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Hydrogeological and hydrochemical characteristics of alluvial aquifers in the Brahmaputra Valley, Assam, India

A. D. Patgiri[1] and Swapna Devi[2]
[1]*Department of Geological Sciences, Gauhati University, Guwahati 781014, India*
[2]*Central Ground Water Board, North Eastern Region, Tarun Nagar, By Lane – 1, Guwahati 781 005, India*

ABSTRACT

The Brahmaputra Valley comprising a thick pile of unconsolidated alluvial deposits encompasses an area of about 63,450 km² in the state of Assam, India. It is composed of unclassified Older and Newer alluvial deposits consisting of boulders, cobbles, pebbles, gravels as well as sand of various grades, silt, and clay. The area is occupied predominantly by Recent and Older floodplains represented by udifluvents (younger alluvial soils), and palenstalfs and haplaquents (older alluvial soils). The Piedmont zone fringing the northern foothill region of the valley is represented by usthorthents (Bhabar Soils) and haplaquolls (Terai Soils).

Hydrogeologically, the northern and southern banks of the river Brahmaputra differ considerably. The northern bank is generally characterised by a single aquifer system of great thickness and varied composition down to a depth of about 150 m, where mostly an unconfined aquifer is found. Semiconfined aquifers are also seen at places where the sediments are stratified. Shallow tube wells yield 30 to 60 m³/hr for a drawdown of 1–2 m. The yield of deep tube wells is found to range from 100 to 250 m³/hr for a drawdown of 4–10 m. The depth to water table in the piedmont zone varies from 5 to 40 m with an average fluctuation of 3–10 m. The average hydraulic conductivity of the aquifer system is found to range from 30 to 200 m/day.

The southern bank is characterised by the presence of unconfined and semiconfined aquifers. Some perfectly confined aquifers as well as some perched aquifers are also encountered locally. Shallow tube wells can yield 25–35 m³/hr for a drawdown of 2 m while deep tube wells are capable of yielding 100–250 m³/hr for a drawdown of 4–8 m. The water table rests within a depth of 2–6 m from the land surface. The average hydraulic conductivity varies from 30 to 200 m/day. The decadal variation of water table in the alluvial aquifer of the Brahmaputra Valley indicates a rising trend of water level. Dynamic groundwater potential of the shallow aquifer zone is within the range of 15,440 mcm.

Hydrochemically, the groundwater of the Brahmaputra Valley is found to be suitable for domestic and irrigation purposes, except for higher concentration of iron. The pH value ranges from 6.8 to 8.7, indicating neutral to slightly alkaline nature of groundwater. Low value of electrical conductivity and total dissolved solids implies fresh nature of groundwater. Piper trilinear plot reveals the preponderance of alkaline earths (Ca, Mg) and weak acids (HCO_3+CO_3) over alkalis (Na, K) and strong acids (SO_4, Cl) in the groundwater of the majority of the study area indicating Ca + Mg - HCO_3 type.

INTRODUCTION

The Brahmaputra Valley constitutes one of the richest repositories of groundwater in India. The valley comprising an area of about 63,450 km² in the state of Assam is bounded by longitudes 89° 30' 00" and 95° 55' 00" E, and latitudes 25° 40' 00" and 27° 30' 00" N (Fig. 1). The valley being composed of a thick pile of unconsolidated alluvial deposits is characterised by the existence of prolific aquifer zones down to a maximum explored depth of 250 m.

The average annual rainfall in the region varies from 1,500 to 3,500 mm, the bulk of which is precipitated between May and September. Winter rainfall is usually scanty but may reach up to 10–15% of annual precipitation. The area enjoys a humid subtropical climate with maximum and minimum temperatures ranging from 27° to 38° C and 6° to 15° C, respectively.

The valley has undergone diversified pedogenesis depending on geology, palaeogeography, and climate resulting in the development of various soil types. The alluvial plain comprising Recent and Older floodplain deposits is represented by udifluvents (younger alluvial soil) as well as palenstalfs and haplaquents (older alluvial soil). The piedmont zone fringing the northern foothill region of the valley is represented by ustorthents (Bhabar soil) and haplaquolls (Terai soil).

The land use pattern of the valley region is characterised by cropped land, forestland, and tea plantation. Cropped land predominates, as agriculture is the mainstay of the population. The present practice of mono cropping, which is solely dependent on monsoon rains, can be effectively converted into multiple-cropping pattern with assured irrigation during lean periods based on rational utilisation of groundwater. The status of groundwater development in the

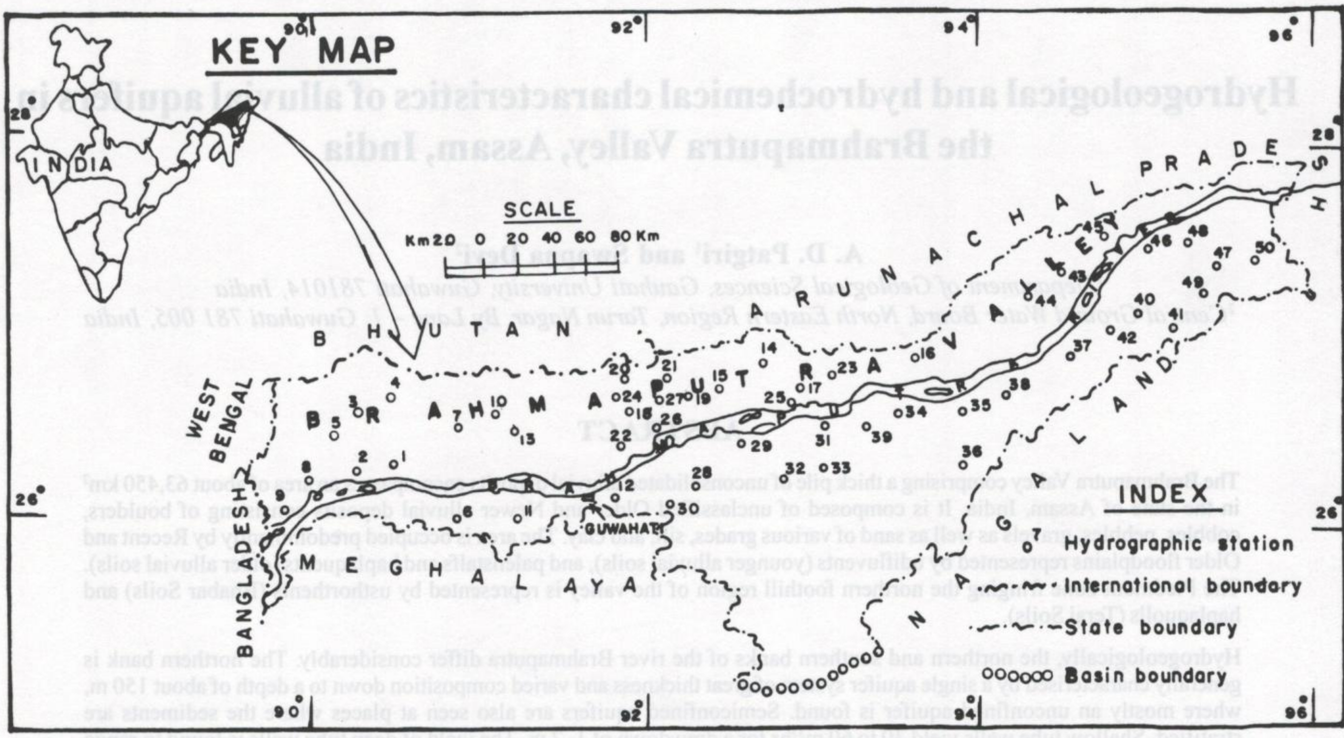

Fig. 1: Location map of the study area showing position of hydrographic network stations

state of Assam is presently very modest and hence the valley with its prolific aquifer zones offers an ample scope for large-scale groundwater development and would thus contribute towards the economic upgrading of the region as a whole.

This paper is aimed at evaluating the hydrogeological framework of the alluvial aquifer zones in the Brahmaputra Valley, aquifer parameters, yield characteristics, and resource potential of shallow aquifer zones as well as assessing the hydrochemical framework of groundwater in terms of hydrochemistry and water quality.

PHYSIOGRAPHY AND DRAINAGE

The northern flank of the valley is characterised by a stepped sequence of three to four geomorphic surfaces. Each surface has a steep slope near the mountain front and a very gentle gradient near the Brahmaputra River corresponding, respectively to the piedmont plain and the floodplain. The southern flank is, however, characterised by a relatively flat alluvial plain with a monotonous gentle gradient towards the river. At places inselbergs of isolated hills comprising gneissic rocks belonging to the Shillong Plateau are found protruding above the valley floor, especially towards the western part.

The mighty river Brahmaputra, which originates in Tibet on the northern slopes of the Himalayas, drains the valley with its innumerable tributaries. The total length of the Brahmaputra River from its origin to its outfall in the bay of Bengal is about 2,880 km; of which 720 km lie in the state of Assam. The tributaries on the northern bank, which originate from the Sub-Himalayan and Trans-Himalayan Ranges, bring down a heavy load of coarser sediments due to high gradient, while those of the southern bank, originating from Khasi, Garo, Mikir and Naga-Patkai Ranges, are characterised by finer sediment load due to low gradient as well as meandering nature of the channels. Most of the major tributaries of the Brahmaputra maintain sizeable base flow during the lean period.

GEOLOGICAL SETTING

The major part of the Brahmaputra Valley is covered by Quaternary sediments comprising Older and Newer alluvial deposits consisting of sand and gravel of various grades with thin bands of silt and clay (Fig. 2). The Older or High Level alluvium was formed by the coalescence of alluvial fans (piedmont zone) along a narrow tract fringing the northern foothills. It comprises coarser clastics ranging in size from sand to boulder. The thickness of alluvial cover is variable and ranges from less than 100 m to more than 1,000 m. Generally, it increases towards the eastern part of the valley where the thickness of alluvium along with Plio-Pleistocene sediments (Dhekiajuli Group) may reach up to 2,000 m (Handique et al. 1989). Groundwater exploration by the Central Ground Water Board, Government of India in the extreme southwest of the valley indicates that the alluvium is from 70 m to 100 m thick, and below it is the crystalline basement.

Sands and gravels are predominant in the northern flank of the valley while the southern flank is characterised by the preponderance of finer clastics comprising sands of various

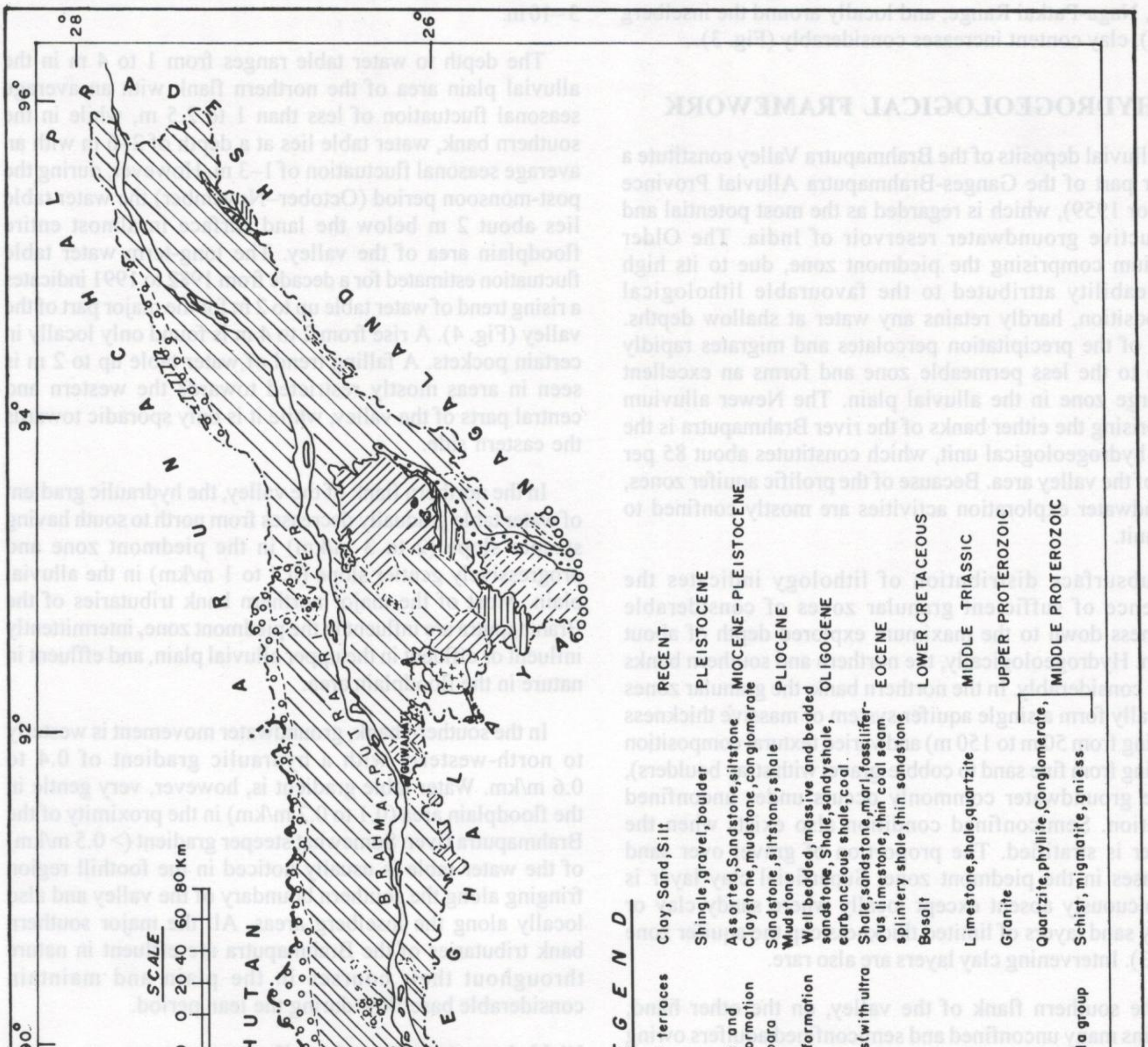

Fig. 2: Geological map of the Brahmaputra Valley, Assam showing various formations

grades, silts, and clays. In the northern flank, the percentage of gravels, particularly the coarser ones, gradually increases towards the north from floodplain to piedmont zone. In the southern flank (in the vicinity of the Shillong Plateau, Mikir Hills, Naga-Patkai Range, and locally around the inselberg areas), clay content increases considerably (Fig. 3).

HYDROGEOLOGICAL FRAMEWORK

Alluvial deposits of the Brahmaputra Valley constitute a major part of the Ganges-Brahmaputra Alluvial Province (Taylor 1959), which is regarded as the most potential and productive groundwater reservoir of India. The Older alluvium comprising the piedmont zone, due to its high permeability attributed to the favourable lithological composition, hardly retains any water at shallow depths. Most of the precipitation percolates and migrates rapidly down to the less permeable zone and forms an excellent recharge zone in the alluvial plain. The Newer alluvium comprising the either banks of the river Brahmaputra is the main hydrogeological unit, which constitutes about 85 per cent of the valley area. Because of the prolific aquifer zones, groundwater exploration activities are mostly confined to this unit.

Subsurface distribution of lithology indicates the existence of sufficient granular zones of considerable thickness down to the maximum explored depth of about 250 m. Hydrogeologically, the northern and southern banks differ considerably. In the northern bank, the granular zones generally form a single aquifer system of massive thickness (ranging from 50 m to 150 m) and varied textural composition (ranging from fine sand to cobble-gravel with stray boulders), where groundwater commonly occurs under unconfined condition. Semiconfined condition also exists when the aquifer is stratified. The proportion of gravel over sand increases in the piedmont zone. Superficial clay layer is conspicuously absent except locally where sandy clay or clayey sand layers of limited thickness cap the aquifer zone (Fig. 3). Intervening clay layers are also rare.

The southern flank of the valley, on the other hand, contains many unconfined and semiconfined aquifers owing to the presence of a number of intervening clay layers. Perched aquifers of very limited extent are also commonly seen especially in the floodplain areas. The surface clay veneer is present throughout the southern flank of the valley (Fig. 3). Aquifers throughout the valley extend regionally except in the western side of the southern flank, where they are discontinuous and localised. In such areas, the aquifers are composed mostly of residual soil (from granite or gneissic rock) and local valley fill deposits, and hence have limited potential.

Water table characteristics

The depth to water table in the piedmont zone usually varies from 5 to 25 m. Exceptionally, very deep water table is found towards the upper piedmont zone in the north-central part of the valley, where water table is encountered down to the depth of 40 m with an average seasonal fluctuation of about 20 m. However, generally seasonal variation of water table in the greater part of the piedmont zone is restricted to 3–10 m.

The depth to water table ranges from 1 to 4 m in the alluvial plain area of the northern flank with an average seasonal fluctuation of less than 1 to 2.5 m, while in the southern bank, water table lies at a depth of 2–6 m with an average seasonal fluctuation of 1–3 m. However, during the post-monsoon period (October–November) the water table lies about 2 m below the land surface in almost entire floodplain area of the valley. The long-term water table fluctuation estimated for a decade from 1982 to 1991 indicates a rising trend of water table up to 2 m for the major part of the valley (Fig. 4). A rise from 2 to 4 m is found only locally in certain pockets. A falling trend of water table up to 2 m is seen in areas mostly restricted towards the western and central parts of the valley, while it is only sporadic towards the eastern side.

In the northern flank of the valley, the hydraulic gradient of water table gradually decreases from north to south having steeper slope (2 to 3 m/km) in the piedmont zone and progressively gentler slope (0.4 to 1 m/km) in the alluvial plain. Most of the major northern bank tributaries of the Brahmaputra are influent in the piedmont zone, intermittently influent or effluent in the upper alluvial plain, and effluent in nature in the floodplain area.

In the southern bank, groundwater movement is westerly to north-westerly with a hydraulic gradient of 0.4 to 0.6 m/km. Water table gradient is, however, very gentle in the floodplain area (0.1 to 0.2 m/km) in the proximity of the Brahmaputra river. Somewhat steeper gradient (> 0.5 m/km) of the water table is usually noticed in the foothill region fringing along the southern boundary of the valley and also locally along the inselberg areas. All the major southern bank tributaries of the Brahmaputra are effluent in nature throughout their courses in the plain and maintain considerable base flow during the lean period.

Yield characteristics and aquifer parameters

Data of yield characteristics of wells in the valley are obtained from shallow tube wells (<50 m depth) and deep tube wells (>50 m depth) constructed by the Central Ground Water Board, Government of India and Irrigation and Public Health Engineering Departments of the Government of Assam for the purpose of groundwater exploration and exploitation. Groundwater exploration in the piedmont zone is very limited. Towards the extreme east, deep tube wells constructed in the lower piedmont zone down to the depth of 90–150 m tapping the 30–40 m thick saturated aquifer zone can yield from 60 to 150 m^3/hr for a maximum drawdown of about 4 m. Due to deep water table as well as high range of seasonal fluctuation, shallow tube wells are generally not feasible in the piedmont zone.

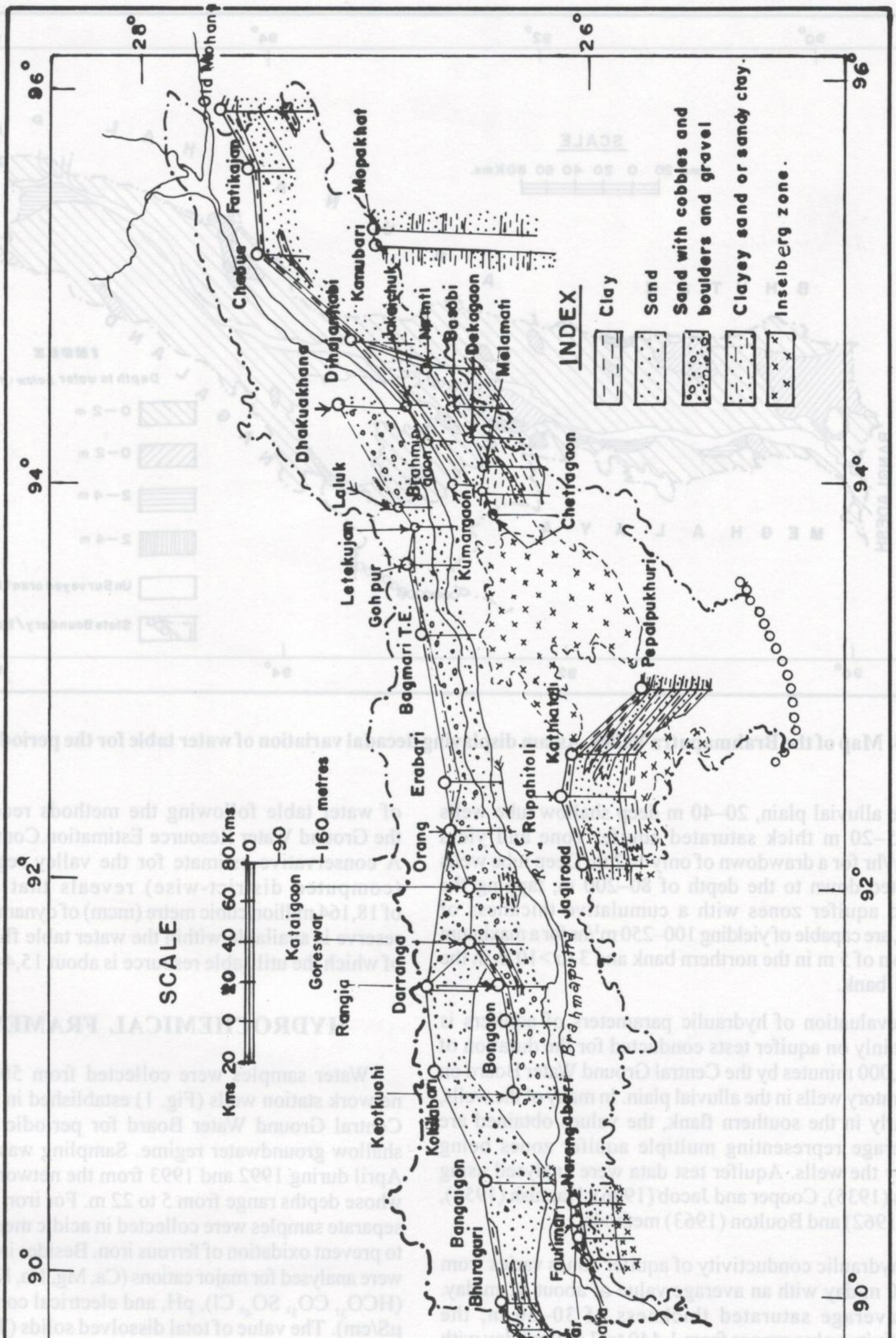

Fig. 3: Panel diagram showing lateral distribution of lithological units in the Brahmaputra Valley, Assam

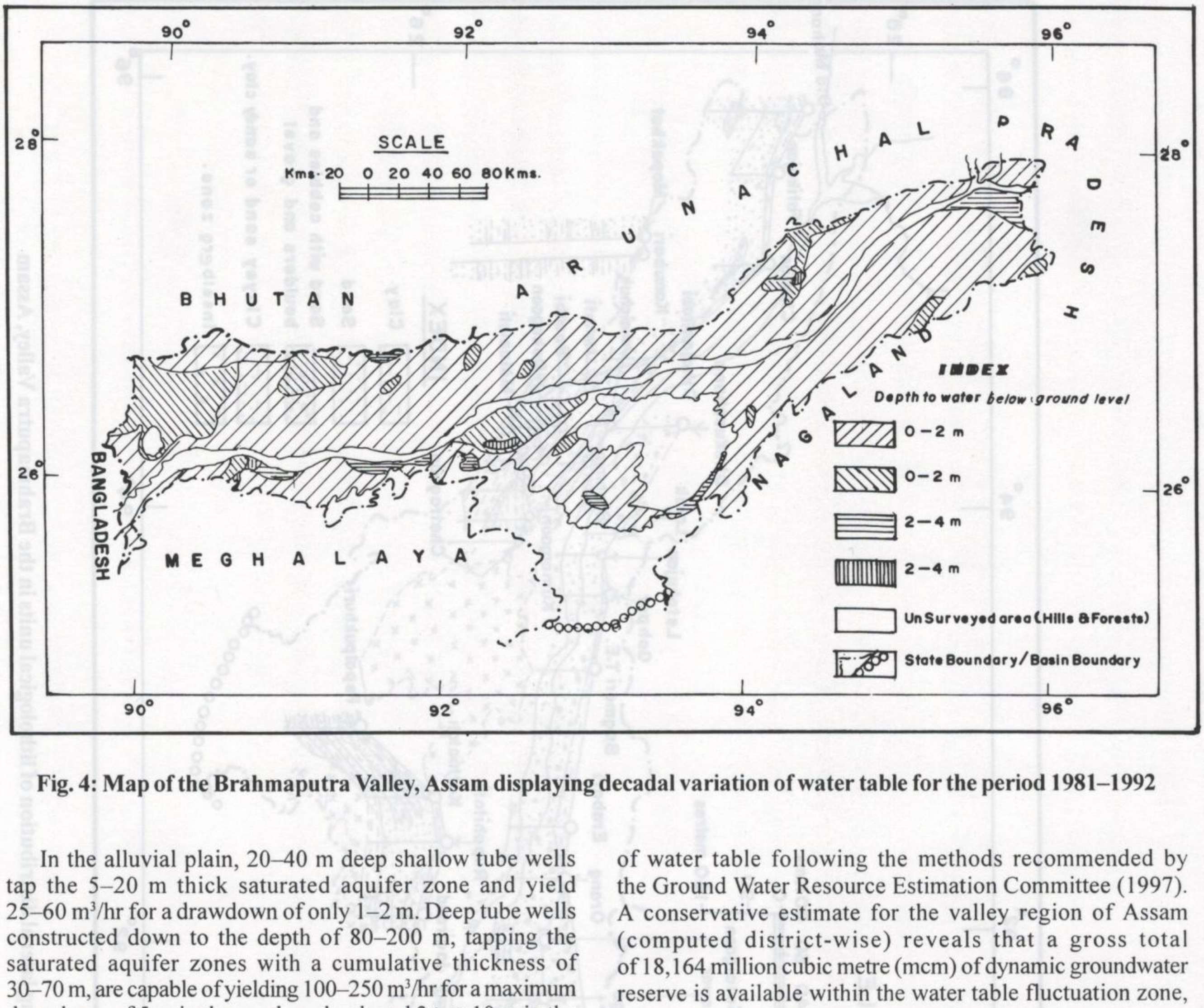

Fig. 4: Map of the Brahmaputra Valley, Assam displaying decadal variation of water table for the period 1981–1992

In the alluvial plain, 20–40 m deep shallow tube wells tap the 5–20 m thick saturated aquifer zone and yield 25–60 m^3/hr for a drawdown of only 1–2 m. Deep tube wells constructed down to the depth of 80–200 m, tapping the saturated aquifer zones with a cumulative thickness of 30–70 m, are capable of yielding 100–250 m^3/hr for a maximum drawdown of 5 m in the northern bank and 3 to >10 m in the southern bank.

The evaluation of hydraulic parameters of aquifers is based mainly on aquifer tests conducted for the duration of at least 1,000 minutes by the Central Ground Water Board on 36 exploratory wells in the alluvial plain. In many of the wells, particularly in the southern flank, the values obtained are only average representing multiple aquifer zones being tapped by the wells. Aquifer test data were analysed using the Theis (1935), Cooper and Jacob (1946), Hantush (1956), Walton (1962) and Boulton (1963) methods.

The hydraulic conductivity of aquifer zones varies from 30 to 200 m/day with an average value of about 82 m/day. For an average saturated thickness of 30–60 m, the transmissivity value ranges from 1,440 to 7,610 m^2/day with an average of about 4,100 m^2/day.

Groundwater potential

The groundwater potential for the Brahmaputra Valley is estimated for the shallow aquifer zone based on the net rise of water table following the methods recommended by the Ground Water Resource Estimation Committee (1997). A conservative estimate for the valley region of Assam (computed district-wise) reveals that a gross total of 18,164 million cubic metre (mcm) of dynamic groundwater reserve is available within the water table fluctuation zone, of which the utilisable resource is about 15,440 mcm.

HYDROCHEMICAL FRAMEWORK

Water samples were collected from 50 hydrographic network station wells (Fig. 1) established in the area by the Central Ground Water Board for periodic monitoring of shallow groundwater regime. Sampling was carried out in April during 1992 and 1993 from the network station wells whose depths range from 5 to 22 m. For iron determination, separate samples were collected in acidic medium (1:1 HCl) to prevent oxidation of ferrous iron. Besides iron, the samples were analysed for major cations (Ca, Mg, Na, K), major anions (HCO_3, CO_3, SO_4, Cl), pH, and electrical conductivity (EC, μS/cm). The value of total dissolved solids (TDS, mg/l) was calculated from the established relationship between TDS and EC. Sodium adsorption ratio (SAR) and residual sodium carbonate (RC) were calculated following standard formulae (Scofield 1933; Eaton 1950) for evaluating the suitability of groundwater for irrigation.

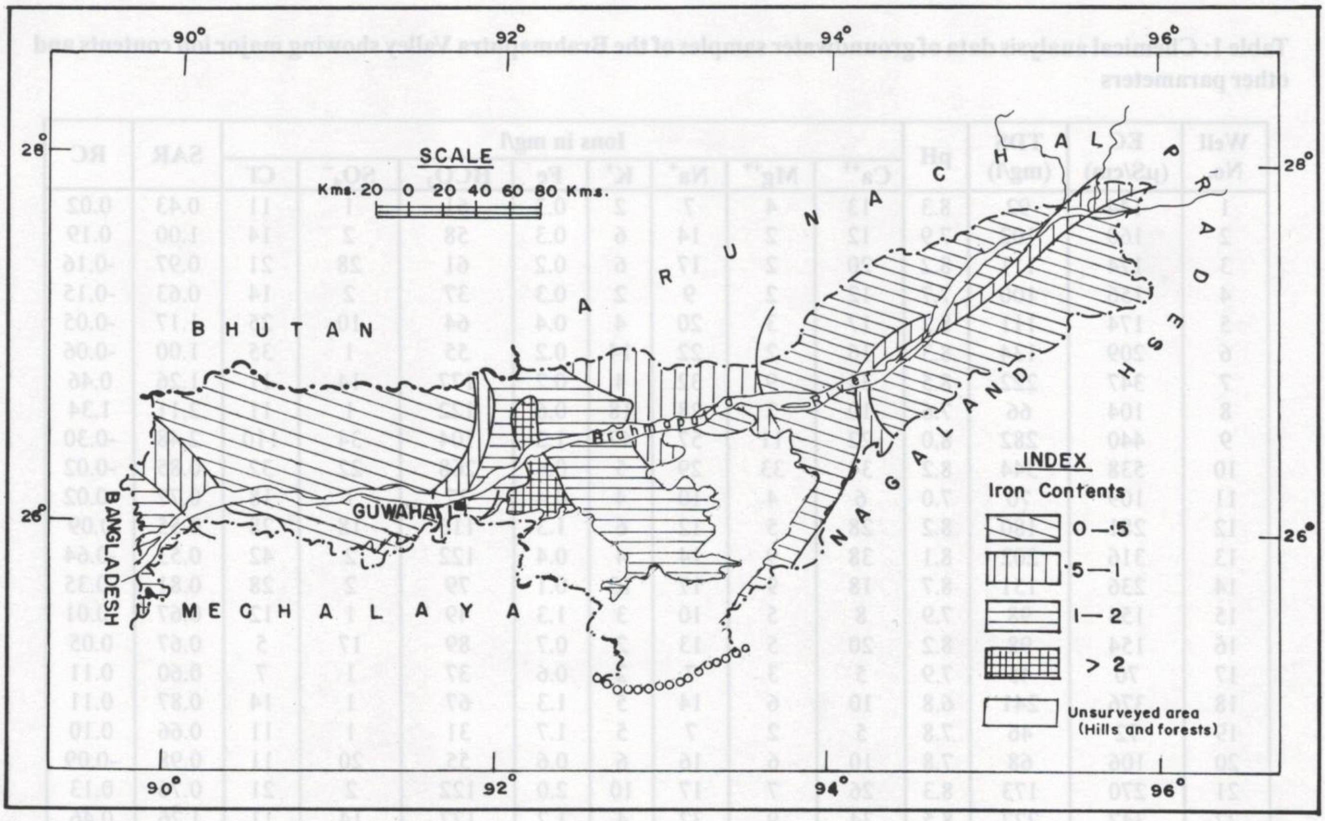

Fig. 5: Iron quality map showing distribution of iron content in groundwater in the Brahmaputra Valley, Assam. Values are in mg/l.

Hydrochemistry

The results of chemical analysis of groundwater samples are given in Table 1. The EC and TDS contents ranged from 70 to 771 μS/cm and 45 to 493 mg/l, respectively indicating fresh nature of groundwater. The pH value ranging from 6.8 to 8.7 indicates almost neutral to feebly alkaline nature of groundwater. Bicarbonate content of groundwater of the valley ranges from 31 to 281 mg/l. The low chloride content in groundwater (varying from 5 to 110 mg/l) is suggestive of its derivation from the atmospheric sources. Carbonate is found to be absent except for a few samples where it is present only in traces. The absence of carbonate ion in groundwater of the area may be attributed to low pH (< 8.2), since below pH of 8.2 most of the carbonate ions add hydrogen to become bicarbonate ions ($H^+ + CO_3^{--} \Leftrightarrow HCO_3^-$) and the ratio of HCO_3 to CO_3 ions increases to more than 100 to 1 (Davies and DeWiest 1966). Sulphate is generally present in high concentration in groundwater due to the stability of the dissociated sulphate ion and also due to the higher solubility of the sulphates of the common cations (Ca, Mg, Na). However, the sulphate content of the study area is found to be somewhat low (which varies from 1 to 45 mg/l) suggesting thereby the absence of sulphate-reducing bacteria in the alluvial soil through which the recharge water percolates.

Calcium content varies from 5 to 76 mg/l while magnesium content is between 2 and 33 mg/l. In the groundwater, the calcium content generally exceeds the magnesium content, in accordance with their relative abundance in rocks, but contrary to the relative solubilities of the salts. In the present study area, Ca:Mg ratio is found to be about 3:1 for most of the 41 samples, while magnesium is found to be marginally higher than calcium in the rest of the samples. Sodium content is varying between 3 and 70 mg/l and that of potassium ranges from 2 to 47 mg/l. Although the abundance of potassium in the earth's crust is about the same as sodium, potassium is commonly less than one tenth the concentration of sodium in natural water (Davies and DeWiest 1966). The Na:K ratio in groundwater of the study area is found to be about 6:1.

The total iron content is the only chemical hazard in the groundwater of the study area. The groundwater of the study area displays a wide range of iron concentration (from 0.1 to 2.5 mg/l) with an average of about 0.75 mg/l. The distribution pattern of iron content in groundwater of the area is shown in the iron quality map (Fig. 5).

The most common ionic sequences for cation are found to be (Na + K) > Ca > Mg (19 samples) and Ca > (Na + K) > Mg (15 samples), while for anion HCO_3 > Cl > SO_4 (44 samples)

Table 1: Chemical analysis data of groundwater samples of the Brahmaputra Valley showing major ion contents and other parameters

Well No.	EC (µS/cm)	TDS (mg/l)	pH	Ions in mg/l								SAR	RC
				Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Fe	HCO_3^{-}	SO_4^{--}	Cl^{-}		
1	144	92	8.3	13	4	7	2	0.3	61	1	11	0.43	0.02
2	160	102	7.9	12	2	14	6	0.3	58	2	14	1.00	0.19
3	174	111	8.2	20	2	17	6	0.2	61	28	21	0.97	-0.16
4	156	100	7.7	12	2	9	2	0.3	37	2	14	0.63	-0.15
5	174	111	8.2	17	3	20	4	0.4	64	10	25	1.17	-0.05
6	209	134	8.3	16	2	22	14	0.2	55	1	35	1.00	-0.06
7	347	222	8.5	34	9	32	4	0.2	177	14	11	1.26	0.46
8	104	66	7.6	10	2	28	18	0.6	122	1	11	2.11	1.34
9	440	282	8.0	22	11	57	47	1.2	104	34	110	2.48	-0.30
10	538	344	8.2	34	33	29	5	0.4	268	22	32	0.85	-0.02
11	109	70	7.0	6	4	10	4	0.4	37	1	18	0.77	-0.02
12	281	180	8.2	28	5	12	6	1.3	116	18	28	0.55	0.09
13	316	202	8.1	38	9	14	4	0.4	122	2	42	0.53	-0.64
14	236	151	8.7	18	9	17	10	0.1	79	2	28	0.81	-0.35
15	154	98	7.9	8	5	10	3	1.3	49	1	12	0.67	-0.01
16	154	98	8.2	20	5	13	2	0.7	89	17	5	0.67	0.05
17	70	45	7.9	5	3	7	2	0.6	37	1	7	0.60	0.11
18	376	241	6.8	10	6	14	5	1.3	67	1	14	0.87	0.11
19	72	46	7.8	5	2	7	5	1.7	31	1	11	0.66	0.10
20	106	68	7.8	10	6	16	6	0.6	55	20	11	0.98	-0.09
21	270	173	8.3	26	7	17	10	2.0	122	2	21	0.76	0.13
22	347	222	8.5	34	9	32	4	1.2	177	14	11	1.26	0.46
23	295	189	8.1	16	9	23	19	0.7	80	11	48	1.14	-0.23
24	771	493	8.2	42	16	70	34	1.4	103	32	42	2.33	-1.71
25	209	134	7.7	14	7	15	3	0.7	55	2	28	0.81	-0.37
26	116	74	7.5	12	2	3	2	2.5	43	1	7	0.21	-0.06
27	617	395	8.2	38	17	38	14	1.8	153	43	75	1.28	-0.79
28	345	221	7.7	28	7	16	7	2.1	122	1	21	0.69	0.03
29	258	165	8.0	76	24	21	11	1.2	154	1	28	0.53	-3.25
30	145	93	7.9	12	4	12	7	2.2	67	1	18	0.76	0.17
31	580	371	7.6	36	18	17	6	0.6	140	1	71	0.58	-0.99
32	689	441	8.5	54	27	54	18	1.1	281	32	74	1.27	-0.32
33	362	232	8.3	30	16	27	4	1.5	171	2	39	0.99	-0.01
34	223	143	7.9	16	6	15	6	0.2	61	19	20	0.81	-0.29
35	112	72	8.0	12	2	12	5	0.8	61	1	11	0.84	0.24
36	126	81	7.8	12	4	11	2	0.4	37	1	14	0.70	-0.32
37	242	155	7.7	35	4	14	8	0.7	104	1	21	0.60	-0.38
38	158	101	8.1	8	7	11	6	0.9	61	2	21	0.69	0.03
39	248	159	7.7	52	4	10	2	0.4	183	1	7	0.35	0.07
40	400	256	8.0	36	10	44	7	0.2	159	26	46	1.67	-0.02
41	472	302	8.2	32	25	44	11	0.4	146	2	78	1.41	-1.26
42	442	283	8.3	26	17	45	9	0.2	159	20	53	1.68	-0.10
43	231	148	8.3	24	7	11	3	0.3	110	1	25	0.51	0.12
44	154	98	8.1	26	2	5	3	0.4	98	1	7	0.26	0.15
45	345	221	8.2	30	23	9	5	0.3	207	1	11	0.30	0.00
46	456	292	8.0	30	18	30	7	0.5	110	21	78	1.06	-1.18
47	190	122	7.6	14	5	22	15	0.2	67	39	18	1.29	-0.01
48	158	101	8.3	24	2	4	2	0.4	98	1	7	0.21	0.25
49	209	134	7.3	13	9	18	3	0.3	43	45	21	0.93	-0.69
50	270	173	8.0	10	5	27	19	0.2	49	29	35	1.73	-0.11

is the most dominant ionic sequence. The plot of cation and anion pairs (Fig. 6) in Pipers trilinear diagram (Piper 1944) shows that 39 samples (out of 50) fall in the diamond-shaped field (Area 1) indicating the preponderance of alkaline earths (Ca, Mg) and weak acids ($HCO_3 + CO_3$) over alkalis (Na, K) and strong acids (SO_4, Cl) in the groundwater of the study area suggesting thereby domination of Ca + Mg – HCO_3 type. In case of only 6 samples (Area 2), alkalis and strong acids predominate over alkaline earths and weak acids. Only one sample (No. 8) falls in Area 4 indicating that primary alkalinity exceeds by 50 per cent. For rest of the 4 samples, no one cation – anion pair exceeds 50 per cent (i.e., Areas 5 and 6).

Water quality

All the constituents and parameters except iron in the groundwater of the study area are found to be well within the maximum allowable limits recommended by the World Health Organisation. Though iron does not cause any health hazard, it is still considered as a nuisance if present in excessive quantities. Iron quality map (Fig. 5) shows that for the majority of the valley area iron content in groundwater is less than the maximum allowable limit of 1 mg/l. Higher concentration of iron (>1 mg/l) is found in the central as well as extreme north-western part of the valley.

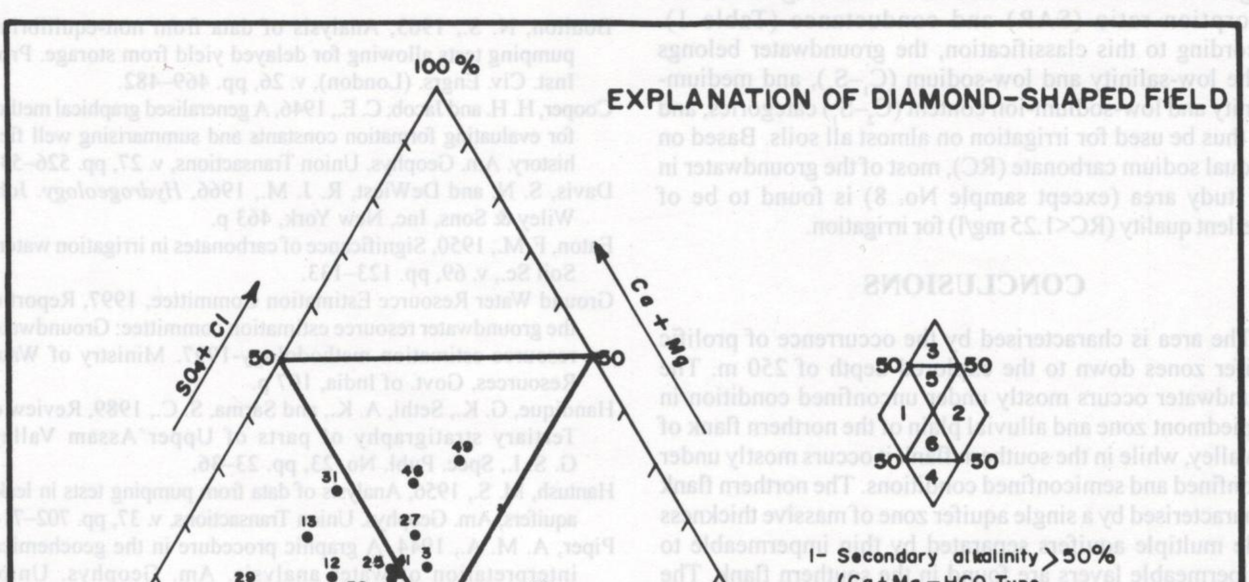

Fig. 6: Piper trilinear plot showing chemical classification of groundwater in Brahmaputra Valley, Assam based on major cation and anion pairs

To examine the suitability of groundwater for irrigation purposes, the classification of U.S. Salinity Laboratory Staff (1954) was applied. Most of the study area representing 33 samples belongs to the low-salinity water (TDS<200 mg/l). According to the classification, the groundwater is suitable for almost all crops on any soil type. The groundwater in rest of the area representing 17 samples falls in the medium-salinity water (TDS =200–500 mg/l) category and may be used for plants with moderate salt tolerance without special practices for salinity control.

U.S. Salinity Laboratory Staff (1954) also states that irrigation water can be classified according to sodium adsorption ratio (SAR) and conductance (Table 1). According to this classification, the groundwater belongs to the low-salinity and low-sodium (C_1–S_1), and medium-salinity and low-sodium-ion content (C_2–S_1) categories, and can thus be used for irrigation on almost all soils. Based on residual sodium carbonate (RC), most of the groundwater in the study area (except sample No. 8) is found to be of excellent quality (RC<1.25 mg/l) for irrigation.

CONCLUSIONS

The area is characterised by the occurrence of prolific aquifer zones down to the explored depth of 250 m. The groundwater occurs mostly under unconfined condition in the piedmont zone and alluvial plain of the northern flank of the valley, while in the southern flank it occurs mostly under unconfined and semiconfined conditions. The northern flank is characterised by a single aquifer zone of massive thickness while multiple aquifers separated by thin impermeable to semipermeable layers are found in the southern flank. The piedmont, bordering the northern foothill region of the valley, acts as a potential recharge zone for the aquifers belonging to the alluvial plain towards the south.

The decadal variation of water table indicates a rise of 2 m for major part of the valley. A fall of 2 to 4 m and rise of up to 4 m is seen sporadically only. Both shallow and deep tube wells with good yield potential are generally feasible in the alluvial plain area on both flanks of the valley, while only deep tube wells are feasible in the piedmont zone.

Hydraulic conductivity and transmissivity values indicate a high potential of aquifer zones. The dynamic groundwater reserve estimated for the shallow aquifer regime pointed out a significant scope for large-scale groundwater development in the area. The low salinity and enrichment of bicarbonate ions over chloride and sulphate ions indicate the meteoric origin of freshwater.

Hydrochemically, the groundwater belongs predominantly to $Ca + Mg - HCO_3$ type and is suitable for domestic and irrigational uses without any special treatment. But the groundwater with high iron content (>1 mg/l) needs some treatment before being used for domestic purposes.

REFERENCES

Boulton, N. S., 1963, Analysis of data from non-equilibrium pumping tests allowing for delayed yield from storage. Proc. Inst. Civ. Engrs. (London), v. 26, pp. 469–482.

Cooper, H. H. and Jacob, C. E., 1946, A generalised graphical method for evaluating formation constants and summarising well field history. Am. Geophys. Union Transactions, v. 27, pp. 526–534.

Davis, S. N. and DeWiest, R. J. M., 1966, *Hydrogeology*. John Wiley & Sons, Inc, New York, 463 p.

Eaton, F. M., 1950, Significance of carbonates in irrigation waters. Soil Sc., v. 69, pp. 123–133.

Ground Water Resource Estimation Committee, 1997, Report of the groundwater resource estimation committee: Groundwater resource estimation methodology-1997. Ministry of Water Resources, Govt. of India, 107 p.

Handique, G. K., Sethi, A. K., and Sarma, S. C., 1989, Review of Tertiary stratigraphy of parts of Upper Assam Valley, G. S. I., Spec. Publ. No. 23, pp. 23–36.

Hantush, M. S., 1956, Analysis of data from pumping tests in leaky aquifers, Am. Geophys. Union Transactions, v. 37, pp. 702–714.

Piper, A. M. A., 1944, A graphic procedure in the geochemical interpretation of water analysis. Am. Geophys. Union Transactions, v. 25, pp. 914–928.

Scofield, C. S., 1933, South Coastal Basin investigation: quality of irrigation water. California Dept. of Public Works, Division of Water Resources, Bull. 40.

Taylor, G. C., 1959, Groundwater provinces of India, Econ. Geol., v. 54(4), pp. 683–697.

Theis, C. V., 1935. The relation between the lowering of the peizometric surface and the rate and duration of discharge of a well using groundwater storage. Am. Geophys. Union Transactions, v. 16, pp. 519–524.

U. S. Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkali soils. US Department of Agriculture, Handbook, v. 60, 160 p.

Walton. W. C., 1962, Selected analytical methods for well and aquifer evaluation. Illinois State Water Survey Bull., No. 49, 81 p.