Ground Water in Folded Cretaceous Sandstone of the Bhachau Area, Kutch, India With Reference to the Kandla Port Water Supply

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1608-B

Prepared in cooperation with the Geological Survey of India and under the auspices of the United States Technical Cooperation Mission to India

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By G. C. TAYLOR, JR., M. M. OZA, A. MITRA, *and* B. N. SEN

CONTRIBUTIONS TO THE HYDROLOGY OF ASIA AND OCEANIA

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By G. C. TAYLOR, JR., M. M. OZA, A. MITRA, and B. N. SEN

ABSTRACT

This report is based on an investigation of the availability of ground-water supplies in the Bhachau area for the nearby Kandla Port and township development undertaken by the Government of India. This seaport lies on an estuary of the Gulf of Kutch in western India and in the eastern part of the State of Kutch. The fieldwork on the investigation was carried on from November 1952 through April 1953 with continuing hydrologic observations through 1954–55. The fieldwork included: geologic mapping and delimitation of the principal aquifers of the region; preparation of water-table maps; a detailed inventory of existing wells and springs; observations of significant water table fluctuations; preparation of isobicarb, isochlor and isosulf maps to show the areal distribution of ground-water salinity.

The Bhachau area includes about 116 square miles in eastern Kutch and lies in a belt of semiarid low-latitude steppes. The mean annual rainfall is about 15 inches, most of which falls from late June to late September during the southwest monsoon. The area includes a central sandy upland ranging from about 100 to 250 feet above sea level; a northern lowland of between about 50 to 125 feet altitude that slopes north to the Great Rann of Kutch; a belt of low buttes and discontinuous ridges ranging from about 200 to 275 feet above sea level; and southern lowland which slopes in a southerly to southeasterly direction from an altitude of about 125 feet to 25 feet or less near the Gulf of Kutch. The principal streams are Kageshwar Vokra and Kara Vokra which drain north to the Great Rann and Kotwala Vokra and Dalwala Vokra which drain south toward the Gulf of Kutch.

The rocks of the Bhachau area include nonmarine and marine sediments of Mesozoic, Tertiary, and Quaternary age and volcanic rocks of late Mesozoic to early Tertiary age. The oldest rocks in the area are medium- to coarse-grained white to buff current-bedded friable sandstone with occasional partings of white silty shale of the Upper Bhuj series that has been assigned to the Early Cretaceous. The soft friable sandstone of the Upper Bhuj series constitutes the most productive ground-water reservoir in the Bhachau area. At present (1955) there are nine irrigated tracts for which water is obtained from dug wells less than 90 feet deep in the Upper Bhuj. These wells are worked by bullocks and "motes" (leather bags) at withdrawal rates ranging from about 6,000 to 24,000

imperial gallons per day; however, many existing individual wells if equipped with mechanical pumps are capable of yielding 100,000 gallons per day.

The Deccan trap of Late Cretaceous to Eocene age occurs in a sequence of basaltic lava flows in the Bhachau area, but trap dikes, sills and plugs that are common in other parts of Kutch have not been observed in the area. Laterite of probable Eocene age is extensive at the top of the Deccan trap, and in places where the lava flows are thin the parent rock has been almost completely lateritized. The Deccan lava flows or the laterite, where the trap is absent, rest disconformably on the Upper Bhuj. No wells have been observed in the Deccan trap of the Bhachau area, but it is possible that locally small supplies of good water may be obtained from these rocks.

The Tertiary sediments, which are assigned to the Manchhar series of Pliocene age, generally rest on the laterite or the Deccan trap; but where both are absent, the Manchhar rests directly on the Upper Bhuj. The Manchhar series includes massive reddish-brown gypseous clay shales, laminated gray siltstones, some limestone, mottled sandstone, and laterite trap gravel. Only meager supplies of brackish water are obtained from wells in these sediments.

Along the channels of Kotwala, Dalwala, Kageshwar, and Kara Vokras are narrow bands of unconsolidated coarse sand with fine gravel of Quaternary age. No wells were observed in these deposits, but it is possible that locally they may contain small supplies of brackish water sufficient for domestic use.

The sandstone of the Upper Bhuj series contains the most important ground-water reservoir in the Bhachau area. This ground-water reservoir which functions essentially as a single hydrologic unit is sustained and recharged in most years by direct infiltration from rainfall and from emphemeral streams while in flood during the southwest monsoon. Discharge from the ground-water reservoir takes place by evaporation and transpiration, by spring flow, and by withdrawals from wells for irrigation. During April 1953 it was estimated that the total ground-water discharge from the Upper Bhuj of the Bhachau area was at a rate of approximately 15.7 acre-feet per day. On the basis of geologic and hydrologic studies, it was concluded that about 1 million imperial gallons per day could be developed from tube wells in the Upper Bhuj of the Bhachau area for the Kandla Port water supply or alternatively some 1,300 acre-feet per year for irrigation.

INTRODUCTION

The partition of British India and the establishment in 1947 of the independent nations of India and Pakistan led to major dislocations of the preexisting economic and social structure with attendant large-scale shifts of population that were due primarily to religious differences. These dislocations included the movement of a large group of Hindu refugees from Sind (Pakistan) and the resettlement of the refugees in Kutch (India). As a means of providing port facilities to serve the economy of northern India that had been disrupted by partition, the Government of India undertook construction of a major seaport at Kandla on the Gulf of Kutch and a link rail connection with the Western Railway system of India. Also as a part of the same enterprise, construction of the new township of Gandhidham to provide homes and trading facilities for the Sindi refugee population was undertaken under the auspices of the Sindhu Resettlement Corporation.

Among the chief problems of the new port facility was proper evaluation of available sources of potable water. Accordingly, investigations were undertaken during 1950–55 in the Anjar-Khedoi region (Taylor and Pathak, 1960), the Dudhai area (Taylor and Oza, 1954), and the Bhachau area that were considered most promising for development of substantial ground-water supplies. The objectives of these investigations were primarily to evaluate the availability of ground water for the port and township and secondarily for irrigation.

This report on the Bhachau area is based on a 6-month field investigation extending from November 1952 through April 1953 with continuing hydrologic observations in April 1954. The fieldwork was done principally by Messrs. M. M. Oza and A. Mitra, geologists, Geological Survey of India. Mr. N. Venkatappayya, geologist, Geological Survey of India, mapped the geology of the southeastern part of the region during the 1953–54 field season. Mr. B. N. Sen, chemist, Geological Survey of India made all of the field chemical analyses used for the preparation of quality of water maps. Instrumental levels to observation wells were run by Mr. R. N. Biswas, surveyor, Geological Survey of India. Mr. George C. Taylor, Jr., groundwater geologist of the U.S. Geological Survey organized the field program, participated briefly in the fieldwork, and helped compile the report.

Field studies included geologic mapping and delimitation of the principal aquifers of the area; preparation of water-table maps to show the source, movement, and disposal of the ground water; a detailed inventory of existing wells in the area to evaluate the extent of ground-water use for irrigation; studies of significant water-table fluctuations; and preparation of isobicarb, isochlor, and isosulf maps to sow the areal distribution of salinity in the ground water.

The investigation was under the general direction of the late Dr. P. K. Ghosh, formerly Superintending Geologist, Engineering Geology and Ground-Water Section, Geological Survey of India. To Mr. K. Mitter, Commissioner of the Kandla Port Development of the Government of India, and to Mr. R. R. Sukrani, Executive Engineer of the Kandla Port Development, the writers are much indebted for facilities which aided the progress of the work.

The Bhachau area lies in Anjar and Bhachau talukas (counties) (fig. 1) of eastern Kutch between lat 23°15′ and 23°22′30″ north and long 70°10′ and 70°25′ east of Greenwich. Map coverage of the area includes parts of Survey of India sheets Nos. 41 I/7/2, 41 I/7/3, 41 I/3/5, 41 I/3/6 on scale 1:25,000 (2.534 in. to a mile). Bhachau.

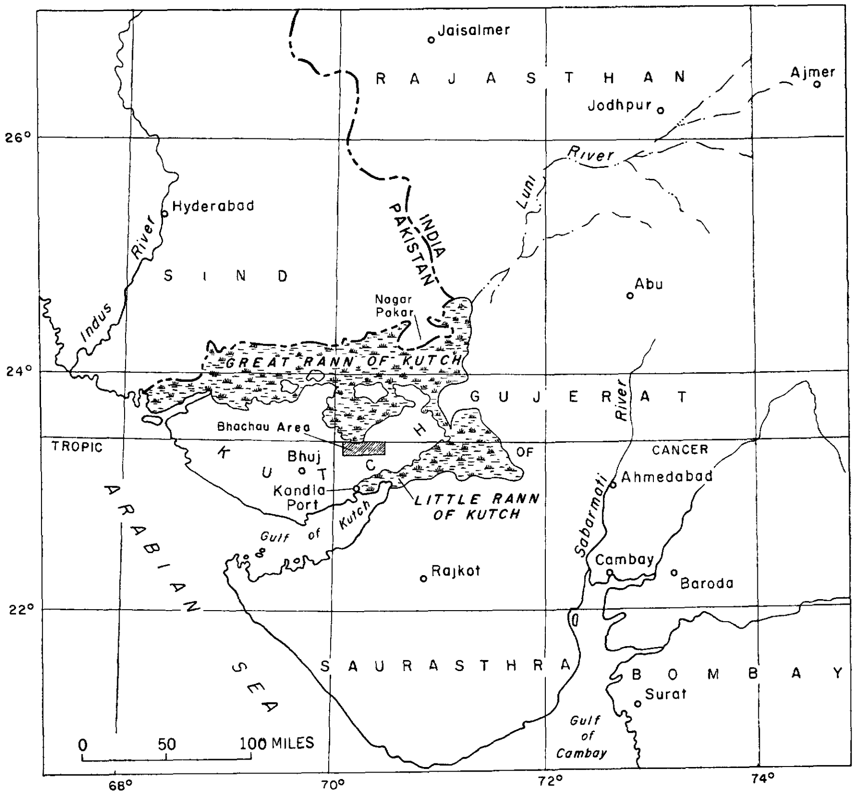

FIGURE 1.—Index map of western India showing the location of the Bhachau area, Kutch.

the principal town of the area and also the taluka headquarters, lies about 22 miles northeast of the Gandhidham township in the Kandla Port development. The map area extends about 14 miles from east to west and 8 miles from north to south. The area studied comprises approximately 116 square miles.

CLIMATE

According to Koppen's classification (Trewartha, 1943, p. 518) of climates, the Bhachau area lies in a belt of low-latitude semiarid steppes. The average annual temperature in this belt is greater than 64.4°F. In addition there is a winter dry season, and the wettest summer month has more than 10 times as much rain as the driest winter month. No temperature data are available for stations in the Bhachau area; however, precipitation data as recorded by the Indian Meteorological Department for Bhachau for 1878 to 1890 and for 1915 to 1945 are given in table 1 and are summarized in table 2. No monthly rainfall data are available for the Bhachau station, but the data given in table 3 for Anjar, about 24 miles southwest of Bhachau, are representative of the seasonal distribution of rainfall in the area. About 90 percent or more of the annual precipitation falls during a 3-month period from late June through late September. July is generally the wettest month in the year. The rainy season usually begins in late June with the southwest monsoon, which brings moisture-laden clouds from the Arabian Sea, and continues in force until late September or early October. During the northeast monsoon which prevails from October to June, light sporadic showers may occur occasionally; but these are of small importance for agriculture, for surface storage in tanks, or for ground-water recharge.

TABLE 1.—*Annual rainfall, in inches, at Bhachau, 1878–90, 1915–45*

[Data from records of the Indian Meteorological Department]

Year	Rainfall	Year	Rainfall
1878	3. 19	1924	11. 21
1879	13. 68	1925	5. 09
1880	27. 16	1926	24. 74
1881	27. 55	1927	25. 12
1882	15. 55	1928	14. 09
1883	15. 16	1929	15. 61
1884	20. 29	1930	15. 21
1885	12. 70	1931	9. 18
1886	16. 46	1932	15. 08
1887	12. 57	1933	21. 30
1888	10. 40	1934	20. 78
1889	16. 19	1935	13. 17
1890	12. 21	1936	14. 40
1915	6. 54	1937	13. 30
1916	11. 23	1938	6. 64
1917	28. 27	1939	3. 62
1918	3. 13	1940	10. 66
1919	14. 92	1941	19. 21
1920	23. 45	1942	8. 13
1921	31. 02	1943	6. 42
1922	18. 50	1944	26. 15
1923	3. 69	1945	24. 33

TABLE 2.—*Summary of rainfall data at Bhachau*

Mean annual rainfall inches	15. 16
Periods of record	1878–90; 1915–45
Number of years of record	44
Maximum annual rainfall of record (and year) inches	31. 02 (1921)
Minimum annual rainfall of record (and year) inches	3. 13 (1918)
Average frequency of years with rainfall less than the mean	1:1. 8
Average frequency of years with rainfall less than half the mean	1:5. 5
Average frequency of years with rainfall more than the mean	1:2. 3
Average frequency of years with rainfall more than 1.5 times the mean	1:5. 0

TABLE 3.—*Average monthly rainfall, in inches, at Anjar*

[Based on 63 years of record from 1878 to 1940]

Month	Rainfall	Month	Rainfall
January	0.07	July	6.68
February	.12	August	2.67
March	.05	September	1.89
April	.05	October	.47
May	.17	November	.10
June	1.68	December	.05
		Year	14.00

As is characteristic of the dry regions of the world, the amount of precipitation in the Bhachau area may vary greatly from year to year. Moreover, dry years may be expected with an average frequency of about once in 5.5 years, and wet years about once in 5 years (table 2). The areal distribution and intensity of rainfall during a given rainy season may also be quite erratic in the Bhachau area as well as in the rest of Kutch.

In the 4-month period from November through February, the weather in the Bhachau area is generally agreeable with pleasantly warm days and cool nights. Daytime temperatures during this period seldom exceed 90° F, and night temperatures occasionally drop as low as 40° F. However, from March until the beginning of the rainy season, the daytime heat is often oppressive, and temperatures greater than 110° F are common. Disagreeably hot winds with dust are also common in April, May, and early June. The heat is mitigated considerably by the southwest monsoon, but when this wanes in October, a brief hot speel generally ensues just before the beginning of cool winter weather.

TOPOGRAPHY AND DRAINAGE

The Bhachau area contains a central sandy upland which is the eastern and broadened continuation of the Kas Hills and contiguous tracts of the Dudhai area (Taylor and Oza, 1954, p. 6); a northern lowland which forms a part of the southern edge of the Great Rann of Kutch; a southern lowland, and a narrow belt of discontinuous low ridges and buttes lying between the central upland and the southern lowland. The central upland is broadest on the west side of the map area, where it is about 5 miles wide. From here the central upland trends eastward for some 14 miles gradually decreasing in width to die out about 1 mile east of Wondh. Altitudes in the upland generally range between 100 and 250 feet above mean sea level being lowest along the northern margin and in the east and highest to the south. The central upland contains the Wondh, Bhachau, Chopadwa, Sikra, Kumbhardi, Kabrau, Amardi, Morghar, Budhramora and Sukhpur irrigated tracts and is thus the most important part of the area from an agricultural standpoint. The northern lowland forms a narrow strip about 50 to 125 feet above sea level that slopes northward from the northern margin of the central upland to the Great Rann of Kutch. South of the central upland, a broken chain of low ridges and buttes trends eastward from the western edge of the map area for some 14 miles to a point about 1 mile east of Wondh. Altitudes along the crestline of these ridges and buttes range from about 200 to 275 feet above sea level. The highest point in the map area (298 ft. above sea level) is on one of the buttes just east of Bhachau. The southern lowland, which lies to the south of the belt of ridges and buttes, slopes south and southeast from an altitude of 125 to about 25 feet above sea level. East of Wondh the northern and southern lowlands merge at an altitude of about 75 feet.

All streams in the Bhachau area are ephemeral and flow only in response to heavy monsoon rains. The east-west axis of the central upland forms the principal drainage divide of the area. From this divide, streams drain northward and northwestward to the salt wastes of the Great Rann of Kutch and southward to tidal estuaries of the Gulf of Kutch. Kotwala Vokra, Dhokawa Vokra, and Dalwala Vokra are among the principal streams draining southward; important streams draining northward include Kageshwar, Vokra and Kara Vokra. There are also numerous minor streams which head on the northern margin of the central upland and drain northward and others which drain southward from the southern slopes of the belt of ridges and buttes.

PHYSIOGRAPHY

The present landforms of the Bhachau area have resulted from erosional processes operating on folded volcanic and sedimentary rocks under semiarid climatic conditions. The most prominent physiographic features of the area are a gently undulating sandy upland carved by erosion in soft friable Upper Bhuj sandstone along an asymmetric anticline; a broken chain of low strike ridges or cuestas etched out of lava flows of the Deccan trap and associated capping laterite; and gently sloping lowlands along the northern and southern margins of the map area formed in soft Tertiary sediments. Apparently these features are in a mature stage of formation in the present erosion cycle; thus, from the crest of the east-west anticline of the central upland, erosion has stripped away a thin discontinuous cover of Deccan trap and perhaps the uppermost 200 to 400 feet of underlying Upper Bhuj sandstone. Present streams are widening the central anticlinal upland by the back stripping of trap cuesta ridges that lie along its southern margin.

The external drainage of the Bhachau area is well established by numerous streams draining north to the Great Rann of Kutch and south to the Gulf of Kutch. Most of these streams are apparently consequent with some minor subsequent tributaries. Consequent drainage developed at the time of the original folding of the anticline, and later erosion of the anticlinal crest has not produced important subsequent drainage, possibly because of the relative lithologic uniformity of the Upper Bhuj sandstone that forms the core of the anticline.

GEOLOGY

SEQUENCE AND GENERAL FEATURES OF THE ROCKS

The rocks of the Bhachau area include marine and continental sedimentary rocks of Mesozotic, Tertiary and Quaternary age and volcanic rocks of late Mesozoic to early Tertiary age. The oldest rocks exposed in the area are massive current-bedded sandstones of the Upper Bhuj series whose age is referred to the Early Cretaceous. Lava flows of the Deccan trap, which is of Late Cretaceous to Tertiary Eocene age, directly overlie the Bhuj series but are absent in the central and northern parts of the map area, probably owing to removal by erosion or to nondeposition. An extensive horizon of laterite developed at the top of the Deccan trap is placed in the post-Deccan Eocene. Mottled sandstone, siltstone, clay shale and conglomerate that overlie the laterite and the Deccan trap are referred to the late Tertiary Manchhar series and are probably Pliocene in age. Thin discontinuous bands of alluvium along the channels of the larger ephemeral streams of the region are considered to be of Quaternary age.

The sequence, lithology and water-bearing character of the several rock units of the Bhachau area are summarized in table 4 and are described in more detail on subsequent pages.

GEOLOGIC HISTORY AND STRATIGRAPHIC RELATIONS OF THE ROCKS

The oldest rocks exposed in the Bhachau area belong to the Bhuj series, which is assigned an age ranging from Late Jurassic to Early Cretaceous. In the contiguous Dudhai area (Taylor and Oza, 1954, p. 7–8) of eastern Kutch, the Bhuj series was separated on the basis of lithology into a lower unit of alternating sandstone, silty sandstone, shale, and siltstone and an upper unit of soft massive friable current-bedded sandstone. The absence of marine fossils, the presence of poorly preserved plant remains, and the physical character of the strata were considered to indicate deposition under alternating fluviatile and estuarine conditions in the lower unit and under predominantly fluviatile conditions in the upper unit. In the Bhachau area, however, the lower unit of the Bhuj series is not exposed and only the upper unit, designated "Upper Bhuj series" is shown in plate 1.

The Bhuj series or "stage" as originally defined by Rajnath (1932, p. 163) included the plant-bearing beds of the upper division of the Umia "series" of Waagen (1873, p. 1) and is approximately equivalent to the "Upper Jurassic series" of Wynne (1872, p. 51–53). On the basis of stratigraphic relations with the marine Ukra beds of Aptian age in extreme western Kutch, Rajnath (1932, p. 171–173) assigned a post-Aptian Cretaceous age to the Bhuj series. However, both the Ukra beds and the Upper Umia Trigonia beds, which have hitherto (Rajnath, 1932, p. 170–171) been used to define the stratigraphic position of the plant-bearing Bhuj series, are evidently thin tongues of marine sediments that encroached but slightly into the western part of Kutch and are presumably absent in the central and eastern parts of the state. The writers are of the opinion that, whereas the uppermost part of the Bhuj series may be of post-Aptian age, there is a strong

TABLE 4.—*Generalized stratigraphic section for the Bhachau area*

System	Geologic age	Rock unit (pl. 1)	Thickness (feet)	Lithologic properties	Water-bearing properties
Quaternary	Recent and Pleistocene	Alluvium	0–20	Unconsolidated sand with some gravel in channels of large ephemeral streams.	Yields small supplies of brackish water to shallow wells.
Tertiary	Pliocene	Manchhar series	0–200+	Semiconsolidated massive reddish-brown gypsiferous clay shale, laminated siltstone, lenses of basalt and laterite gravel, mottled sandstone, and locally some limestone.	Yields meager supplies of brackish to salty water to wells.
		—Unconformity—			
	Eocene	Laterite	0–50	Ferruginous laterite (iron cap) and aluminous ferruginous laterite.	Locally yields small supplies of brackish water to wells.
	Late Cretaceous and Eocene	Deccan trap	0–250+	Lava flows of dense black nonvesicular to amygdaloidal basalt.	Generally above the regional zone of saturation but locally may yield small supplies of potable water to wells.
		—Unconformity—			
Cretaceous	Early Cretaceous	Upper Bhuj series	464+	Medium- to coarse-grained white to buff current-bedded friable sandstone with occasional partings of white silty shale.	Contains principal ground-water reservoir in Bhachau area. Yields moderate to large supplies of good to brackish water to wells and springs.

probability that the rest of the series may range down through the Early Cretaceous and into the Late Jurassic. The Upper Bhuj series as mapped in the Bhachau area is placed in the Early Cretaceous.

In most of the Kutch, the Bhuj series is separated from overlying lava flows of the Deccan trap by a slight unconformity which may represent a brief period of erosion or nondeposition. The attitudes of Bhuj strata and of the overlying Deccan lava flows, however, are in most places essentially parallel. The Bhachau area lies near the northern margin of the great Deccan lava field where the flows become thin and discontinuous. Trap flows are absent in the central upland and along most of its northern margin; however, a chain of low knolls and hillocks of trap, marks the northern edge of the central upland from a point about 1 mile northeast of Bhachau to a point about a quarter of a mile north of Wondh. The southern margin of the central upland is also marked by discontinuous "cuesta" buttes of Deccan trap (pl. 1). Although trap plugs, dikes, and dike swarms are commonly associated with the extrusion of the Deccan lava flows in other parts of Kutch, such intrusive forms have not been recognized in the Bhachau area. The flows of the Deccan trap and the associated plugs and dikes in western India have generally been assigned an age ranging from Late Cretaceous to Early Eocene (Krishnan, 1949, p. 406–410).

Capping the Deccan trap in Kutch is a widespread zone of laterite, whose age has been referred to the Eocene because it is overlain by marine Eocene beds of the Laki series in western Kutch. This zone evidently corresponds to a prolonged period of subaerial weathering under a monsoon climate of alternating wet and dry seasons. In the Bhachau area the laterite zone is particularly well developed in the belt of low ridges and buttes lying between the central upland and the southern lowland. In places in this belt the trap flows have been completely lateritized (pl. 1).

In western and central Kutch the Deccan trap is generally overlain by a thick sequence of marine, estuarine, and continental Tertiary strata of the Laki, Kirthar, Gaj, Nari, and Manchhar series, whose age ranges from middle Eocene to Pleistocene (Krishnan, 1949, p. 446). In the Bhachau area, however, the Laki, Kirthar, Gaj, and Nari are absent and sediments referred to the Manchhar series of probable Pliocene age rest on the laterite or the Deccan trap and where these are absent directly on the Upper Bhuj series (pl. 1). The lithologic character of the Menchhar sediments in the Bhachau area suggests deposition under fluviatile, estuarine, and shallow-water marine conditions.

Probably in conjunction with middle Miocene (Krishnan, 1949, p. 414) and subsequent orogenic movements of the Himalayan region, and of Sind and Baluchistan, the rocks of Kutch were compressed into folds along three major anticlinal axes separated by broad synclinal depressions. The axes of the folds trend generally northwest in western Kutch but swing to an eastward trend in the central and eastern part of the state. The axis of the great Habo anticline, which lies along the northern margin of the Kutch mainland, extends into the Bhachau area from the west as the Wondh-Amardi anticlinal axis, continues east for about 14 miles and closes and plunges about 1 mile east of Wondh (pl. 1).

PHYSICAL CHARACTER AND WATER-BEARING PROPERTIES OF THE ROCKS

UPPER BHUJ SERIES (LOWER CRETACEOUS)

The central upland, which trends from west to east across the map area for 14 miles, is underlain by rocks of the Upper Bhuj series (pl. 1). These rocks are predominantly sandstone with minor partings of silty shale, shale, and siltstone that probably form less than 10 percent of the gross thickness of the Upper Bhuj series. The sandstone is commonly medium to coarse grained and white to buff. It consists very largely of quartz grains that in most places are only slightly cemented by fine argillaceous or feldspathic material, so that the rocks are generally soft and friable. Locally, the sandstone contains thin lenticular streaks of well-rounded quartz pebbles and clay galls. Current bedding is highly developed in the standstone beds and in many places obscures normal stratification. Intercalated with the sandstone are thin partings of silty shale, shale and micaceous siltstone whose colors range from white and gray to pale red and purple. In places the shale contains poorly preserved impressions of plants and thin carbonaceous layers.

Good exposures of Upper Bhuj rocks are not common owing to low relief and to their prevailing softness; however, typical white to buff friable medium- to coarse-grained current-bedded sandstone is well exposed in a 130-foot bluff at the eastern outskirts of Bhachau, in another bluff about 2 miles west of Bhachau, and in the channels of the larger ephemeral watercourses draining north and south from the central upland. In a 75-foot butte about 1 mile north of Chopadwa, white current-bedded sandstone is capped by a layer of hard black ferruginous sandstone with hematitic claystone. Ferruginous layers of sandstone are also common near the contact with overlying Deccan trap. A section of typical Upper Bhuj rocks measured by the writers in an abandoned railway cut about 1 mile east-northeast of Bhachau is described in table 5. The section described in table 5 is typical of the physical and lithologic character of the upper part of the Upper Bhuj series. The sandstone beds all characteristically contain fine-grained white feldspathic or kaolinitic material which is interstitial with the quartz grains; moreover, permeable sandstone predominates as relatively impermeable shale and siltstone form only about 7 percent of the measured section. The maximum thickness of Upper Bhuj observed in the Bhachau area was 464 fet at the section described in table 5. In the contiguous Dudhai area to the west, where a greater thickness is exposed, it is estimated that the Upper Bhuj is at least 1,000 feet thick. (Taylor and Oza, 1954, p. 15.)

TABLE 5.—*Section of the Deccan trap and the Upper Bhuj series in abandoned railway cut about 1 mile east-northeast of Bhachau*

	Thickness (feet)
Deccan trap:	
Basalt, hard, dense, fine-grained, nonvesicular; transected by veinlets 3 to 6 in. wide of zeolites, calcite, and hard fine-grained brown chalcedony. Shows typical columnar jointing and ellipsodial weathering. Near base is 2- to 3-ft layer of altered soft gray trap. Conformably overlies Upper Bhuj	132
Upper Bhuj series:	
1. Siltstone, fine sandy; streaks of pale-yellow clay shale	7
2. Sandstone, medium- to fine-grained, silty, ferruginous; pale to brick-red, a few coarse-grained streaks	8
3. Sandstone, medium- to coarse-grained, argillaceous, thin-bedded, yellowish brown to brick red; alternating hard ferruginous and soft friable layers 3 to 6 in. thick	18
4. Sandstone, coarse-grained, friable, argillaceous, current-bedded and massive; lenses of pebbly pale-red quartz conglomerate; some lenses of medium-grained sandstone with occasional thin hard 1- to 2-in. ferruginous streaks	40
5. Sandstone, coarse- to medium-grained, friable, argillaceous, pink to white; discontinuous streaks of pale-gray clay shale and clay galls	20
6. Sandstone, medium- to coarse-grained, argillaceous pink to white; alternate friable and hard ferruginous layers 1 to 2 ft thick and occasional streaks of clay galls and lenses of clay shale 2 to 6 in. thick	23
7. Sandstone, coarse-grained, argillaceous, friable, current-bedded, pale-gray to white; streaks of fine quartz conglomerate and occasional thin ½ to 1-in. bands of clay shale	113
8. Siltstone and shale, lenticular, thin-bedded, dove-gray	6
9. Sandstonelike member 7	17
10. Shale, dove-gray lenticular-bedded	1
11. Sandstonelike member 7	72
12. Siltstone, fine-grained, sandy, compact, even-bedded, pale-gray	10
13. Sandstone, coarse- to medium-grained, argillaceous, friable current-bedded pale-gray; occasional thin partings of pale-gray siltstone and clay shale	79
14. Siltstone and clay shale, compact, even-bedded, pale-gray	12
15. Sandstone, like member 7	35
Total exposed thickness of Upper Bhuj series	464
Base of Upper Bhuj covered.	

The soft friable sandstone of the Upper Bhuj series is moderately to very permeable and forms the principal water-bearing horizon in the Bhachau area as well as in much of central and eastern Kutch. As indicated by table 5, a number of thick permeable sandstone beds occur in the upper part of the Upper Bhuj, and these most likely form important aquifers from a few tens to as much as 1,000 feet or more below land surface in the central upland of the Bhachau area. Most of the wells shown in plate 1 tap water in sandstone of the Upper Bhuj at depths of less than 90 feet. From such shallow dug wells the present (1955) draft per individual well for small-scale irrigation ranges from about 6,000 to 24,000 gallons per day; however, the potential yields obtainable from properly constructed and screened drilled wells sunk to 250 feet or more into the Upper Bhuj probably exceed 400 imperial gpm per well. The hydrologic features of the ground water in the Upper Bhuj series are discussed in more detail in the section of this report entitled "Ground water in the Upper Bhuj series."

DECCAN TRAP (UPPER CRETACEOUS TO EOCENE)

Lava flows of the Deccan trap are relatively thin and discontinuous in the Bhachau area that lies near the northern limit of the great Deccan lava field of western India. Except for a narrow strip northeast of Bhachau and west-northwest of Wondh (pl. 1) trap flows are absent along the northern margin of the central upland. The trap flows occur discontinuously along the southern margin of the upland, but from a point about one and one quarter miles east of Chopadwa to about 2 miles west-southwest of Lunwa, the original sequence of flows was probably relatively thin and was almost completely lateritized (pl. 1). The individual flows of the Deccan trap sequence range from very hard dark-gray to black dense nonvesicular olivine basalt to soft earthy-brown to gray amygadloidal basalt. The thickness of the individual lava flows in the Bhachau area ranges from about 20 to 50 feet; however, it is generally difficult to distinguish the tops and bottom of individual lava flows owing to low relief and to the poor exposures. The exposed thickness of trap flows in the area is generally less than 150 feet, but in covered downdip extensions in the southern lowland it is inferred that the total thickness of the flows may reach 300 feet or more. A typical section in the Deccan trap measured in the abandoned railway cut about 1½ miles seat-northeast of Bhachau is described in table 5.

In most parts of the Bhachau area, the exposed margins of the Deccan trap are above the regional zone of saturation; however, in or near ephemeral water-courses and near the contacts with Manchhar

690-420—63——2

deposits on the northern margin of the southern lowland, it is possible that shallow wells in the trap may yield small supplies of potable water. The trap flows in buried downdip extensions beneath the southern lowland are likely to contain only small supplies of brackish water. No wells dug in the Deccan trap have been observed in the Bhachau area.

LATERITE (EOCENE)

In Kutch an extensive horizon of laterite is commonly developed at the top of the Deccan trap and corresponds to a prolonged period of weathering and deep in place decay of the host rock probably under a monsoon climate of alternating wet and dry seasons. Nummulitic limestones of the Eocene Laki and Kirthar series overlie the laterite horizon in western Kutch, but in the central and eastern parts of the state, the laterite is covered by progressively younger Tertiary formations; thus, in the Bhachau area sediments of the Manchhar series rest directly on the laterite. Owing to stratigraphic relations in western Kutch, the age of the laterite horizon is generally referred to the Eocene.

The laterite horizon in the Bhachau area is most extensively exposed in the belt lying between the central upland and the southern lowland (pl. 1). Along the northern margin of the central upland, the laterite is not generally exposed either because of removal by erosion or because of overlap by Manchhar sediments, and similarly in places along the southern margin of the upland the laterite is also absent (pl. 1).

The laterite as developed on the Deccan trap of the Bhachau area can usually be divided into an upper unit of ferruginous laterite or "iron cap" and a lower unit of aluminous-ferruginous laterite. Both of these units, however are essentially gradational into one another. The ferruginous laterite or "iron cap" is generally from about 5 to 15 feet thick and is dark red, reddish brown, or purple and is compact dense to spongy. The material is rich in iron oxides or hydroxides. The "iron cap" grades down into mottled white, yellow and yellowish-brown aluminous or lithomargic clay of soft unctuous texture. Above the weathered trap of the host rock, a zone of earthy red and yellow ochre mixed with white aluminous clay in a mass of nodular or vermicular structure generally occurs. The "iron cap" is moderately resistant to erosion and where present forms low but conspicuous cuesta ridges which serve as convenient stratigraphic markers. On the other hand, the aluminous-ferruginous unit is quite soft and generally does not crop out distinctly except where protected by the "iron cap." The thickness of the laterite horizon varies considerably from place to place in the Bhachau area and the base of the horizon is commonly not well exposed. It is inferred, however, that maximum thickness probably does not exceed 50 feet.

In most of the Bhachau area, the laterite generally lies above the zone of saturation and is not water bearing. Locally, however, near Chopadwa and Lunwa, shallow wells tap water in laterite. In the vicinity of Chopadwa, shallow wells 30 to 40 feet deep apparently tap some water in the basal part of the laterite as well as in the underlying sandstones of the Upper Bhuj series. The yields obtained from the laterite in these wells are reported to be meager, and the water is somewhat brackish. Judging by the records of these wells, it appears that the Deccan trap formerly present in the vicinity of Chopadwa has been completely lateritized, so that the laterite horizon now rests directly on the Upper Bhuj series.

MANCHHAR SERIES (PLIOCENE)

In the lowland tract along the northern side of the Bhachau area (pl. 1) and again in the southern lowland are fluviatile, estuarine, and marine sediments that have been referred to the upper part of the Manchhar series and are probably of Pliocene age. These sediments include intercalated gypsiferous clay or clay shale, laminated soft siltstone and silty shale, discontinuous beds of trap and laterite gravel or conglomerate, mottled sandstone, and occasional thin beds of limestone.

Outcrops of Manchhar sediments are relatively scarce in the Bhachau area owing to thick soil cover and to low relief. The beds are exposed to a limited extent, however, along an ephemeral watercourse about three-quarters of a mile west of Kumbhardi where about 10 feet of gray unctuous clay shale and mottled sandstone is exposed. North of the Bhuj-Manchhar contact between Kumbhardi and Kabrau, the Manchhar sediments include thin intercalated beds of mottled yellowish-brown and cream-colored sandstone and greasy-gray and reddish-brown gypsiferous clay shales with occasional lenses of trap and laterite conglomerate near the contact. Similar materials occur north of that contact between Khumbardi and Sikra. About one-half mile east-northeast of Sikra, 15 feet of the basal member of the Manchhar is exposed. This member is here composed of a poorly sorted conglomerate with subangular pebbles of trap, ferruginous sandstone, siliceous sandstone, hematitic laterite, and limestone in a sandy to silty matrix. The conglomerate rests directly on white friable medium-grained sandstone of the Upper Bhuj. Elsewhere along the Bhuj-Manchhar contact between Patiapar on the west and Wondh on the east, the predominating materials found in shallow cuts are reddish-brown clay or clay shale with thin veinlets or scattered crystals of gypsum. About 1 mile northeast of Bhachau, however, poorly exposed beds of nodular limestone 3 to 4 inches thick are intercalated with fine-grained hard micaceous sandstone. Shallow cuts along a secondary road about three-quarters of a mile west-northwest of Wondh show thin platy dove-gray limestone in 1- to 2-inch layers intercalated with conglomerate which contains ¼- to ½-inch clay and laterite pebbles with interstitial gypsum. On a low hillock about 2 miles east-northeast of Bhachau is a layer about 2 to 3 feet thick of spongy siliceous limestone, containing poorly preserved gastropod fossils, that overlies soft earthy sandstone.

In the southern lowland to the south of the contact of the laterite or trap with the Tertiary and between the meridians of Wondh and Bhachau, the Manchhar near the contact is a conglomerate containing hematitic laterite, trap and quartz pebbles. Intercalated locally with the conglomerate is gypsiferous clay shale and mottled sandstone. About 1½ miles east-southeast of Bhachau in a shallow watercourse are exposures of variegated purple, green, and red laterite overlain by pale-gray to light yellowish-brown laminated clay shale and siltstone containing scattered crystals of gypsum. From the meridian of Bhachau westward to the western edge of the map area, the sediments of the Manchhar are predominantly reddish-brown, white, and buff gypsiferous clay shales with occasional beds of laminated silstone or sandstone and lenses of conglomerate.

The Manchhar sediments of the northern lowland generally have northerly dips of from about 1° to 3°. Locally, however, near the contact with the Deccan trap, the Manchhar beds may have northerly dips of as much as 15° or more as for example in the strip about 1 to 2 miles northeast of Bhachau (pl. 1). In the channel of Kagihar Ka Vokra about 300 feet west of the Kageshwar Mahadev temple and about 1½ miles east of Kumbhardi, Manchhar sediments dip vertically in what is apparently a silicified fault zone. An elliptically shaped outlier of Manchhar clays about 3 miles long was mapped by N. Venkatappayya in a strip lying south of the Kabrau and Kumbhardi irrigated tracts (pl. 1). This outlier apparently lies in a minor downfold in Upper Bhuj strata.

In the southern lowland, Manchhar sediments generally have southerly dips of about 100 feet to the mile or less but in the southwestern part of the map area, dips of up to 4° are observed (fig. 2). Along the northern margin of the southern lowland, Manchhar sediments generally rest with slight disconformity either on the laterite or on the Deccan trap. In salients near Bhachau and Sukhpur, however, the Manchhar sediments apparently overlap both the trap and the laterite and rest directly on the Upper Bhuj. Judging from the dip and width of outcrop, the Manchhar sediments may attain an estimated thickness of perhaps 200 feet or more in the southeastern corner of the map area and possibly a thickness of the same order of magnitude along the northern edge.

The Manchhar sediments of the Bhachau area are for the most part impermeable and yield only meager water supplies to shallow wells that tap water in thin sandy beds intercalated with clays. In most places the water is too brackfish or salty to be used for irrigation or drinking. No wells have been observed in Manchhar sediments of the map area (pl. 1), but near Chhadwala, which lies about 3 miles east-southeast of Wondh, are several wells which tap brackfish water apparently in this sandy layers intercalated with dove-gray laminated silstones, micaceous clay shales, indurated conglomerate, and mottled sandstones at depths ranging from 25 to 45 feet. A well constructed near the embankment of a small tank just east of Chhadwala yields fresh water that is probably seepage from the tank. Wells in Rampur, a village that lies about 5½ miles north-northeast of Wondh, tap brackfish water in massive fine-grained sandstone within 50 feet of the land surface. Generally the potential yields of wells in Manchhar sediments are no more than a few thousand gallons per day.

ALLUVIUM (PLEISTOCENE AND RECENT)

Narrow bands of alluvium lie along the channels of Kotwala Vokra, Dhokawa Vokra, and Kalwala Vokra in the southerly drainage and along Kageshwar Vokra and Kara Vokra in the northerly drainage. The alluvium is composed largely of medium to coarse unconsolidated quartz sand with some gravel mainly of quartz, trap, and laterite pebbles. Generally, these deposits are no more than 20 feet thick.

No wells in alluvium have been observed in the Bhachau area, but locally these deposits may contain small supplies of water that is likely to be brackish.

GEOLOGIC STRUCTURE

As suggested by Auden (1951, p. 116), Kutch should be considered an eastern extension of the mobile orogenic belt of Sind and Baluchistan rather than a part of the unfolded and stable peninsular foreland as hitherto has been supposed. In this orogeny Mesozoic and Tertiary terrestrial and marine sediments and the Deccan trap were involved in folding movements that began in middle Tertiary time and continued intermittently into the Quaternary. These stresses are still operative as indicated by the great earthquake which affected all Kutch in 1819 and lesser quakes in 1844 and 1945 (Wynne, 1872, p. 29–47). More recently an earthquake of moderate to severe intensity occurred on July 22, 1956. This quake, whose epicenter was at Anjar, also caused considerable damage in the Bhachau area.

The general trend of anticlinal folds in Kutch is northwest in the western part of the state but swings to the east in the eastern part. Moreover, along major anticlinal axes the folds are segmented in an en echelon manner which Auden (1951, p. 113–114) suggests may have been caused by oblique tear faulting. Typically, the anticlinal folds of Kutch are asymmetrical with gentle dips on the south flanks and steep dips on the north flanks which in places are bound by strike faults. Also typical of Kutch folds are remarkable small domes and structural saddles commonly alined along the anticlinal axes like beads on a string. The trends, en echelon arrangement and asymmetrical shape of Kutch folds suggests (Auden, 1951, p. 113; 1952, p. 57) that the forces acted in couples against a western projection of the Indian peninsular shield represented by the Precambrian crystalline rocks of Nagar Pakar along the northern margin of the Great Rann of Kutch.

The principal structural feature of the Bhachau region is the asymmetric Wondh-Amardi anticline that enters the area on the west continues eastward for about 14 miles and closes and plunges about 1 mile east of Wondh (pl. 1). This structure is in fact the eastern extension and termination of the great Habo anticline (Auden, 1952, p. 58) that lies along the northern edge of the Kutch mainland. Strike faults are probably present along the north side of the Wondh-Amardi anticline in the Bhachau region, however, the field evidence for such faulting is not conclusive and faults are not shown in plate 1. At one point in the channel of Kagihar ka Vokra about 300 feet west of the Kageshwar Mahadev temple and about 1½ miles east of Kumbhardi, Manchhar sediments strike N. 30° and dip vertically in what is apparently a silicified fault zone. Elsewhere along the Tertiary-Upper Bhuj contact on the north flank of the anticline, field evidence of faulting is generally lacking—possibly because erosion has reduced Upper Bhuj and Manchhar sediments in the contact zone to an almost featureless surface. South of the axis of the Wondh-Amardi anticline, the Upper Bhuj series, the overlying Deccan trap, and the laterite dip southerly at from about 3° to 15° into a broad structural downwarp which is filled with late Tertiary fluviatile, estuarine, and marine deposits. Likewise on the north side of the anticline, Upper Bhuj sediments dip northerly at from about 20° to 55° into a structural trough which is filled with similar late Tertiary and Quaternary deposits of the Great Rann of Kutch and which is bounded on the north by the en echelon anticlinal folds of the Rann Islands. South of Kabrau and Kumbhardi is a minor downfold or syncline in the Upper Bhuj that contains an outlier of Manchhar sediments (pl. 1).

GROUND WATER IN THE UPPER BHUJ SERIES

OCCURRENCE

The principal ground-water reservoir in the Bhachau area occurs in the permeable sandstone of the Upper Bhuj series. The upper limit of this reservoir is marked by a water table below which the rocks of the Bhuj series are believed to be almost continuously saturated to a depth of 1,000 feet or more.

At shallow depth in the ground-water reservoir, that is between the water table and about 100 feet below, water in the Upper Bhuj is generally unconfined. At greater depth, however, it is inferred that the Upper Bhuj contains water under confined conditions. Hydrostatic heads in the shallow part of the ground-water reservoir are indicated by existing dug wells none of which extends more than 25 feet below the water table. At greater depths in the reservoir, hydrostatic heads are inferred to be lower than the water table in the recharge area, that is in the central upland, but higher than the water table in the discharge areas such as those east of Wondh and northwest of Sikra (pl. 1).

FORM AND DEPTH OF THE WATER TABLE

The form of the water table for April 1953 in the Upper Bhuj series is shown by 5-foot contours in plate 1. These contours show the water table near the lowest stage of the climatic year and are based on measurements of the altitudes of the water surface in 84 observation wells and 5 tracts of phreatophytes where the water table is at or near the surface. Sea-level datum for these altitudes was determined by spirit levelling.

As indicated in plate 1 the water table slopes generally eastward from an altitude of about 105 feet just west of the Dayapur and Bhachau irrigated tracts to an altitude of less than 80 feet in the natural discharge area east of Wondh. Between the meridians of Kabrau and Sikra, the water table slopes north to northeast from an altitude of 120 feet or more along the axis of the central upland to less than 100 feet along the Manchhar-Upper Bhuj contact near Sikra. West of the meridian of Kabrau, the water table slopes northwest from an altitude of 120 feet or more in the central upland to less than 80 feet near Budhramora. In the area ½ to 1 mile north of Chopadwa, the water table has a southerly slope. It appears, therefore, on the basis of incomplete data that the water table slopes away from an elongated ground-water high whose apex is located about 1½ to 2 miles south of the Kabrau, Kumbhardi and Sikra irrigated tracts in the central upland (pl. 1).

The water table crops out in springs and seeps or lies within a few feet of the land surface in areas of natural ground-water discharge north of Amardi, northeast of Kabrau, northwest of Sikra and east of Wondh as shown by shading in plate 1. The greatest observed depth to water below land surface was 76 feet in a well that lies in the irrigated tract about three quarters of a mile west of Chopadwa (pl. 1); however, along the topographic divide of the central upland the depth to water may be as much as 100 feet or more below land surface. The ranges in and the median depths to water in wells tapping water in Upper Bhuj sandstone in nine irrigated tracts of the Bhachau area are shown in table 6. The ranges and medians given are based on water levels measured between October 1952 and April 1953. It is noted that the deepest water levels occur in the Wondh and Bhachau irrigated tracts and the shallowest, in the Kabrau-Pankadsar tract. In the other irrigated tracts water levels of moderate depth occur. Depths to water below land surface in typical wells during April 1953 are shown in plate 1.

TABLE 6.—*Range and median depths to water in irrigated tracts*

Irrigated tract	Wells observed	Range in depth to water (feet below land surface)	Median depth to water (feet below land surface)
Bhachau	230	30–75	46
Wondh	129	8–78	49
Sikra	117	8–57	40
Khumbhardi	57	19–45	33
Kabrau-Pankadsar	22	15–39	28
Amardi	75	15–57	33
Morghar	11	13–48	36
Budhramora	50	26–48	34
Chopadwa	37	15–78	34

FLUCTUATIONS OF THE WATER TABLE

In the Bhachau area the water table is known to fluctuate in response to infiltration from rainfall and from runoff in stream channels, to discharge by evaporation and transpiration, to spring discharge, and to withdrawals from wells for irrigation. In addition, fluctuations not distinguished may occur for other reasons.

Each year a seasonal rise in the water table occurs concurrently with the rain-bearing southwest monsoon which ordinarily lasts from late June until the end of September. Such rises are caused largely by increments to the ground-water reservoir by direct infiltration from rain and to less extent by infiltration from ephemeral streams in flood. Some rise also results from recovery of water levels owing to diminished irrigation draft on the ground-water reservoir during the rainy season. Cultivators in the Bhachau area report that water levels in wells rose by 6 to 10 feet or more, largely as a result of the above-average monsoon rains of 1953, which were of the order of 120 percent of the mean. Smaller rises are registered in years with average or below-average precipitation. During years with less than half the average precipitation, infiltration to ground water may be very small or negligible. As suggested in table 2, such years may occur with an average frequency of about 1 out of every 5.5 years in the Bhachau area. During the dry season or northeast monsoon which lasts from October until the following June, a gradual decline of the water table occurs as ground-water storage is depleted by evaporation and transpiration, by spring flow, and by withdrawals from wells for irrigation, domestic, and stock use.

As White (1932, p. 24–54) and others have shown, certain species of plants commonly send their roots down to the water table or to the capillary fringe and by transpiration induce a diurnal fluctuation in the water-table stage in shallow water tracts. These plants are phreatophytes or ground-water plants (Robinson, 1958, p. 9) that in the Bhachau area include palms, willows, tamarisk, sedges, salt grass and other unidentified species. An automatic water-stage recorder was placed on a shallow pit dug in the extensive tract of salt-grass half a mile east of Wondh. The records obtained indicate a diurnal fluctuation of about 0.05 foot during January 1953. These fluctucations are probably caused in part by transpiration of ground-water plants and in part by evaporation of water from the soil zone. Transpiration and evaporation also contribute to the seasonal decline of the water table through the dry season, but the overall effects of this draft have not been evaluated in the present study.

Daily and seasonal fluctuations of the water table in the cultivated tracts are also caused by withdrawals of water from wells for irrigation. The hydrographs of figure 2 show typical fluctuations of water levels in well 422 in the Bhachau irrigated tract, well 925 in the Amardi tract and well 691 in the Sikra tract, respectively. These fluctuations are caused largely by intermittent withdrawals from neighboring wells in these irrigated tracts. The draft from irrigation wells also doubtless contributes to the seasonal decline of the water table, but sufficient data are not available from the present investigation to determine the magnitude of this effect.

In addition to these fluctuations of relatively short term, the water table no doubt rises and falls progressively during longer periods that correspond to cycles of wet and dry years. For example, water levels in observation wells in April 1954 were considerably above their position in April 1953 owing to above-average monsoon rains in 1953 and to deficient rain in the 1952 monsoon. Thus there was a net increase

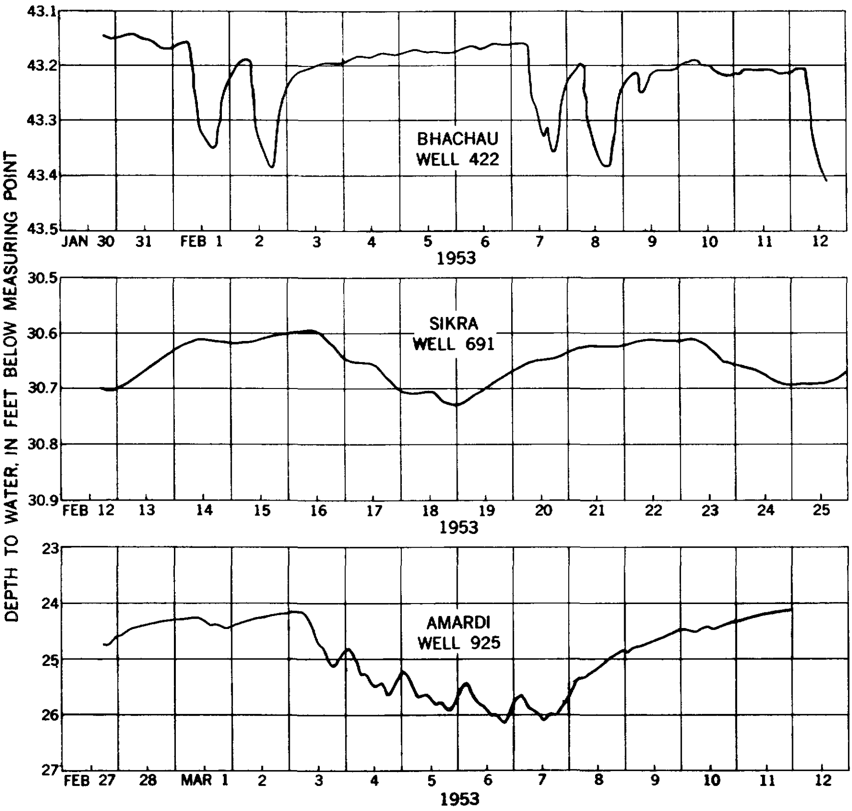

FIGURE 2.—Hydrographs showing fluctuations of water levels in wells 422, 691 and 925 caused by withdrawals from neighboring wells.

in carryover ground-water storage between the two observations. The magnitude of the increase is indicated by water levels measured in observation wells in the several irrigated tracts as summarized in table 7. It is noted that the greatest rise of water level between April 1953 and April 1954 occurred in the Bhachau irrigated tract and

TABLE 7.—*Range and median net rise in water level in observation wells between April 1953 and April 1954*

Irrigated tract	Wells measured	Range in net rise (feet)	Median net rise (feet)
Bhachau	32	3.27–14.34	7.72
Wondh	10	2.99–8.50	5.31
Sikra	10	2.96–9.14	5.85
Khumbardi	4	5.25–7.43	5.68
Kabrau-Pankadsar	4	3.73–5.01	4.02
Amardi	6	3.80–5.68	5.25
Morghar	2	4.04–5.57	4.04
Budhramora	5	5.40–6.38	6.05
Chopadwa	7	2.14–3.10	2.78

the least in the Chopadwa tract. If it is assumed that the specific yield of the water-bearing material is 10 percent, then a net rise of 7.7 feet in the 1,142 acres of the Bhachau tract would be equivalent to a carryover of 879 acre-feet of water. Similarly in the 138 acres of the Chopadwa tract with a net rise of 2.2 feet, the carryover would be only 29 acre-feet.

SOURCE, MOVEMENT, AND DISPOSAL

The ground-water reservoir, which occurs in the Upper Bhuj series is sustained and recharged in most years by infiltration from rainfall. A part of the rain which falls returns to the atmosphere by evaporation, a part runs off on the surface in streams, but a considerable part seeps down to the water table to recharge the ground-water body. Available data were not sufficient to determine the nature and amount of the recharge accurately. Recharge probably takes place, however, by direct infiltration from rain on the land surface, by infiltration from ephemeral streams while in flood, and by return seepage from irrigation in cultivated tracts. In most of the central upland belt, the Upper Bhuj is mantled by sandy soil or loose sand that is moderately permeable and absorptive, and thus surficial conditions are optimum for infiltration. Recharge is potentially possible throughout this belt where the water table is 10 feet or more below the land surface. In an average year the recharge may be of the order of 20 percent of the annual rainfall; however, the amount of recharge is probably greater in years with above average precipitation. Such years occur with an average frequency of once every 2.3 years (table 2). In years with less than half the mean rainfall recharge is probably very small or negligible.

Water moves along flow lines in the ground-water reservoir that are oriented normal to the contours on the water table as shown in plate 1; moreover, the water is in constant motion from areas of intake or recharge toward areas of discharge or disposal. Although differences in permeability exist among component members of the Upper Bhuj series, the formation functions essentially as a single hydrologic unit. The water table contours for April 1953 (pl. 1) indicate that near Bhachau and Wondh, ground water was moving eastward toward points of natural discharge in phreatophyte tracts east of Wondh and northeast of Bhachau; that near Chopadwa, ground-water movement was southward to southeastward toward the irrigation wells in the vicinity of the village; that in the vicinity of Sikra, Kumbhardi, and Kabrau the ground water was moving generally northward toward the phreatophyte tracts north of Sikra and Kabrau; that in the Amardi and Budharmora sectors ground water was moving westward and northwestward toward the springs and phreatophyte tracts along Dudhai Creek (Taylor and Oza, 1954, pl. 1) west of the Bhachau area; and that local deflections of water-table contours near Kumbhardi, Sikra, Dayapur, Bhachau, and Wondh resulted from withdrawals of ground water from wells for irrigation.

The movement of ground water through permeable Upper Bhuj sandstone in the Bhachau area is controlled in part by the interrelations of geologic structure, stratigraphy, and topography and in part by withdrawals from wells for irrigation in cultivated tracts. In the Bhachau and Wondh tracts, ground-water movement is eastward toward the phreatophyte tract and springs east of Wondh that occur in a topographic low on the nose of the plunging Wondh-Amardi anticline (pl. 1). In the Kabrau, Kumbhardi, and Sikra tracts the northerly movement of ground water is across and normal nearly to the axis of the Wondh-Amardi anticline. This movement is from the higher recharge area in the central upland toward phreatophyte tracts that occur in topographic lows along the stratigraphic contact of the Bhuj and Manchhar series north of Kabrau and Sikra. Thus in these tracts, ground-water movement is controlled to a considerable extent by topography and the stratigraphic barrier of relatively impervious Manchhar sediments north of the Bhuj-Manchhar contact (pl. 1). This same barrier apparently also tends to deflect ground-water movement in the Amardi and Budhramora tracts to the west and northwest toward springs and phreatophyte tracts along Dudhai Creek (Taylor and Oza, 1954, pl. 1) west of the map area. As indicated by the water-table contours (pl. 1) near Kumbhardi, Sikra, Dayapur, Bhachau and Wondh, local diversion of ground-water flow from its natural direction of movement has resulted from withdrawals for irrigation in cultivated tracts near these villages. Small troughs in the water table resulting from such withdrawals are particularly well developed south of Kumbhardi, southeast of Sikra, southeast of Dayapur, west of Bhachau, and west of Wondh (pl. 1).

Ground-water discharge from Upper Bhuj strata in the Bhachau area takes place principally by evaporation and transpiration of ground-water plants, by spring flow, and by withdrawals from wells for irrigation. Evaporation and transpiration occur principally in those tracts where the water table is less than 10 feet below the land surface. Formerly such tracts were more extensive than at present; however, owing to the draft on ground water from irrigation wells near these tracts there has been some lowering of the water table and a corresponding reduction in the areal extent of the shallow-water tracts. The location and extent of tracts of shallow water table (areas of phreatophytic vegetation) in April 1953 are shown by shading in plate 1 and are described in table 8. These tracts support more or less vigorous growths of ground-water plants or phreatophytes which include palms, willows, salt-grass, tamarisk, and sedges. These plants evidently dissipate a considerable volume of ground water by transpiration. Where the water table is at or near the surface or the capillary fringe extends to the surface, there is also active ground-water discharge by evaporation. The amount of transpiration and evaporation (evapotranspiration) varies considerably from day to day and from season to season depending on the rate of plant growth, temperature, relative humidity, wind movement, and other factors. In the Bhachau area, ground-water discharge by evapotranspiration is most active in phreatophyte tracts totaling about 317 acres whose extent and location are described in table 8 and are shown by shading in plate 1. Reliable data on the rate of evapotranspiration in phreatophyte tracts of the Bhachau area are not available; however, in the contiguous Dudhai area to the west of the rate of evapotranspiration during April 1952 was estimated at 0.0078 feet of water per day (Taylor and Oza, 1954, p. 24). If the rate of evapotranspiration in the Bhachau region can be assumed to be of the same order of magnitude during April 1953, then the ground-water discharge from 317 acres of shallow-water tracts was of the order of 2.5 acre-feet per day or roughly 679,000 imperial gallons per day.

TABLE 8.—*Location and areal extent, in acres, of shallow-water tracts*

About 0.3 mile north-northwest of Amardi	12
About 0.2 mile northeast of Kabrau	10
A strip extending from 0.5 mile northwest of Sikra to 0.3 mile east of Sikra	30
Two small tracts 1.2 miles north-northeast of Bhachau	11
A tract from 0.1 to 1 mile east of Wondh	254
Total in Bhachau area	317

Ground-water discharge by spring flow occurs in appreciably quantity only in the shallow-water tract east of Wondh. In this tract are several small springs which issue from Upper Bhuj sandstones and whose aggregate discharge in April 1953 was about 25 imperial gallons per minute or roughly 0.13 acre-foot per day. This water is locally dissipated by evaporation.

On the basis of a detailed inventory of existing wells in the Bhachau area, the total rate of withdrawal of ground water for irrigation in 1953 from nine cultivated tracts was estimated at about 4,680 acre-feet per year. This is equivalent to an average draft of approximately 12.8 acre-feet per day or about 3,476,000 imperial gallons per day. Thus in April 1953 the natural ground-water discharge was of the order of 2.6 acre-feet per day by evapotranspiration and by spring flow and the artificial discharge by withdrawals from wells for irrigation was about 12.8 acre-feet per day. The combined discharge of ground water from Upper Bhuj aquifers of the Bhachau area by evaporation, transpiration, spring-flow, and withdrawals for irrigation was of the order of 15.4 acre-feet per day in April 1953.

CHEMICAL QUALITY

Samples for chemical analysis were taken during March-April 1953 from 170 wells of the Bhachau area to determine the general chemical character of the water in the shallow part of the ground-water reservoir. All these samples were analyzed for bicarbonate, chloride, and sulfate by Mr. B. N. Sen, chemist, Geological Survey of India, in a field laboratory at Bhachau. The analytical results are summarized in tables 9 and 10. As indicated in these tables, chloride is generally the most abundant of the three anionic constituents; bicarbonate is intermediate; and sulfate is the least abundant.

TABLE 9.—*Summary of results of chemical analyses of water samples from the Bhachau area, March–April 1953*

	Parts per million							
	Number of samples in range				Percent of samples in range			
	0–200	200–500	500–1000	1000+	0–200	200–500	500–1000	1000+
Bicarbonate (HCO_3)	3	139	26	2	2	82	15	1
Chloride (Cl)	37	40	42	51	22	23	25	30
Sulfate (SO_4)	96	58	13	3	56	34	8	2

TABLE 10.—*Range and median content of bicarbonate, chloride and sulfate in the Bhachau area, March–April 1953*

Irrigated tract	Wells sampled	Parts per million								
		Bicarbonate (HCO_3)			Chloride (Cl)			Sulfate (SO_4)		
		Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median
Bhachau	53	850	200	400	3,895	26	443	1,290	Trace	170
Wondh	26	1,075	150	400	4,554	26	639	1,020	Trace	150
Sikra	25	675	225	400	2,401	52	600	610	10	120
Khumbardi	14	525	300	375	1,631	313	626	390	50	200
Kabrau-Pankadsar	8	500	325	375	2,009	548	1,122	390	110	260
Amardi	11	500	325	350	3,158	352	848	630	80	200
Morghar	4	475	325	375	2,975	221	1,344	740	70	230
Budhramora	13	550	225	350	1,018	65	195	540	Trace	70
Chopadwa	11	1,125	100	320	2,740	52	234	1,590	Trace	50

Plates 2, 3, and 4 show the areal distribution of bicarbonates, chlorides, and sulfates, respectively, in the shallow ground water of the Upper Bhuj series during March–April 1953. A comparative inspection of plates 2, 3, and 4 indicates that the areal distribution patterns of the three anions are generally similar. Among the three anions for which maps were constructed, the chloride map (pl. 3) gives possibly the best index of the general distribution of ground-water salinity in the Bhachau area. The water of best chemical quality—less than 100 ppm (parts per million) of chlorides—occurs in the undeveloped and unirrigated parts of the central upland. All along the northern margin of the central upland from Budhramora to Dayapur is a belt from 0.1 to 0.75 mile wide in which the chloride content exceeds 500 ppm and the water is slightly to markedly brackish. In this belt, the chloride content is commonly 1,500 ppm or more near the northern limit of the Upper Bhuj series. From the vicinity of Bhachau extending north-northeastward to the northern limit of the Upper Bhuj contact is a second belt about 1 mile wide in which the shallow ground water contains chlorides in concentrations greater than 500 ppm. Between Bhachau and Wondh is a belt of low chlorides (pl. 3) in which the water is of very good chemical quality; however, beginning in the area about 1 mile west of Wondh and proceeding eastward, the chloride content gradually increases from about 500 ppm to more than 3,000 ppm in the phreatophyte tract east of Wondh (pl. 3).

A comparative inspection of plates 1 and 3 indicates a fairly well marked relation of the distribution of ground-water salinity with the pattern of ground-water circulation. Thus the isochlor lines of plate 3 show progressive increases in salinity downgradient with the slope of the water table particularly in the belt of northerly ground-water flow between Amardi and Sikra. A similar pattern is indicated by isosulf lines of plate 4.

The high content of dissolved solids in the shallow ground water of certain sectors of the Bhachau area results from the continuing process of evapotranspiration in phreatophyte tracts with accumulation and concentration of residual salts; return seepage from the irrigation of cultivated fields that tends to leach down salts accumulated in the soil zone by evaporation; saliferous seepage from human and animal ordure near villages; and combinations of these factors. High salinity in the belt stretching from Budhramora to Sikra is apparently the effect of a combination of residual concentration by evapotranspiration as well as concentration by return seepage from irrigation. The high-chloride belt extending north from the vicinity of Bhachau is probably primarily the result of recurrent down leaching of salts by return seepage from irrigation. Again, high salinity in the Wondh tract appears to be related both to concentration by evapotranspiration and to return seepage from irrigation. In contrast, the salinity of the shallow ground water in the recharge area of the central upland is relatively low probably owing to recurrent dilution by infiltration from rain and to absence of irrigation.

No information is available on the chemical character of the water in the deeper parts of the ground-water reservoir. The results of deep wells drilled in the Anjar-Khedoi (Taylor and Pathak, 1960, p. 83–84) and Dudhai, (Taylor and Oza, 1954, p. 31) areas indicate the content of dissolved solids probably would be substantially higher there than in the shallow part of the ground-water reservoir.

Sufficient data were not available from the present investigation to evaluate seasonal or long-term fluctuations in ground-water salinity. Cultivators report verbally that salinity in the shallow water irrigated tracts probably is generally highest at the end of the dry season and lowest during or shortly following the period of monsoon recharge. It is also reported that perceptible increases in salinity in the shallow ground water occur during dry cycles of two or more years.

PRESENT UTILIZATION

As based on a detailed inventory extending from November 1952 to April 1953, there were some 742 wells in the Bhachau area that tap water-bearing sandstone at depths of less than 90 feet in the Upper Bhuj series. All the wells that were inventoried are located on plate 1. Detailed hydrologic data for these wells are not included in the present report but are available for consultation in the file of the Geological Survey of India in Calcutta. At the time of the inventory, all wells in the Bhachau area were open, dug construction and of relatively large diameter. The depths of the dug wells range from 13 to 87 feet, and most of these extend to depths of 5 to 15 feet below the water table. Water for irrigation and, to a lesser extent, for domestic and livestock purposes was drawn almost exclusively by a "mote" (leather bag) each worked by a yoke of bullocks. The approximate average draft per mote per day in the Bhachau region is about 6,000 imperial gallons. Thus the present (1955) draft from individual irrigation wells by this means ranges from about 6,000 to 24,000 imperial gallons per day with one to four motes working simultaneously in the same well. Potentially, however, many individual dug wells of the Bhachau area are capable of yielding as much as 100,000 imperial gallons per day when fitted with mechanical pumps.

The principal crops irrigated from wells are wheat and millet and to lesser extent garden vegetables and fruits such as papayas, guavas, mangoes, and bananas. In April 1953 there were 4,165 acres in the Bhachau area (map area of plate 1) that were being permanently or intermittently irrigated from wells during an irrigation season which lasts about 8 to 10 months a year. This acreage was covered by some 486 active wells from which water is drawn by motes and bullocks. At the time of the well inventory in 1952–53, the total draft for irrigation was at an average rate of about 4,680 acre-feet per year or an average of 12.8 acre-feet per day. The acreage irrigated, the number of active wells, the annual draft from wells, and the average yearly water use per acre in the several irrigated tracts of the Bhachau area are given in table 11.

TABLE 11.—*Summary of irrigated acreage and water use in the Bhachau area, 1952–53*

Irrigated tract	Area irrigated by wells (acres)	Active wells in tract	Average annual draft from wells (acre-feet)	Average yearly water use per acre (acre-feet)
Bhachau	1,142	141	1,379	1.2
Wondh	764	102	893	1.2
Sikra	674	76	603	.9
Kumbhardi	412	45	465	1.1
Kabrau-Pankadsar	107	18	179	1.7
Amardi	368	38	454	1.2
Morghar	102	8	73	.7
Budhramora	458	37	395	.9
Chopadwa	138	21	242	1.7
Total or average	4,165	486	4,683	1.1

Table 11 shows that the irrigated area covered per individual well averages only about 8.6 acres. Column E in table 10 also gives a comparative picture of the intensity of cultivation and water use among the several irrigated tracts. Thus in the Kabrau-Pankadsar and Chopadwa tracts there is a comparatively high proportion of permanently irrigated fruit and garden crops, and average water use (1.7 acre-feet per acre) is higher than in any of the other irrigated tracts. A considerable part of the cultivated grain land in the Morghar tract is irrigated only intermittently so the average water use (0.7 acre-feet per acre) is lower than in other tracts in the Bhachau area.

FUTURE DEVELOPMENT

The natural ground-water discharge from the Bhachau area is estimated, on the basis of the present investigation, to be about 2.9 acre-feet, or 787,000 imperial gallons, per day. This water is now wasted by evaporation, by transpiration by worthless ground-water plants, and by unused spring flow. A large part of this natural discharge could be salvaged and recovered from the tube wells put down in favorable parts of the Bhachau area.

It is estimated that more than 60 percent of the natural discharge or about 500,000 imperial gallons a day could be developed from drilled production wells in the Bhachau area for the Kandla Port water supply without serious detriment to present irrigation supplies

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in cultivated tracts. An additional draft of perhaps 500,000 imperial gallons a day might also be made on the ground-water body, but the eventuality of some lowering of water levels in existing irrigation wells would have to be anticipated. In any case, sites for new production wells should be carefully selected to minimize drawdowns of water levels in wells and to avoid contamination from brackish-water tracts. From the results of the present study the tract of Upper Bhuj standstone in the central upland that lies south of the 100 ppm isochlor (pl. 3) between the meridians of Budhramora and Sikra is believed to be most suitable for drilling production wells. In this tract the water table is generally within 80 feet of the surface; permeable and productive aquifers are present to a depth of several hundred feet below the land surface, and the ground water is of fair to good chemical quality.

To improve the Kandla Port water supply the following sites for construction of tube wells are suggested:

1. 1 mile due south of Budhramora.
2. 1 mile due south of Amardi.
3. 1.2 miles due south of Khumbhardi.
4. 1.2 miles due south of Sikra.
5. 1.2 miles due north of Chopadwa.

At each of these five sites the requisite depth of drilling would be about 350 feet. In each place is is suggested that the well be drilled in such a manner that blank 12- to 14-inch casing can be set from the surface to a depth of about 135 feet. Through water-bearing strata between 135 and 350 feet, the well should be drilled so as to accommodate either a 10-inch prefabricated well screen or a 10-inch slotted casing with appropriate gravel envelope. The water-bearing materials at the sites indicated are medium- to coarse-grained soft friable sandstones. Thus the well screens selected for these materials should have slot openings of such width as to retain approximately 60 percent of the sand sizes and allow 40 percent to enter the well and be pumped out. In this manner a natural envelope of coarse sand and fine gravel will be gradually built up around the well screen. Alternatively slotted casing with gravel packing can be placed in the water-bearing zones between 125 and 350 feet. For gravel packing natural rounded gravel of ⅛- to ¼-inch diameter should be used. After completion, each well should be thoroughly developed by pumping, surging, and backwashing in order to remove finer sand and silt sizes from in and around the well envelope.

To minimize local drawdowns in water level and to avoid possible brackish water contamination, the pumping draft from each tube well should be maintained at an optimum of 250,000 imperial gallons a day or less. This would call for a daily 8-hour pumping schedule at each well at the rate of about 500 imperial gpm. Thus with four supply wells and one well for emergency or standby use it would be possible to develop about 1 million imperial gallons a day from the Bhachau area for the Kandla Port water supply.

If water supply for Kandla Port is developed in the Bhachau region, it would not be desirable or feasible to expand present groundwater use for irrigation. Indeed, restrictive measures may even be necessary to protect this potential water supply for the port and township during its later stages of growth. If on the other hand eventual development of water from the Bhachau area is not foreseen or contemplated in the future, then ground water now unused could be recovered through drilled production wells for irrigation. Such wells could be located at intervals of 0.5 to 0.75 mile along an east-west line passing 1 mile south of Budhramora, 1 mile south of Amardi, 1.2 miles south of Khumbhardi, and 1.2 miles south of Sikra. The optimum number, depth, construction, and pumping draft would be about the same as those suggested for the Kandla Port water supply.

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