

Escalation of salinity levels in the quaternary aquifers of the Ganga alluvial plain, India

Anil Kumar Misra · Ajai Mishra

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Abstract A detailed water quality analysis was carried out in the quaternary aquifer system of the marginal alluvial plain (Ganga Plain) in Bah Tahsil, Agra district, India. The electrical conductivity of 50 samples each from dug wells, hand pumps and tube wells was analysed for the study of salinity levels in shallow, intermediate and deep aquifers. Out of 50, 20 samples of each were also analysed for other chemical constituents such as Na^+ , K^+ , Cl^- , F^- and TDS. The analyses show drastic changes in the salinity levels of shallow, intermediate and deep aquifers. The deep aquifers are more saline compared to the shallow and intermediate aquifers. On the contrary, the concentration of chemical constituents such as Na^+ , K^+ , Cl^- and F^- was more in the shallow aquifers compared to the deep aquifers. Moreover, there is an indication that the salinity and concentration of the above chemical constituents also escalate with time in each aquifer. The chemical constituents such as Na^+ , K^+ , Cl^- , F^- and TDS range from 51 to 165 mg/l, 1 to 14 mg/l, 224 to 1,459 mg/l, 0 to 1.5 mg/l and 750 to 2,650 mg/l, respectively. Over a 3-year period, the salinity levels have sharply increased and the average F level has increased by 0.1–0.3 mg/l. An attempt has been made

here to discuss the factors causing the variation and escalation of chemical constituents and salinity in the water of the three aquifers.

Keywords Quaternary aquifers · Ganga Plain · Salinity levels · Deep aquifers · Hydraulic conductivity

Introduction

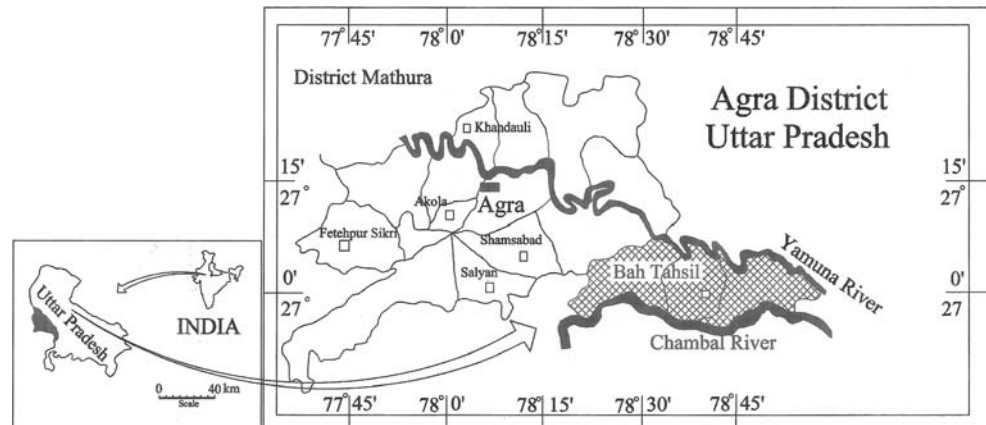
Salinity is a major quality limitation of groundwater, which is influenced by human actions such as irrigation and disposal of wastewaters; seawater intrusion occurs in response to excessive extraction from coastal aquifers and the major ions responsible for salinization are Na^+ , K^+ , Ca^{2+} , Mg^{2+} and Cl^- (SET 2003). Moreover, groundwater salinity is also influenced by the quality of the source (recharging) water. Majority of the districts of western Uttar Pradesh are facing problems of groundwater salinity and water scarcity. The problem is compounded by the deteriorating quality of water due to pollution from industrial, agricultural and municipal sources and over-exploitation of its limited reserves. The most common problem is the contamination of fresh groundwater by saline water in this region. In humid areas, and where recharge is abundant, potential groundwater salinization is limited because of natural flushing by freshwater. However, in the semiarid to arid climatic conditions, in areas such as the present study area, the absence of natural flushing by freshwater makes groundwater prone to enhanced salinization.

In Agra district, the quality of groundwater is quite variable. A major part of the district is located in the marginal alluvial plain, with some portion falling in the

A. K. Misra (✉)
Seismology Division,
Department of Science and Technology,
Government of India, Technology Bhawan,
New Mehrauli Road, New Delhi 110016, India
e-mail: anilgeology@rediffmail.com

A. Mishra
Department of Geology, University of Lucknow,
Lucknow 226007, India

Fig. 1 Study area, showing location of the Bah Tahsil in Agra district



central alluvial plain of the Ganga Plain. Bah block was recognized as a critical (dark) block in 1998 (Fig. 1) by the state groundwater department. The study area is marked by the rocks of the Vindhyan group in the subsurface, which are overlain by a thick pile of unconsolidated sediments of the Ganga Plain, and groundwater is mostly saline to highly saline in nature.

In view of the persistent problems of groundwater quality and salinity in the region, the assessment of groundwater quality was carried out in shallow, intermediate and deep aquifers. As such, groundwater management and assessment of water quality are difficult because it might take many years to separate their causes and effects. The present study is an attempt to examine the factors causing variation and deterioration in water quality of the shallow, intermediate and deep aquifers in the alluvial plain of Agra.

Study area

Agra district occupies the southwestern part of the state of Uttar Pradesh (India) and is bounded by the state of Rajasthan in the west and the state of Madhya Pradesh in the south. Bah Tahsil is the easternmost part of Agra district and belongs to both the marginal and central alluvial plain (Ganga Plain). The Bah Tahsil area is situated between 26°45' and 27°0'N latitudes and between 78°10' and 78°50'E longitudes at approximately 178 m above sea level. The study area has a semi-arid to arid climate with an average monthly temperature varying between 38 and 46°C in the summer and between 25 and 32°C in the winter. The average weather conditions allow recognizing six well-marked traditional seasons, i.e. spring (March–April), summer (May–June), monsoon (July–August), sharada (September–October), hemanta (November–December) and winter (January–February). The average annual rainfall variation is between 600 and 650 mm.

Geology and hydrogeology

The study area is a part of the Indo-Gangetic Plain. A major part of the area is covered by Gangetic alluvial deposits of the quaternary period comprising gravel, sand, silt, clay and kankar in various proportions (Misra 2005; Misra and Mishra 2006). The thickness of the alluvial cover around the study area ranges from 200 to 250 m. In the lower part just above the basement, thick horizons of arkosic gravel–coarse sand are present. They are followed by a clay–kankar (calcrete nodules) succession with thin, fine sand intercalations. The topmost 10 m are invariably made up of clay with kankar and distinct calcrete horizons (Singh 1996). River Yamuna act as a lifeline and is the main river flowing through the district. In the study area, the groundwater occurs both in unconfined and confined conditions.

The entire Agra district is facing problems related with water quality. Even in Agra city, the groundwater environment is plagued by the dual ills of saline water occurrence below 30/40 mgbl as well as the sporadic presence of fluorides and nitrates much above the permissible limits (CGWB 2003).

Hydrogeomorphologically, Agra district can be divided (Fig. 2) into five major units: alluvial plain, structural valley, valley fills, structural hills and ravines. The alluvial plains are mostly composed of gravel, pebbles, sand and silt. The groundwater prospects appear to be good in this unit. Structural valleys in the region are composed of fine to medium sand, which is highly porous and permeable. In this area, the water table position ranges from 8 to 15 m. The valley fills mostly lie very close to hilly ranges in the structural valleys, consisting of boulders, cobbles, pebbles, gravels, sand, silt and clay. The shallowest water table position is recorded in these areas. The structural hills are composed of Vindhyan sandstones having undulating

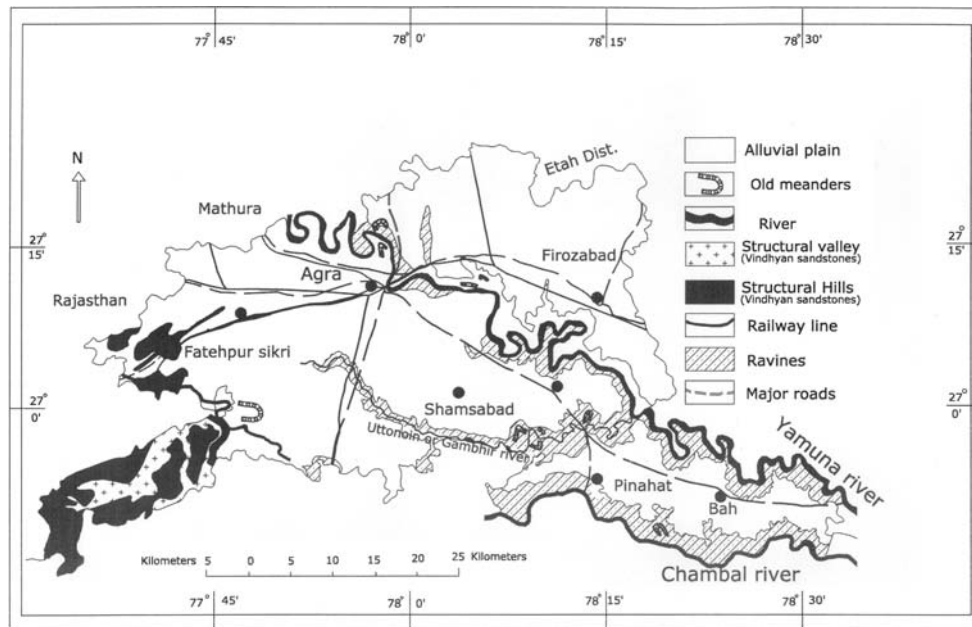


Fig. 2 Hydrogeomorphological map of the Agra district, India

terrain. The presence of ravines on either side of River Yamuna is a major geomorphic feature. The water table in this area ranges between 25 and 28 m.

Status of water resources

The Ganga alluvial plain is one of the largest groundwater repositories of the earth. For several decades, the drainage basin of the Ganga Plain has been used for the disposal of domestic and industrial wastes, which has adversely affected the quality of water, sediments and agricultural soil of the plain (IUGG 2003). The water potential of the study area is the main source of surface and groundwater, which experiences very low annual precipitation. The water table in the entire Bah Tahsil varies between 20 and 25 m. Since no comprehensive and scientific investigations have been carried out in the region so far as part of a complete hydrological appraisal of the watershed, information on baseline hydrological characteristics and also on spatio-temporal aspects of water resources is not available. In the agricultural sector, the consumption of water is also very high. Since the agricultural sector is increasing by leaps and bounds, the demand for irrigation water is increasing, but due to the saline nature of groundwater in some parts, it cannot be used for irrigation purposes.

The large-scale deforestation, mainly due to urbanization, fuel and fodder needs, and unscientifically managed agricultural practices in Bah Tahsil are some of the major human transformation processes that have

been causing reduction in groundwater recharge through increased overland flow and declining rate of infiltration.

Objectives and scope

The main aim of the present work is to study the salinity levels and groundwater quality in shallow, intermediate and deep aquifers of Bah Tahsil. The problems of varying salinity and concentration of chemical constituents (Na^+ , K^+ , Cl^- , TDS and F^-) in the aquifers of the area have been investigated. This study had two main objectives: (1) to evaluate the salinity levels in shallow, intermediate and deep aquifers and classify the areas with their salinity levels, in July 2001 and 2004 and (2) to evaluate the concentration of some of the major constituents of groundwater such as Na^+ , K^+ , Cl^- , TDS and F^- in shallow, intermediate and deep aquifers in July 2001 and 2004. This work would help in the understanding of the water quality in the alluvial plains.

Methodology

Samples, 50 each from dug wells, hand pumps and tube wells in close proximity were collected in July 2001 and 2004 for the comparative study of salinity levels in the shallow, intermediate and deep aquifers. In most of the cases, the samples collected from hand pumps and tube wells were used for several hours prior to sampling.

The groundwater samples were collected in glass bottles after rinsing with the sample water. The sample bottles were immediately sealed using rubber stoppers and aluminium protective caps crimped with a hand-held crimping device. The dug wells, hand pumps and tube wells range in depth from 10 to 20 m, 20 to 50 m and 60 to 150 m, respectively. The electrical conductivity (EC) and pH of the 50 samples were analysed on the spot, while 20 samples each of dug wells, hand pumps and tube wells were also analysed for other chemical constituents in the laboratories.

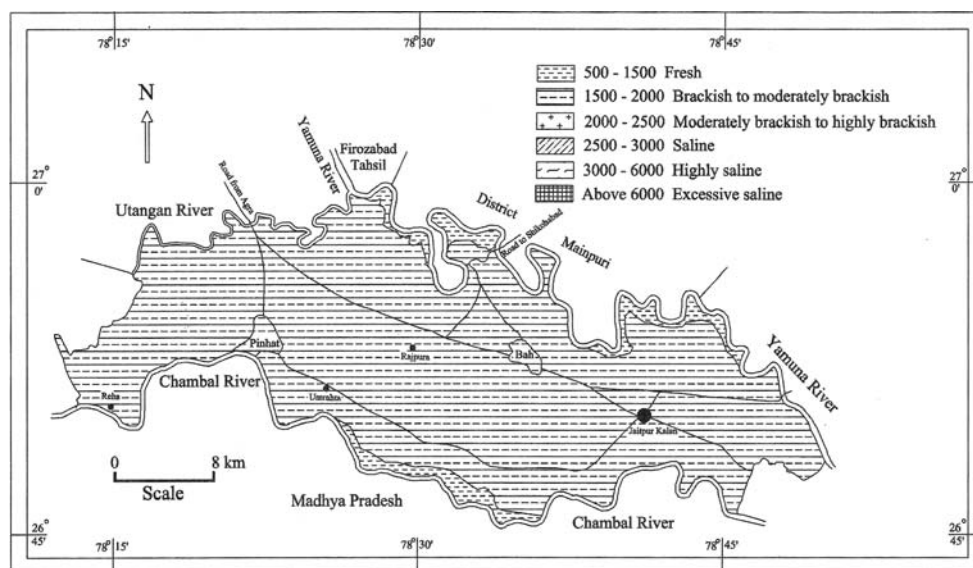
Traditionally, groundwater has been classified based on its TDS content, which has been applied particularly to the non-fresh water and groundwater (TDS > 1,000 mg/l). Such a classification however, has little relevance. So, the term saline will be adopted for that water, which has specific conductance in excess of about 2,000 $\mu\text{mho/cm}$ at 25°C, as given in Table 1 (Tamta 1999; CSSRI 1994; MOWR 1997; Gupta and Gupta 1987). The salinity levels in the aquifers were classified on the basis of their electrical conductivity. The international standard for drinking water with respect to total dissolved solids, recommended by WHO, is 1,500 mg/l as the maximum permissible level

Table 1 Groundwater classification using specific conductance ($\mu\text{mho/cm}$)

| Class | Specific conductance ($\mu\text{mho/cm}$) 25°C |
|-----------------|--|
| Non-saline | Less than 2,000 |
| Slightly saline | 2,000–4,000 |
| Saline | 4,000–6,000 |
| Very saline | >6,000 |

Source: Tamta (1999)

Fig. 3 Water quality in shallow aquifers in the study area in April 2001



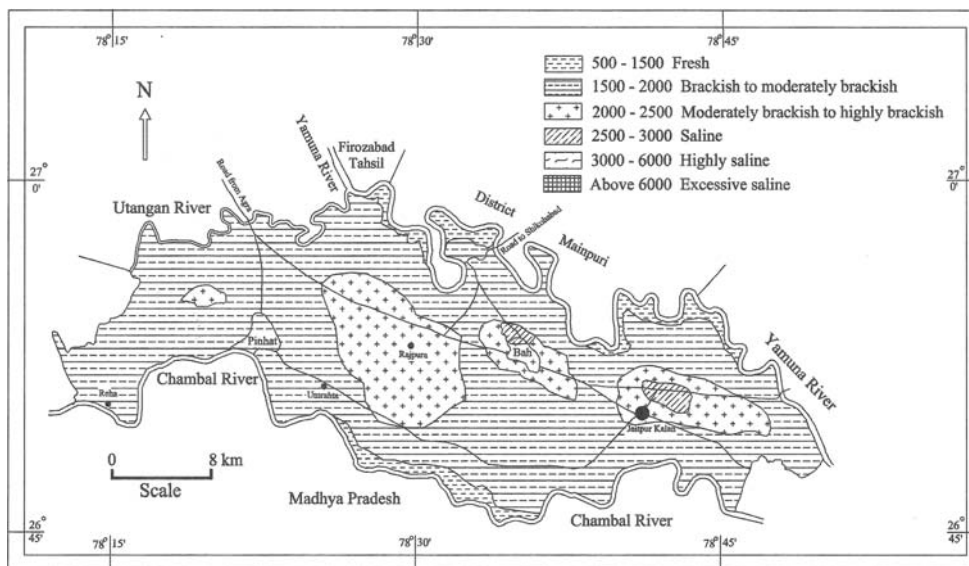
and 500 mg/l as the highest desirable level. The same standard is used to classify the groundwater quality in aquifers.

Water samples for fluoride were analysed by using the SPADNS colorimetric method. A calibration standard ranging from 0 to 1.4 mg F^-/l was prepared by diluting an appropriate volume of standard F^- solution. To 50 ml of standard solution, 10.0 ml of the SPADNS reagent was added and mixed well. The spectrophotometer (Perkin Elmer model LAMBDA 40) was set at a wavelength of 570 nm, and a calibration graph was prepared from different standard F^- concentrations. When the graph gave a straight line, the instrument was considered ready for measurement of F in the samples. The total dissolved solid was calculated using the formula given by Todd (Todd 1959). The chemical constituents, such as Na^+ , K^+ and Cl^- , were analysed on the basis of the standard water quality procedures (Brown et al. 1974) in the department of geology, University of Lucknow.

Results and discussion

Generally, saline soils were formed due to the buildup of soluble salts in the soil. This is because of the low precipitation during the summer months at a time of high evaporation and crop growth, which might lead to increased water movement to the surface. The plants use the water and the salts are left behind in the soil, which eventually begin to accumulate. A saline seep is formed through the excess water entering into the ground. This movement causes the groundwater to flow downslope and through subsoil (Tóth et al. 2006;

Fig. 4 Water quality in shallow aquifers in the study area in April 2004



Schoups et al. 2003; Salama et al. 1999). This is probably one of the major reasons for the continuous escalation of salinity in the shallow, intermediate and deep aquifers in the study area.

However, a majority of the rivers of the Ganga Plain originate from the Himalayan mountain ranges, where precipitation is generally high and the concentration of total dissolved solids (TDS) in the rivers is low. But when these rivers flow through arid to semi-arid regions of the Ganga Plain, the concentration of salts in their lower reaches rises through evaporation. When this water is diverted to canals for irrigation, the salt concentration is escalated by evapotranspiration and it increases the dryland salinity (Misra et al. 2006a). Thus, the canal network in the study area is also

responsible for increase in the dryland salinity and groundwater salinity.

Figures 3 and 4 show the salinity levels in shallow aquifers in the years 2001 and 2004, based on electrical conductivity, while Figs. 5, 6, 7 and 8 represent the same study for intermediate and deep aquifers carried out in the years 2001 and 2004, respectively. The study reveals that deep aquifers are more saline compared to shallow and intermediate aquifers. The groundwater quality in these aquifers has deteriorated through time. The salinity levels in shallow and intermediate aquifers are same in a majority of areas despite the differences in EC. The water in these aquifers was found ranging from brackish to moderately brackish in 2001; but in 2004, it was found to be highly brackish to saline in a

Fig. 5 Water quality in intermediate aquifers in the study area in April 2001

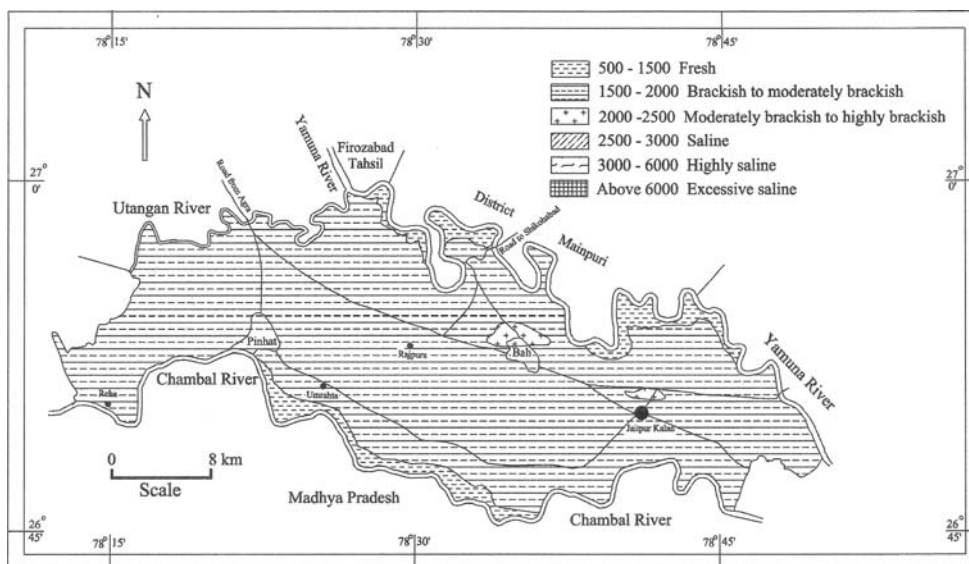


Fig. 6 Water quality in intermediate aquifers in the study area in April 2004

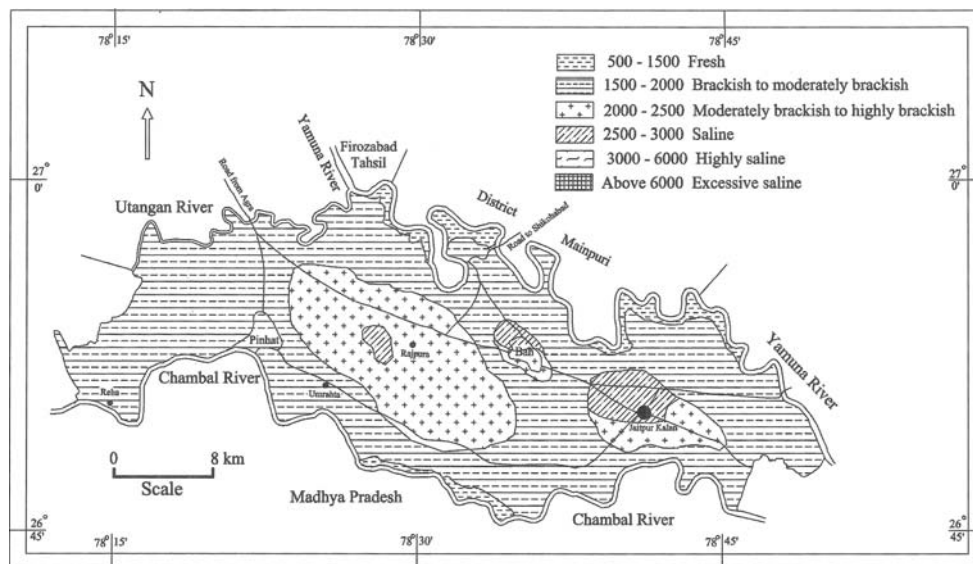
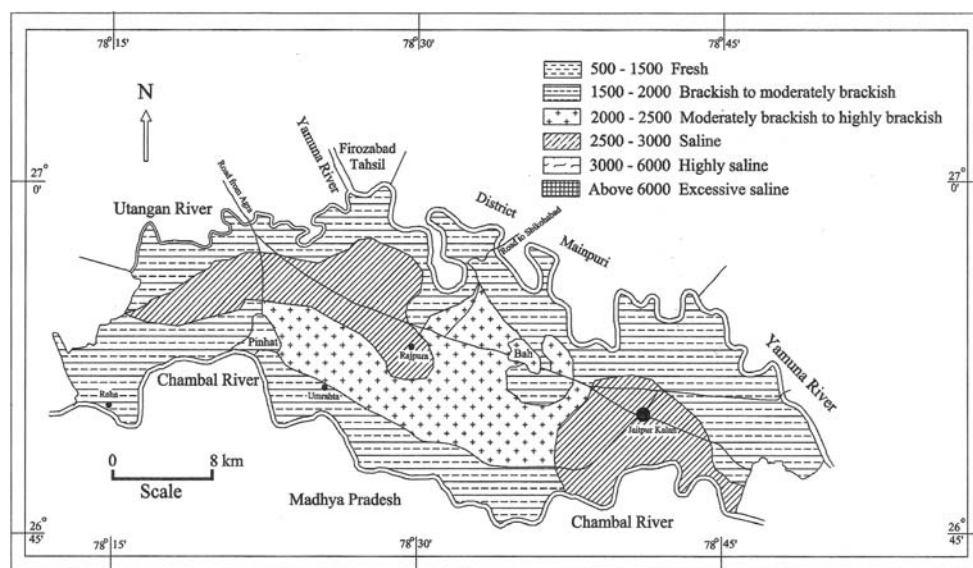


Fig. 7 Water quality in deep aquifers in the study area in April 2001

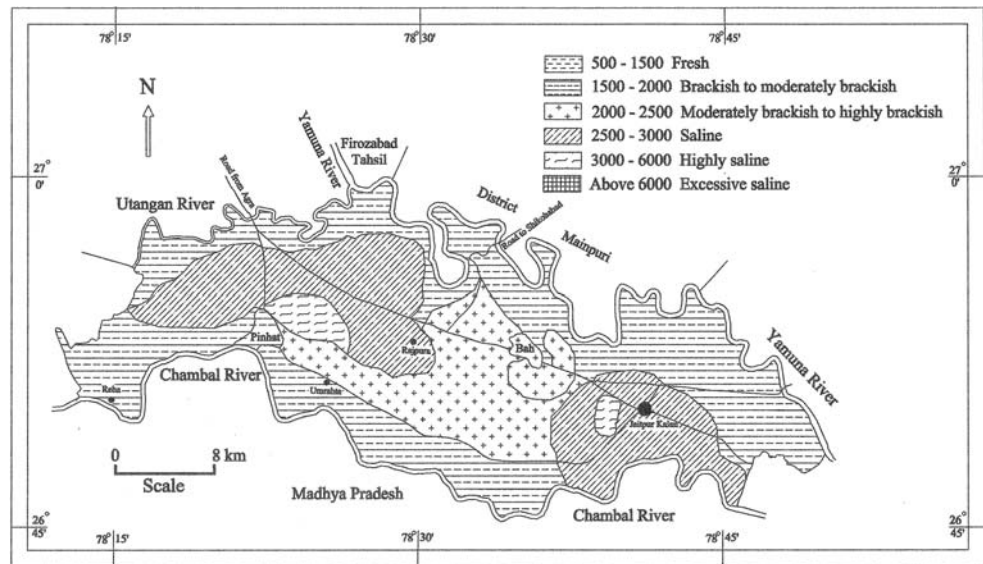


few areas. While the salinity level in deep aquifers was found to be brackish to saline in 2001, in 2004 it was brackish to highly brackish in a majority of the portions and saline to very highly saline in nature in some portions. Fresh groundwater is found in very limited areas, only along either side of the rivers in shallow and intermediate aquifers in some locations, which may be due to the infiltration and percolation of fresh water from the river. The variation and escalation in salinity levels have been found less in deep aquifers compared to the shallow and intermediate aquifers through time. As indicated above, the deep aquifers are more saline in comparison to the superficial aquifers. It seems that the excessive drilling of tube wells and high yield tube wells are probably causing deterioration of water

quality in the shallow and intermediate aquifers. Most of the deep aquifers in the study area were found to be confined to semi-confined in nature in geoelectrical investigations, aquifers of such nature possess some hydrostatic pressure and whenever these aquifers were drilled with bore wells, the pressure caused the upward movement of water, leading to deterioration of shallow aquifers (Misra and Mishra 2006).

Tables 2, 3 and 4 show the chemical composition of groundwater collected from the dug wells, hand pumps and tube wells in the study area. It is noted that the groundwater of the shallow and intermediate aquifers are characterized by a high concentration of Na^+ , K^+ , Cl^- , F^- and TDS than the deep aquifers. The variation in these parameters between the waters of the two

Fig. 8 Water quality in deep aquifers in the study area in April 2004



types of aquifers is believed to result from the interplay of the following factors.

According to the previous studies, the sodic soils of the Indo-Gangetic Plains have derived their sodicity from in-situ weathering of alkali aluminosilicates (Bhargava et al. 1981; Kapoor et al. 1981). It is also postulated that salt-rich geological formations have contributed to these alluvial deposits (Kumar et al. 1993, 1995; Kumar 1998) of the Ganga Plain. The main

characteristics of soil horizons of the area are the high content of carbonate, distributed throughout the depth of the profile. In addition, the study area shows frequent alternations of mud and clay layers in the subsurface lithology and have very low hydraulic conductivity (Misra 2005). All these factors together constitute a favourable condition for the maximum absorption of Na^+ , K^+ , Cl^- and F^- by the clay minerals in the soil of shallow and intermediate aquifers

Table 2 Chemical composition of groundwater in the study region in April 2001 and 2004

| Dug well Samples nos. shown in figure | pH | | EC | | TDS | | K^+ | | Na^+ | | Cl^- | | F^- | |
|---------------------------------------|------------|------------|------------|------------|------------|------------|--------------|------------|---------------|------------|---------------|------------|--------------|------------|
| | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 |
| 1 D | 7.5 | 7.4 | 1,757 | 1,980 | 810 | 870 | 3 | 5 | 130 | 145 | 450 | 480 | 0.8 | 0.9 |
| 2 D | 8.0 | 8.1 | 1,780 | 2,230 | 880 | 1,486 | 6 | 8 | 85 | 89 | 780 | 795 | 0.5 | 1.2 |
| 3 D | 7.1 | 7.3 | 1,610 | 1,910 | 1,055 | 1,680 | 12 | 13 | 92 | 94 | 390 | 450 | 1.0 | 1.5 |
| 4 D | 7.3 | 7.9 | 1,980 | 2,565 | 1,010 | 1,600 | 4 | 8 | 110 | 150 | 835 | 910 | 0.3 | 0.6 |
| 5 D | 8.2 | 8.0 | 1,680 | 2,340 | 1,086 | 2,650 | 8 | 10 | 89 | 98 | 1,120 | 1,450 | 1.2 | 1.4 |
| 6 D | 7.9 | 7.5 | 1,700 | 1,980 | 515 | 945 | 10 | 14 | 170 | 210 | 645 | 810 | 1.0 | 1.3 |
| 7 D | 7.0 | 7.4 | 1,375 | 1,545 | 2,400 | 3,785 | 2 | 6 | 122 | 125 | 746 | 945 | 1.3 | 1.5 |
| 8 D | 7.3 | 7.8 | 1,080 | 1,582 | 1,390 | 2,282 | 5 | 4 | 90 | 97 | 655 | 782 | 0.7 | 1.0 |
| 9 D | 7.9 | 7.9 | 1,980 | 2,680 | 1,040 | 1,984 | 7 | 9 | 175 | 185 | 780 | 884 | 0.9 | 1.3 |
| 10 D | 7.7 | 7.5 | 2,010 | 2,740 | 2,019 | 3,485 | 8 | 10 | 132 | 162 | 544 | 645 | 0.2 | 1.4 |
| 11 D | 6.9 | 7.2 | 1,990 | 2,580 | 780 | 1,780 | 5 | 7 | 104 | 130 | 1,085 | 1,182 | 0.3 | 1.6 |
| 12 D | 8.2 | 8.3 | 1,835 | 2,910 | 877 | 1,040 | 9 | 11 | 155 | 182 | 982 | 1,102 | 0.1 | 0.4 |
| 13 D | 8.0 | 7.9 | 1,582 | 1,998 | 1,090 | 1,270 | 11 | 14 | 75 | 92 | 782 | 975 | 0.7 | 0.9 |
| 14 D | 7.1 | 7.6 | 1,743 | 1,975 | 1,280 | 1,345 | 6 | 7 | 98 | 108 | 244 | 292 | 1.0 | 1.1 |
| 15 D | 7.3 | 7.8 | 1,702 | 1,892 | 1,075 | 1,879 | 5 | 5 | 122 | 125 | 382 | 485 | 0.6 | 0.9 |
| 16 D | 7.9 | 8.2 | 745 | 985 | 1,180 | 1,884 | 7 | 8 | 132 | 142 | 485 | 530 | 0.9 | 1.3 |
| 17 D | 7.4 | 7.6 | 1,768 | 2,710 | 2,010 | 2,660 | 5 | 4 | 140 | 139 | 742 | 992 | 0.5 | 1.1 |
| 18 D | 7.8 | 7.5 | 715 | 995 | 2,180 | 2,843 | 9 | 9 | 62 | 79 | 890 | 995 | 0.8 | 1.2 |
| 19 D | 7.3 | 7.9 | 1,840 | 1,983 | 725 | 890 | 4 | 7 | 101 | 117 | 912 | 973 | 1.0 | 1.4 |
| 20 D | 8.2 | 8.5 | 1,722 | 1,985 | 1,382 | 2,385 | 10 | 13 | 145 | 162 | 1,032 | 1,145 | 1.1 | 1.2 |

D = Dug well (All values are in mg/l, except pH and EC. Units of EC are mmho/cm)

Table 3 Chemical composition of groundwater in the study region in April 2001 and 2004

| Hand pump samples nos. shown in figure | pH | | EC | | TDS | | K ⁺ | | Na ⁺ | | Cl ⁻ | | F ⁻ | |
|--|------------|------------|------------|------------|------------|------------|----------------|------------|-----------------|------------|-----------------|------------|----------------|------------|
| | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 |
| 1 H | 7.3 | 7.6 | 1,880 | 1,900 | 810 | 995 | 4 | 6 | 140 | 155 | 750 | 970 | 0.1 | 0.3 |
| 2 H | 8.3 | 8.0 | 1,982 | 2,620 | 1,150 | 1,510 | 6 | 7 | 75 | 83 | 410 | 525 | 0 | 0.1 |
| 3 H | 7.6 | 7.9 | 1,720 | 1,975 | 1,080 | 1,582 | 9 | 11 | 82 | 110 | 382 | 410 | 1.1 | 1.2 |
| 4 H | 6.9 | 6.7 | 2,485 | 2,780 | 1,085 | 1,610 | 4 | 4 | 134 | 152 | 662 | 792 | 0.1 | 0.3 |
| 5 H | 7.3 | 7.9 | 1,792 | 2,450 | 1,185 | 2,240 | 7 | 9 | 92 | 105 | 1,210 | 1,410 | 0.6 | 0.9 |
| 6 H | 7.9 | 7.2 | 1,972 | 2,082 | 900 | 1,077 | 10 | 11 | 110 | 117 | 984 | 1,044 | 1.0 | 1.2 |
| 7 H | 8.2 | 8.0 | 1,784 | 2,074 | 2,140 | 3,280 | 5 | 8 | 48 | 57 | 423 | 582 | 0.2 | 0.7 |
| 8 H | 7.0 | 7.1 | 1,782 | 1,925 | 1,485 | 2,230 | 7 | 9 | 128 | 132 | 635 | 775 | 1.1 | 1.3 |
| 9 H | 6.8 | 7.0 | 1,434 | 2,746 | 1,082 | 1,910 | 9 | 8 | 145 | 162 | 910 | 994 | 0.6 | 0.9 |
| 10 H | 7.9 | 7.5 | 2,125 | 2,594 | 2,128 | 3,240 | 1 | 3 | 116 | 138 | 632 | 735 | 0.3 | 0.8 |
| 11 H | 8.0 | 8.2 | 1,992 | 2,310 | 805 | 1,795 | 3 | 5 | 82 | 93 | 816 | 845 | 0.6 | 0.9 |
| 12 H | 7.6 | 7.9 | 1,970 | 2,227 | 940 | 1,070 | 7 | 10 | 135 | 148 | 737 | 897 | 0 | 0.2 |
| 13 H | 7.0 | 7.3 | 1,763 | 1,970 | 1,183 | 1,242 | 6 | 8 | 98 | 97 | 864 | 910 | 0.5 | 0.7 |
| 14 H | 8.3 | 8.3 | 2,017 | 2,067 | 1,410 | 1,405 | 8 | 11 | 77 | 115 | 591 | 738 | 1.0 | 1.2 |
| 15 H | 8.1 | 7.6 | 1,643 | 1,877 | 1,280 | 1,882 | 11 | 14 | 141 | 150 | 288 | 510 | 0.8 | 0.9 |
| 16 H | 7.3 | 7.4 | 935 | 1,080 | 1,480 | 2,010 | 3 | 7 | 118 | 142 | 637 | 792 | 0.4 | 0.7 |
| 17 H | 7.5 | 7.1 | 1,882 | 1,975 | 1,983 | 2,973 | 2 | 8 | 148 | 165 | 412 | 547 | 0.2 | 0.6 |
| 18 H | 6.9 | 7.5 | 1,729 | 1,902 | 1,755 | 2,882 | 7 | 9 | 79 | 97 | 810 | 968 | 0.6 | 0.5 |
| 19 H | 7.0 | 7.9 | 2,489 | 2,675 | 1,075 | 1,010 | 8 | 10 | 129 | 164 | 1,054 | 4,465 | 0.7 | 0.9 |
| 20 H | 8.1 | 8.2 | 1,791 | 1,960 | 1,371 | 2,282 | 6 | 8 | 118 | 152 | 762 | 875 | 0.9 | 1.2 |

H = Hand pumps (All values are in mg/l, except pH and EC. Units of EC are mmho/cm)

Table 4 Chemical composition of groundwater in the study region in April 2001 and 2004

| Tube well samples nos. shown in figure | pH | | EC | | TDS | | K ⁺ | | Na ⁺ | | Cl ⁻ | | F ⁻ | |
|--|------------|------------|------------|------------|------------|------------|----------------|------------|-----------------|------------|-----------------|------------|----------------|------------|
| | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 | April 2001 | April 2004 |
| 1 T | 7.6 | 7.6 | 1,700 | 1,910 | 800 | 912 | 4 | 17 | 82 | 150 | 310 | 385 | 0.2 | 0.4 |
| 2 T | 7.9 | 7.3 | 1,985 | 2,810 | 1,150 | 1,540 | 6 | 5 | 78 | 73 | 650 | 681 | 0.6 | 0.9 |
| 3 T | 7.2 | 8.4 | 1,780 | 2,342 | 1,700 | 2,010 | 6 | 7 | 64 | 72 | 375 | 442 | 0.3 | 0.4 |
| 4 T | 6.9 | 8.3 | 2,950 | 3,115 | 1,344 | 1,264 | 2 | 4 | 98 | 105 | 840 | 870 | 0 | 0.1 |
| 5 T | 8.0 | 7.9 | 1,700 | 2,682 | 2,010 | 2,634 | 4 | 6 | 65 | 78 | 985 | 1,015 | 0.8 | 0.8 |
| 6 T | 7.1 | 6.9 | 1,680 | 2,250 | 750 | 995 | 6 | 8 | 110 | 122 | 1,080 | 725 | 0.4 | 0.8 |
| 7 T | 8.2 | 7.0 | 1,980 | 2,385 | 3,500 | 3,510 | 1 | 4 | 102 | 109 | 685 | 721 | 0.7 | 1.1 |
| 8 T | 6.9 | 7.6 | 1,740 | 2,130 | 2,100 | 2,015 | 4 | 8 | 73 | 85 | 510 | 564 | 0.1 | 0.4 |
| 9 T | 7.0 | 7.2 | 2,380 | 3,710 | 1,800 | 2,086 | 5 | 10 | 84 | 92 | 632 | 679 | 0.8 | 0.7 |
| 10 T | 7.5 | 7.8 | 2,950 | 3,650 | 3,200 | 3,415 | 4 | 5 | 105 | 119 | 533 | 587 | 0 | 0.2 |
| 11 T | 7.9 | 8.0 | 2,585 | 2,945 | 1,500 | 1,912 | 3 | 8 | 110 | 131 | 845 | 891 | 0.1 | 0.4 |
| 12 T | 7.2 | 8.1 | 2,782 | 3,060 | 984 | 1,150 | 7 | 10 | 125 | 134 | 762 | 788 | 0 | 0.3 |
| 13 T | 8.0 | 7.2 | 2,882 | 3,310 | 1,200 | 1,472 | 10 | 11 | 59 | 65 | 695 | 724 | 0.5 | 0.6 |
| 14 T | 7.6 | 8.0 | 2,687 | 2,884 | 1,358 | 1,506 | 7 | 5 | 81 | 95 | 231 | 352 | 1.1 | 1.3 |
| 15 T | 7.9 | 7.5 | 2,582 | 2,610 | 1,700 | 2,082 | 3 | 4 | 103 | 114 | 368 | 387 | 0.8 | 0.8 |
| 16 T | 7.2 | 6.9 | 1,840 | 2,045 | 1,650 | 2,243 | 7 | 8 | 121 | 135 | 224 | 257 | 0.5 | 0.6 |
| 17 T | 7.8 | 7.8 | 1,810 | 2,482 | 2,400 | 2,715 | 2 | 5 | 138 | 142 | 680 | 910 | 0.4 | 0.7 |
| 18 T | 7.0 | 7.9 | 1,890 | 2,082 | 2,600 | 3,014 | 8 | 9 | 51 | 64 | 794 | 814 | 0.3 | 0.5 |
| 19 T | 8.2 | 7.0 | 2,180 | 2,870 | 780 | 1,139 | 3 | 7 | 99 | 115 | 884 | 905 | 0.7 | 0.9 |
| 20 T | 8.4 | 7.8 | 2,445 | 2,787 | 1,810 | 2,856 | 7 | 10 | 122 | 141 | 921 | 955 | 0.5 | 0.6 |

T = Tube well (All values are in mg/l, except pH and EC. Units of EC are mmho/cm)

compared to the deep aquifers. Moreover, the extremely low hydraulic conductivity between the shallow and deep zones also suggests that the recharge sources for both deep and shallow zones are different;

otherwise all the aquifers would have similar water quality (Misra et al. 2006b).

Generally, Na⁺, K⁺, Cl⁻, and F⁻ are added to the soil from several anthropogenic sources both directly,

through phosphate fertilizers, and indirectly, through atmospheric pollution from industries and burning of fossil fuels (Drury et al. 1980). The frequent alternations of clay and mud layers in the subsurface, which act as an impermeable layer, prevent the infiltration and percolation of chemical constituents from shallow to deep aquifers of the region. Moreover, under such conditions, the deep aquifers are unaffected from seepage and leaching of anthropogenic pollutants from the surface. These factors are also responsible for the variation of major constituents in shallow, intermediate and deep aquifers of the region.

Such studies on groundwater quality monitoring in aquifers would help to identify safe aquifer zones for drinking water and provide, by means of hydrogeological and geochemical data, a solution to the quality problems in groundwater.

Conclusion

The study indicates that there are several reasons for groundwater salinity in the study area, such as: minute quantities of salts dissolved in rainwater are added to the groundwater; the canal network in the region continuously escalates the dryland salinity and groundwater salinity; further, the low precipitation and high evaporation due to arid climatic conditions in the region also enhance the groundwater salinity. The increase in salinity levels through time shows that the salts present in the dryland are mobilized and transported by groundwater, capillary rise, evaporation and leaching. This might be increasing the accumulation and depletion of salts in the shallow, intermediate and deep aquifers.

The salinity level variation in deep aquifers is only marginal compared to the shallow and intermediate aquifers. It also indicates that there is a relatively low concentration of constituents, Na^+ , K^+ , Cl^- and F^- , in deep aquifers as compared to the shallow and intermediate aquifers. This is possibly due to poor hydraulic conductivity between the shallow and deep zones. Although the concentration of these chemical constituents in a majority of the sites is within the maximum permissible limits, the continuous escalation of these constituents in groundwater can pose a potential health hazard in future.

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