploratory Tube wells Organisation.

The exploratory drilling in Jodhpur, Bikaner, Nagaur, Churu, and Sri Ganganagar Districts show that the in these Districts either the thickness of the granular zone is insufficient or the yield from the wells is very poor.

Considering all these factors, the potential water bearing zones of Western Rajasthan, where further exploration is indicated, are as follows:-

(1) Lathi Formation in Jaisalmer:- From the exploratory drilling

series contain several aquifers with good transmissibility and quality is also with in permissible limit for all types of uses. The Bathi formation roughly covers an area of 5000 sq.km(1950 sq miles) in Jaisalmer District.

(2) Barmer Sand Stone Formation :- Exploratory drilling at Botia near Barmer indicates that in a section of considerable thickness, a material having quite a high porosity exists. But the quality of water is not very encouraging. The depth to water table also exceeds 76 metres (250 ft). But the acute scarcity and dire necessity of water outway these detering factors.

(3) Older Alluvium and Malani Volcanics of Jalore District:- In Jalore district, the older alluvium generally lies below the zone of saturation and the ground water circulates through the interstatal openings of sand and gravel under unconfined conditions. Confined ground water also exists in undifferentiated clay formation and the Malani suite of Igneous rock.

(4) Vindhyan Lime Stone Formation east of Jodhpur.

Generally the Vindhyan lime stone formation has solution openings and fracture partings which are not well developed and hence they do not contain any appreciable amount of ground water.

However, as described earlier in para 10.10, three Tube wells dug near Borunda village (Long 73°-49' E and Lat 26° 23' N) show exceptional yield. Some local structural feature may be responsible for this. The area has not been geologically mapped and nothing definite could be said about it at this stage.

(5) Alluvial Formation Around Sikar:- The two exploratory tube wells one near Sikar & the other near Palsana indicate that saturated granular sections are encountered in the Recent and Sub-recent formations of Sikar area. The tube wells may not yield prolific quantities of water but wells yielding moderate quantities of water would be feasible.

The quality of water is excellent.

10.3 EFFECT OF PERENNIAL IRRIGATION CHANNELS ON FUTURE GROUND WATER DEVELOPMENT.

The Gang Canal, Bhakra Canal and the proposed Rajasthan Canal are all designed as perennial irrigation channel for the Districts of Sri Ganganagar, Bikaner and Jaisalmer.

A brief reference was made in para 4.3 (d) about the effect of these channel systems on ground water. After prolonged irrigation in the region from these perennial canals, the water table in the area is bound to rise, inspite of the fact that for the Rajasthan Canal system the main canals are lined . The water losses even from the unlined branch canals, distributaries, minors and field channels as well as the fields them-selves would be considerable, these being estimated to be of the order of 55% of the total discharge.

At present, the top layer of soil in the region is dry wind blown sand. Most of the moisture seebing will therefore be retained in the top layers of the soil and may thus get lost by evaporation from the soil surface. There may, thus be only very little recharge of ground water from this in the begining.

Ultimately, when the water content of the top soil layers reaches the field capacity of the soil, the water will percolate downwards and will go add to the ground water of the region. The water table will then start rising.

This fact is also indicated by the contours of the depth of water table shown on Plate No.4.3 for the Gang Canal System. The depth of water table in the areas served by this system, which is now in operation for some 50 years is 100 ftor less below ground surface. But in the adjoining areas of command of Rajasthan Canal system, the depth varies between 100 to 200 ft. below ground level.

After a few decades, the water table in the area may rise to an extent at which the pumping may be economical. Then the irrigation from tube wells to supplement the canal irrigation will not only be feasible but may become necessary in order to present water logging conditions in the area.

However, at present no correct assessment of the period needed for the rise in water table and the probable yield from the tube wells can be made.

10.4 SUGGESTIONS FOR FUTURE EXPLORATION

(1) A geophysical survey, probably by seismic methods, should be under taken in order to deremine the contour of the basement below both the superficial unconsolidated formations and the older sediments. By this means it may also be possible to locate some of the burried valleys of the former topography take encroached by sand, which may still act as ground water arteries as wells ar depressions of the older sedimentory formations, in the impervious rocks.

Auden (2) has suggested the following lines of seismic traverses:-

(i) Latitudinal-

(a) latitute 25° 40' from the the Siwana Hills to Marwar Junction.

(b) latitude 26° 24' from near Vinjorai to Kolldnu and east wards to longitude 74°

(c) latitude 26° 36' from just south of Jaisalmer to Merta Rd.

(d) latitude 27° 10' from north of Jaisalmer to Phalodi and Nagaur.

(ii) Longitudinal-

(a) longitude 71° 10' from the Siwana hills to the northern edge of the Jaisalmer outcrop.

(b) longitude 72° from the Sukri river to latitude 28°;

(c) longitude 73° from near Erinpura Road to latitude 28°.

(2) Exploratory borings and hydrological tests should then be carried out on the potential water bearing Zones indicated by those Geophysical surveys. In the hydrological tests it is necessary to study the porosities and specific yield (or storage co-efficient for confined aquifers) of sedimentary formations to obtain information on the amount of water which can be yielded to the wells.

(3) Chemical analysis of water samples collected from the exploratory bore holes and other existing wells is also necessary to see whether the quality of water in suitable for irrigation and other uses.

Periodical chemical analysis is also necessary from the production wells, where the water is being utilised, to determine if there are any systematic variations in concentrations of dissolved salts, They are also necessary to study the co-relation of the variation of salt concentration with annual precipitation and run-off. Such study for Pali region was carried out by Taylor (46) for one season only for Pali region and is described earlier in para 8.5.

(4) Water level measurements should be done periodically round the year ~~the year~~ in order to study the seasonal as well as annual variations in the water level. This is very necessary for areas where production tube wells have been installed to see whether the water table falls down with sustained pumping over a number of years. Such study is also necessary in the areas served by perennial canal systems to study the rise of water table with continued application of irrigation water.

Seasonal variation of water table will help in the ground water inventory to asses the seasonal recharge and discharge of ground water.

(5) To prepare a correct ground water inventory and to assess the ground water resources of the region by the water balance equation, it is necessary to have prolonged record of the surface run off of all important rivers of Luni system. For this purpose the observations started by the Irrigation Department of the Government of Rajasthan should be continued and intensified. Automatic gauge recorders may also be provided where-ever necessary.

(6) The specific regions suitable for ground water development described in para 10.2 should be investigated in greater details and should be given priority.

The development of ground water in Lathi Formation should be systematically taken up. To ascertain properly the productive zone of Lathi series, detailed geological mapping of the area followed by a profile of exploratory bore holes taken at short distances across the whole formation is necessary.

Specific yields of the wells should also be determined and the effect of interference in the neighbouring wells should be studied to ascertain the economic spacings of the neighbouring wells.

The probable annual recharge of ground water should also be carefully investigated, especially in view of the fact that Khosla's formula gives a nil run off in the area concerned by Lathi series. The ground water contours of the region plotted by Vijayrajhyan show that the main direction of ground water flow in Lathi Formation is from south to north and north-west. This also indicates that the source of external recharge, if any, is possible in the southern portion of the region only. This needs to be carefully investigated and confirmed.

In the development of the ground water in Barmer Sand Stone, an important consideration, besides detailed geological mapping is to study the crop tolerance of the soil in area and to see if some specific types of salt tolerant and sone crops can withstand the marginal quality of water.

7. Studies will be necessary of the effects of waters with different contents of chlorides and sulphates on soil productivity in relation to different crops. This work should be carried out for a period of years, in case it is shown that the prolonged use of certain waters, not found to be immediate toxicity, ultimately has a deleterious effect on crop growth.

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