

# Chapter 5

## Groundwater of Hard Rock Aquifers of India

Prabhat Chandra Chandra

**Abstract** About two-thirds geographical area of India is occupied by hard rocks comprising granite, gneiss, schist, quartzite, charnockite, khondalite, banded gneissic complex, basalt and intrusive, etc. Out of the twenty-nine States in the country, in twenty-two States the spread of hard rock areas varies from about 0.3 million km<sup>2</sup> to more than 5000 km<sup>2</sup>, and a number of mega-cities are located in the hard rocks. The occurrence of aquifers in these rocks is heterogeneous, in near-surface weathered zone, in underlying saprolite, in discontinuous fractured zones and along joints, veins and litho-contacts. The abstraction of these aquifers depends on their availability, storage, yielding capacity and water quality. To tap the deeper yielding fractured zone aquifer and obtain higher yield, the borewells are sunk to 200 m depth. The yield from the top weathered zone aquifer within 20–30 m depth ranges from 0.9 to 1.8 cubic metre per hour (m<sup>3</sup>/h). The cumulative yield from the weathered zone and underlying saprolite may range up to 9–10.8 m<sup>3</sup>/h. The yielding fractured zones are mostly encountered within 100–150 m depth and could occur deeper also, as observed in Karnataka State in southern part of India, but the frequency of occurrence is meagre. Generally, the weathered zone, saprolite and the yielding fractured zones up to 60–100 m depth are tapped by hand pumps and shallow borewells. The borewell yield less than 3.6 m<sup>3</sup>/h is termed 'low'. In India, the groundwater investigation in hard rocks is carried out using surface geophysical surveys generally comprising resistivity sounding, profiling and imaging supported by satellite imageries and lineament maps. Heliborne electromagnetic and magnetic surveys have also been conducted. In several parts, a declining trend in groundwater level is observed, for which artificial recharge methods are adopted. The higher concentrations of fluoride in groundwater are observed in several parts.

---

P. C. Chandra (✉)  
CGWB, Patna, India  
e-mail: chandrapc67.gwgp@gmail.com

P. C. Chandra  
The World Bank, New Delhi, India

P. C. Chandra  
WAPCOS Ltd., New Delhi, India

**Keywords** Hard rock aquifer in India · Weathered and fractured zone aquifers  
Hard rock geophysics · Heliborne geophysics · Artificial recharge  
Higher fluoride concentration

## 5.1 Introduction

Compact and massive rocks—generally the igneous and metamorphics—which do not possess primary porosity and hydraulic conductivity are known as hard rocks. They are also known as fractured or fissured rocks. The carbonate rocks can also be considered as hard rocks but are excluded from the present discussion as the mode of groundwater occurrence differs from the igneous and metamorphic rocks. About two-thirds geographical area of India is occupied by hard rocks (Chap. 1, Figs. 1.4 and 1.5). The hard rocks comprise a variety of rock types, viz. granite, gneiss, schist, quartzite, charnockite, khondalite, banded gneissic complex, basalt and intrusive, etc. (CGWB 2012). Out of the twenty-nine States in India, in twenty-two States the spread of hard rock areas varies from about 0.3 million km<sup>2</sup> to more than 5000 km<sup>2</sup> (Tables 5.1 and 5.2), and there are a number of mega-cities located in the hard rocks. There are 112 districts in 11 states having 75% area occupied by basalts or crystallines (Krishnan et al. 2009). More related information regarding groundwater of South Asia are available in Mukherjee et al. (2018) and regarding hard rocks are available in Geological Society of India (2008) and Chandra (2015).

## 5.2 Hard Rock Hydrogeology

The groundwater occurrence in hard rocks is heterogeneous and complex. It occurs in the near-surface weathered zone, in the underlying saprolite, in discontinuous fractured zones and along joints, veins and litho-contacts. The abstraction of these aquifers depends on their availability, storage, yielding capacity and water quality. The weathered zone, where the original texture of the parent rock is totally destroyed, generally has good porosity and behaves as a moderately yielding granular aquifer. However, in some of the granitic terrain with abundance of clays in the weathered zone formed as alteration product of feldspars and mica, the yield is poor. In basaltic terrain also, the faster chemical weathering of mafic minerals may cause abundance of clays and consequent reduction in yield. The occurrence of groundwater in quartzite, phyllite and schist is also controlled by weathering, joints, fissures, folds, schistosity and bedding plane. In compact formations underlying the weathered zone, the occurrences of groundwater are in secondary pore spaces developed through processes of fracturing and jointing. Besides, the faults and shear zones hold better groundwater storage and flow, if mylonite which reduces the hydraulic conductivity (Gustafson and Krasny 1993) is not present. The flow of groundwater at depth depends on the interconnections of fractures. The structures like basic dyke intrusive and quartz

**Table 5.1** States in India with hard rock area more than 5000 km<sup>2</sup>

	State	Area km <sup>2</sup> (% area of the state) occupied by hard rock	Major rock type
1	Maharashtra	267,305 (90.19)	Basalt
2	Andhra Pradesh and Telangana	193,314 (72.09)	Banded Gneissic Complex (BGC)
3	Karnataka	184,317 (93.61)	BGC, Basalt, Schist
4	Madhya Pradesh	176,863 (59.72)	Basalt, BGC
5	Odisha	97,866 (65.77)	BGC, Khondalite
6	Tamil Nadu	88,387 (72.15)	Gneiss, Charnockite
7	Gujarat	87,524 (49.86)	Basalt
8	Jammu and Kashmir	80,168 (36.21)	Granite
9	Rajasthan	78,179 (23.65)	BGC, Gneiss, Granite
10	Chhattisgarh	70,778 (54.06)	BGC, Gneiss
11	Jharkhand	65,508 (84.41)	BGC, Schist
12	Kerala	37,201 (89.0)	Charnockite, Gneiss, Khondalite
13	Uttarakhand	35,125 (67.26)	Schist, Quartzite, Gneiss, BGC
14	Himachal Pradesh	32,941 (60.32)	Schist, Quartzite, Gneiss, BGC
15	Uttar Pradesh	16,686 (7.2)	BGC, Quartzite
16	Arunachal Pradesh	14,821 (18.68)	Granite
17	West Bengal	8717 (10.62)	BGC, Schist
18	Assam	8359 (11.06)	BGC
19	Meghalaya	8222 (38.07)	BGC, Granite
20	Bihar	6137 (6.77)	BGC
21	Sikkim	5192 (75.42)	Gneiss, Schist

Source CGWB (2012)

**Table 5.2** Area covered by various types of hard rock lithology

Major hard rock aquifer	Area covered (km <sup>2</sup> )
Basalt	512,302
BGC	478,382
Gneiss	158,753
Schist	140,935
Granite	100,991
Charnockite	76,359
Quartzite	46,904
Khondalite	32,913
Intrusive	19,895

reef may act either as barrier or conduit for groundwater flow. Also, they can store groundwater. All these depend on the dimension and orientation of these structures with respect to the general groundwater flow direction and on the compaction, weathering and fracturing in them. A classical example is of Bundelkhand Granite Gneiss Complex of Jhansi district, Uttar Pradesh, India, where groundwater occurrences and movement are controlled by a large number of linear quartz reef or giant quartz vein (GQV) oriented in NE-SW to NNE-SSW and the basic dyke swarm in NW-SE direction. The quartz reefs run for kilometres as ridges and at places appear truncated, in all probability by the numerous intersecting dykes which could be the last phase of intrusive episode in the area.

The near-surface weathered zone aquifer can be considered regionally extensive because it is present almost everywhere in the hard rock terrain. However, the thinning of saturated zone, irregular weathering and exposed compact rock surroundings in places make the weathered zone aquifer discontinuous. Also, the decline in groundwater level during summer months results in a reduction of saturated thickness. The areal extents and thickness of the weathered zone control the aquifer storage capacity. The seasonally varying saturated thickness of the weathered zone sustained by the recharging monsoon precipitation and other sources affects the well yield. The weathered zone of less than 10 m thickness can form an effective aquifer only when there is a high recharge (Larsson 1984). A weathered zone with saturated thickness about 30–40 m generally forms a good aquifer. However, its hydraulic characteristics may vary laterally as well as with depth, resulting in location-specific varied well yield. Mostly, the groundwater flow is at the base of the weathered zone (Jones 1985) which is generally characterized by relatively low porosity and high hydraulic conductivity.

The low-yielding weathered zone aquifer, generally of 10–20 m thickness, can be developed for local water supply by large-diameter dug wells and shallow hand pumps. Dug-cum-borewells or borewells can be sunk where weathered zone thickness is considerably high. As observed, in the hard rocks of Jharkhand, India, the yield from weathered zone aquifer alone ranges from 0.9 to 1.8 m<sup>3</sup>/h and when the underlying saprolite is included, the yield increases up to about 9.6 m<sup>3</sup>/h (Dev Burman and Das 1990; Chandra et al. 1994). However, Singhal and Gupta (1999) and Subramanian (1992) report a wider yield range of about 0.36–32 m<sup>3</sup>/h for dug wells in different hard rock types.

A system of joints and interweaving fractures often occurs in the compact impervious rock in places and depth. It is the combined effect of cooling process, physical and geochemical properties and processes, stresses through geologic time, percolating groundwater and the palaeo-climatic conditions. The fractures related to tectonics, originate with maximum intensity from the fault zones and may continue to large distances. Fractures mostly occur within a few hundred metres from the earth surface, and the opening is generally in the order of millimetre to centimetre. The fractures, linear in nature, may occur as a distinct planer feature or as a group of close-spaced planer features. Larsson (1984) indicate dense fracturing of limited length in fine-grained rocks as compared to that in coarse-grained rocks. The fracturing is more in low-grade metamorphic rocks compared to that in high-grade metamorphics.

In the deeper fractured zones, which receive water through near-surface weathered zone and saprolite, shallow vertical fractures and joints, and also through deep weathering in fault zones, the local to regional-scale storage and movement of groundwater are controlled by the distribution of interconnected deeper fractures and their openness. The tensional fractures are more open and transmissive compared to shear fractures (Singhal 2008). The horizontal fractures and joints control the direction of groundwater flow. The interconnection between the fractures locally and regionally is necessary to maintain the hydraulic continuity over a large area and sustain the well yield. Though the volume of water in the fracture will be barely a few percent of the bulk volume, the flow through it could be high. The micro-fracturing associated with the fractured zones, having different orientations, creates and enhances the permeability locally. These micro-fractures also behave as conduits to increase the groundwater storage and in totality may form a zone of potential aquifer. Thus, the realization of the presence of the fractures and their character is essential in groundwater development and understanding the complexities in the groundwater flow regime. The information obtained from groundwater exploration up to 200–300 m depth in hard rock areas of India reveal that with depth the fractures diminish in intensity, frequency and dimension and also close. Though the chance of intersecting the fractures abruptly reduces with depth, an isolated fracture encountered at depth in the borehole can dramatically increase the yield if interconnected with other fractures hydraulically and getting recharged through the weathered zone. That is, the locally isolated deep fracture could also be productive and contribute maximum yield. The occurrences of such isolated yielding fractures increase in areas of thick weathered zone. Only with this hope, occasionally the borehole drilling is continued deeper. But, beyond a certain depth the water well drilling will be, in general, uneconomical.

The hydrogeological uncertainty prevails even within a fractured zone. The wells sunk to same depth within a few metres may have different yield as they may encounter different number of saturated fractures. That is, the findings of one well may not always be useful to pinpoint another drilling site. As far as the general hydraulic conductivity of fractured zone is concerned, qualitatively the deeper fractured zones have lesser hydraulic conductivity. The fractured zones of more regional character have better hydraulic conductivity. Krasny and Sharp (2007) indicate that areas or zones with long fractures, larger density of fracturing and greater fracture aperture have higher hydraulic conductivity. Compared to soft rock, the hydraulic conductivity is quite low ranging from  $10^{-11}$  to  $10^{-2}$  m/s (metre per second). For the aquifers in granites and meta-sediments of Jharkhand State, India, up to about 200 m depth, the hydraulic conductivity ranges from about  $1 \times 10^{-7}$  to  $0.7 \times 10^{-6}$  m/s and transmissivity ranges from  $0.23 \times 10^{-4}$  to  $3.24 \times 10^{-4}$  m<sup>2</sup>/s (CGWB 2012a).

The boreholes drilled up to 300 m depth in hard rocks of Jharkhand State, in eastern part of India, revealed the occurrence of saturated and unsaturated fractured zones up to a depth of 285 m (Dev Burman and Das 1990). The unsaturated ones

were either non-productive or completely dry. The saturated fractured zones are qualitatively grouped depth-wise as shallow and deep or shallow, medium depth and deep. The saturated fractured zones occurring within 50–60 m depth are grouped as shallow and are tapped by hand pumps. In this area, prominent saturated fractured zones occur up to 110 m depth in the younger granites and up to 140 m in the older granites. The poorly interconnected fractured zones yield for a short while and get dewatered. The maximum yield obtained from individual zone in younger and older granites were 10.8 and 21.6 m<sup>3</sup>/h, respectively. A number of 500 m deep-water wells were drilled by Central Ground Water Board (2012b) in granites, gneisses and schists of Karnataka state in the southern part of India. The yielding fractured zones were encountered up to a depth of 389 m. The maximum cumulative yield of a well was reported as 54 m<sup>3</sup>/h. The weathered zone in this area was almost dried-up as the water table was deep, at 68 m in places. The fractured zones immediately underlying the 75-m-thick weathered zone were either dry or had a very poor yield (CGWB 2009). The water in the deeper fractured zones was due to their regional connections to other distant fractured zones.

Besides the granites and gneisses, another hard rock terrain is the Deccan Trap Basalts (DTB) which occupy about 500,000 km<sup>2</sup> in the west-central part of India. The DTB comprises a number of horizontal to sub-horizontal lava flows. The thickness of individual lava flow varies from 1 to 160 m (Singhal 1997; Mahoney 1988). The flows are separated by 'red bole' or 'green bole' comprising tuffaceous, scoriaceous or pyroclastic material accumulated during the hiatus between the two successive flows (Kale and Kulkarni 1992; Adyalkar et al. 1975). According to Ghosh et al. (2006), the red bole is formed by weathering of basalt and the green bole is a mixture of weathered basalt and remnants of volcanic ashes. The sheet joints in the bole bed make it friable (Kale and Kulkarni 1992). The bole bed thickness varies from a few centimetres to a metre. It is regionally persistent and forms the marker bed to demarcate the flows. Generally, the flow unit is massive at its bottom and vesicular towards the top. The vesicular part constitutes about one-fourth to one-third of a flow unit (Saha and Agrawal 2006). The near-surface part of the basalt flow sequence is weathered.

The groundwater condition in DTB differs from that in the granitic terrain. The flows of basalt produce stratification, and therefore, the hydrogeological character of basalt varies from a typical fractured hard rock to heterogeneous, anisotropic near-porous rock (Custodio 2007). The secondary porosity introduced by the interconnected vesicles, cooling and sheet joints, weathering and fracturing, vertical to sub-vertical fractures and joints in the compact basalts develop the repositories of groundwater and form the basalt aquifers. The interflow zones also form aquifers where it is without clay predominance. The groundwater flow paths are formed by horizontal sheet joints and vertical fractures and joints. The sheet joints increase the transmissive capacity (Saha and Agrawal 2006). Deolankar (1980) and Surinaidu et al. (2013) report a better transmissivity for the near-surface weathered basalt compared to the vesicular and fractured-jointed basalts. The maximum yield of dug well in weathered basalt is reported as around 29 m<sup>3</sup>/h, and in places, it is more than that from shallow borewell (Dhonde 2009).

### 5.3 Development of Hard Rock Aquifers

In hard rock areas, groundwater is being tapped mostly through age-old practice of hand-dug well structures. The depth of dug well is controlled by the thickness of the weathered zone. Generally, dug wells are 2.5–4 m in diameter and 10–15 m deep. In some areas, large-diameter and deeper dug wells are constructed. The dug wells are prevalent in areas with shallow water table allowing a good volume of water getting collected in the dug well. In areas with a sufficiently thick saturated weathered zone and shallow water table dug-cum borewells are constructed. To meet the increasing demand and declining water table shallow to deep borewells are constructed tapping the weathered zone, saprolite and also the underlying fractured zones. Constructing a dug well in shallow weathered zone is easy trouble-free, economical and without any financial risk and does not require much technical support. The dug wells can supply domestic water and to some extent support the local irrigation. However, in the past few decades there is a sharp reduction in dug well construction as the cost of construction is comparable to that of a shallow borewell. The yield of a borewell depends on a complex multiplicity of many factors, like rock composition, weathering, clay content in the weathered zone, presence of saprolite, its proximity to lineament, dimension of lineament, presence of joint and fractured zone, depth drilled, number of saturated fractured zones encountered within the depth drilled, topography and the annual recharge. In general, the yield of shallow wells in weathered zone is around  $3.6 \text{ m}^3/\text{h}$  (Clark 1985) and mostly caters to local needs. In granitic terrain, wells with yield less than  $3.6 \text{ m}^3/\text{h}$  are classified as low-yielding or failure wells. The wells with yield  $3.6\text{--}18 \text{ m}^3/\text{h}$  can be considered as moderate yielding and more than  $18 \text{ m}^3/\text{h}$  as high yielding.

In areas with deeper water table, where either the saturated weathered zone is hardly a few metres thick or it is totally dewatered, for a better yield borewells are drilled deeper to tap the saturated fracture zones at depths. That is, drilling depth is more in areas where yield from top weathered zone and saprolite is poor. Besides, the depth of drilling can be related to demand. For greater yields, wells are drilled deeper with the hope of encountering yielding fractures at depths. Other than groundwater condition, the depth of drilling is also controlled by the money available for it. Those who can afford, try for deep-water well drilling.

In the hard rock terrain of India, the water wells are drilled mostly by government agencies for community water supply and irrigation. Water wells are drilled by private individuals also. Generally, the wells for drinking water supply are drilled to a depth of 60–100 m. To tap the yielding deep fractured zones, wells as deep as 300 m and in places up to 500 m have been drilled by Central Ground Water Board (Government of India). The deeper drilling being quite expensive, it is avoided, unless it is essential to tap the deep fractured zones. As such, the depth of borehole drilling can be considered as minimum or economic that gets groundwater yield of adequate quantity and acceptable quality. The reduction in yield with time due to declining water table has affected the depth of drilling which has, in general,

**Table 5.3** General range of weathered zone thickness, depth range of fractured zone occurrences and the yield

Rock type	Weathered zone thickness (m)	Depth range (m) of fractured zone occurrences	Range of cumulative yield (m <sup>3</sup> /h) from borewell
Basalt	5–60	20–280	0.5–20
BGC	3–100	12–200	Up to 150
Gneiss	3–25	20–200	0.5–104
Granite	5–40	15–200	0.4–60
Schist	4–80	10–180	0.5–23.4
Quartzite	5–30	14–150	Up to 16.7
Charnockite	5–45	15–430	Up to 126
Khondalite	5–20	4–291	0.8–62.5
Intrusives	6–13	12–17, 100–150	Up to 10.75

Source CGWB (2012)

increased. The general ranges of cumulative yield of borewell tapping weathered zone, saprolite and the fractured zones in different rock types are summarized from CGWB (2012) and presented in Table 5.3.

In the hard rocks of Jharkhand state of India, for which two case studies are presented latter, the results of exploration carried out by CGWB (Government of India) up to a depth of 300 m indicated a well yield ranging from 0.72 to 9.6 m<sup>3</sup>/h, for the weathered zone and saprolite occurring up to the depth ranging from 12 to 25 m (Dev Burman and Das 1990; CGWB 2012a). The fractured zones were encountered up to a maximum depth of 285 m. However, the saturated fractured zones mostly occurred in the depth range of 20–150 m. The yield of individual fractured zone ranged from 0.9 to 41.4 m<sup>3</sup>/h. The yield of saprolite and underlying shallow fractured zones increased and that of the fractured zones occurring beyond 100 m depth decreased during pumping compared to drilling. The possible reason for the increase in yield of saprolite and shallow fractures during pumping test was explained by Dev Burman and Das (1990) as involvement of a large volume of rock surrounding the well and wider connectivity of shallow fractured zones during the test. It was observed that the drawdown for saprolite was less as compared to that for the fractured zones. In the Bundelkhand Granite Gneiss Complex of Jhansi and Lalitpur districts of Uttar Pradesh, though the productive fractured zones were encountered up to 200 m depth (the depth of drilling), they were mostly limited to depths about 50 m (WAPCOS 2016).

In fractured rock yield of a borewell does not increase with depth continuously like sedimentaries. The yield obtained either from uncased weathered zone or shallow fractured zone will continue as a constant yield for a depth drilled beyond these zones, and then there will be a sudden increase in yield as soon as another yielding fractured zone at depth is punctured. A dry fractured zone at depth getting connected to a yielding fractured zone will draw water and reduce the overall yield



also the increase or decrease in yield will depend on relative hydrostatic head of the deeper fractured zones. A number of dry fractured zones were encountered in boreholes drilled in Jharkhand. It is observed that the probability of encountering fractured zones, in general, decreases with depth. So, for tapping the shallow fractured zones the depth of water well drilling could be 60–100 m. It could be up to 200 m depth or beyond, if there is some scientific information, say geophysical results, indicating the presence of deeper fractured zones. In DTB, the borewells are generally drilled up to about 200 m depth to tap the deeper flow units and the flow contacts. The borewell up to a depth of 352 m was drilled by CGWB in DTB (Parchure 2010). The yield of borewells in DTB varied over a wide range from less than 3.6 to 176.4 m<sup>3</sup>/h with an average yield within 20 m<sup>3</sup>/h.

#### 5.4 Aquifer Mapping in Hard Rocks of India

‘Aquifer mapping’ is a holistic approach to aquifer management. It is to assess quantity, quality and sustainability of aquifers through multidisciplinary integrated studies. The aim is to provide comprehensive information on aquifers, on their characteristics, their interaction with surface water systems, their health, the future stress the aquifers can bear and approaches for conservation and protection required for their management.

Keeping in view the heterogeneities and rapid hydrogeological variations, the site-specific geological and hydrogeological characterization or in other words delineation of hard rock aquifers either for locating well sites or for artificial recharge structures warrants a systematic integrated regional to site-scale field investigations. This is essential because in most cases the hydrogeological uncertainty either makes the programme expensive or compels to abandon it. The aim of the investigation will vary as per the objective. It could be delineation of weathered zone and defining its saturated thickness, demarcation of area with its thickening, saprolite, fractured zone and its orientation, basic intrusive and quartz reef, etc.

Since geomorphology and structures play an important role in groundwater occurrences in hard rock, to get a regional view, the investigation is initiated through mapping of lineaments using satellite imagery. These lineaments may be associated with geological structures, and their hydrogeological relevance is ascertained through geological field observations. The areas traversed by regional lineament, higher density of lineaments and criss-crossing lineaments have better prospect for thick weathered and fractured zones. The wells located on or near lineaments generally have better yield.

According to CGWB (2012), about 1,276,000 km<sup>2</sup> hard rock area of the country is suitable for groundwater development and artificial recharge. Aquifer mapping can be taken up in this entire area in a phased manner with prioritization.

## 5.5 Surface Geophysical Survey

The subsurface investigation in hard rocks is initiated through geophysical surveys preferably across lineaments. The surveys are aimed at identifying the hydrogeological anomalies, i.e. identifying and interpreting the variations in physical properties of the subsurface and transforming them into hydrogeological inferences subjectively. The usefulness of any geophysical method rests in its capability to pick up and resolve with least ambiguity, the anomalies caused by small target occurring at depths, having less-contrasting physical properties with the host. The shallow occurrences, bigger dimensions and better physical property contrast make the target identification easier and confident. The weathered zone and saprolite, saturated shallow fractured zones, basic dykes and the quartz reefs can be delineated. The orientation of fractured zones, their connectivity, water content and quality and flow direction can only be approximated. While the weathered zone can be characterized easily, it is difficult to delineate the thin saprolite and deeper fractured zones.

The commonly used geophysical methods are electrical resistivity, electromagnetic and magnetic. The electrical resistivity and electromagnetic methods are quite popular as they are most responsive to the variations in the physical property—the electrical conductivity caused by the variations in the occurrence of groundwater and its quality in terms of electrical conductivity. These methods are employed through different techniques—the sounding and profiling to get respectively the vertical and lateral variations in electrical resistivity and approximate the subsurface structures. The modern technique of merging profiling and sounding is known as imaging. Resistivity imaging provides two ( $x$ - $z$  plane)- or three-dimensional picture of the subsurface. The geophysical surveys are conducted mainly for two purposes—either to assess the suitability of a water well drilling site located and selected on the basis of demand and habitation or to select favourable sites geophysically in a large area and then locate suitable drilling sites based on geophysical results. For a large area study, the geophysical surveys can be conducted in two phases: the reconnaissance and detailed. The reconnaissance surveys are conducted to narrow down the zone of interest for detailing. The reconnaissance is carried out by any one of the fast-coverage methods, viz. total magnetic field, very low frequency (VLF) and single frequency electromagnetic (FEM) profiling or a combination of these methods can also be used. The location, width and extents of basic dykes, lithological contacts and also thickening of weathered zone can be assessed by the magnetic survey. The detailing is done by a combination of techniques like Gradient Resistivity Profiling (GRP) and Vertical Electrical Sounding (VES) or Electrical Resistivity Tomography (ERT) and multi-frequency and multi-spacing FEM. The dual moment time domain electromagnetic (TEM) sounding can also be conducted. Since in hard rock areas, the fractured zones are manifested on the surface mostly as lineaments, the economical approach is to first carry-out parallel profile GRP across lineaments obtained through satellite imageries and confirm the presence of associated conductive fractured zone. It is followed by VES conducted

along the conductive zone delineated or ERT across the linear conductive zone picked up in GRP. Though ERT produces a 2-D picture of the subsurface and is better and faster compared to VES and resistivity profiling, which gives only 1-D information, the data acquisition cost for large-scale ERT is high. It may not be economically feasible and also not required. Selectively locating ERT across the conductive zone picked up by GRP is a better and economical approach.

## 5.6 Heliborne Geophysical Survey

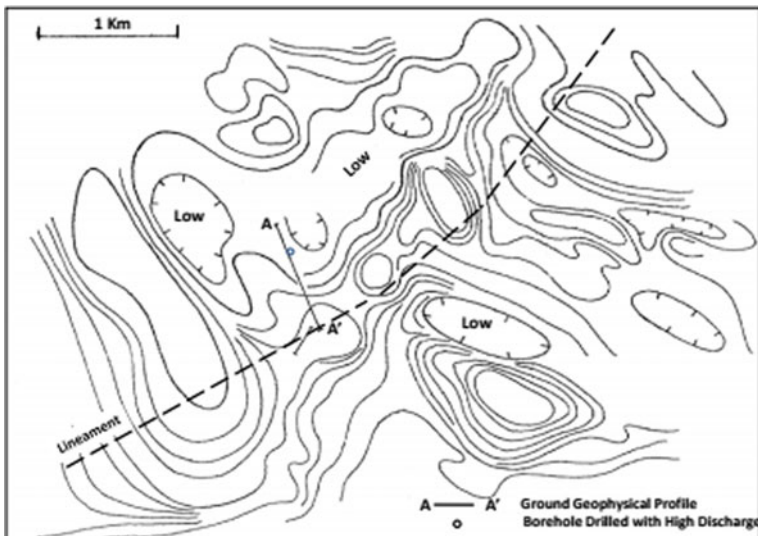
The modern approach to aquifer mapping in hard rock is through helicopter-borne electromagnetic and magnetic surveys also known as heliTEM and heliMAG surveys. The advantage of heliborne survey is that it produces dense data coverage, fast data acquisition and provides accessibility to inaccessible areas and rugged terrains. The heliborne TEM in combination with magnetic surveys has been introduced to delineate the weathered zone and the shallow fractured zones. It has been conducted for aquifer mapping in several countries. In India, CSIR-National Geophysical Research Institute, Hyderabad, India, and Central Ground Water Board, Government of India jointly conducted the heliborne surveys for the World Bank funded aquifer mapping pilot project (AQUIM) of the Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India (Ahmed 2014 and Chandra et al. 2016). The heliTEM and heliMAG surveys were conducted in six different hydrogeological terrain of India with the objective of evaluating the efficacy of these surveys under varied hydrogeological conditions. Out of the six different hydrogeological terrain of India, three are in the hard rock terrain. They represent alluvium covered (thickness up to 70 m) highly folded and faulted hard rock area of Rajasthan, weathered fractured granite gneiss area of Karnataka and the basaltic terrain of Maharashtra. The heliMAG total field survey was conducted to decipher the subsurface structural fabric of the hard rock terrain, while the heliTEM survey was conducted with dual (low and high) moment transmitter to map the near-surface as well as the deeper hydrogeological conditions. The aquifers in the alluvial cover, in the weathered zone and in the deeper fractured zones were mapped, and the structures of hydrogeological significance were delineated. Once the heliborne results are validated through borehole drilling up to appropriate depths, the approach could be proved and established for aquifer mapping in hard rock areas.

## 5.7 Case Studies on Integrated Geophysical Survey

The results of integrated surface geophysical survey in three areas, viz. the Chhotanagpur granite gneiss of West Bengal (site 1), meta-sediments of Jharkhand (site 2) and Bundelkhand Gneissic Complex of Uttar Pradesh (sites 3 and 4) States

of India are discussed here. The sites 1 and 2 were surveyed during 1986–88, and the sites 3 and 4 were surveyed in 2016. These are discussed here to show the efficacy of multi-technique geophysical surveys to arrive at the best common anomaly and also the variations in approach over the past 30 years. The present-day use of ERT has become a major geophysical contribution in hard rock exploration which was not available earlier. The results are shown in Figs. 5.1 through 5.6.

At all these sites, the surveys were initiated by locating the lineaments and placing the surface geophysical survey profiles across the lineaments. Since the aeromagnetic data were made available for parts of Jharkhand and West Bengal, for sites 1 and 2 the ground geophysical survey profiles were placed in areas of coincident photo lineament and aeromagnetic lineament (Figs. 5.1 and 5.3). The surveys were initiated in West Bengal and Jharkhand through reconnaissance total field magnetic profiling. At site 1 in granite gneiss (Fig. 5.1), the magnetic profiling was followed by 100 m transmitter-receiver spacing FEM profiling. The anomalies for higher transmitter frequencies were prominent (Fig. 5.2a). The FEM anomalies at higher transmitter frequencies were enhanced due to the presence of conductive overburden (weathered zone). The conductivity of the overburden was estimated by VES. The shape of the FEM anomaly revealed the presence of northwest dipping parallel relatively more conductive bodies underneath the conductive overburden. The GRP anomalies manifested three prominent resistivity lows, confirming the FEM anomalies. The interpretation of VES conducted on the GRP ‘low’ anomalies



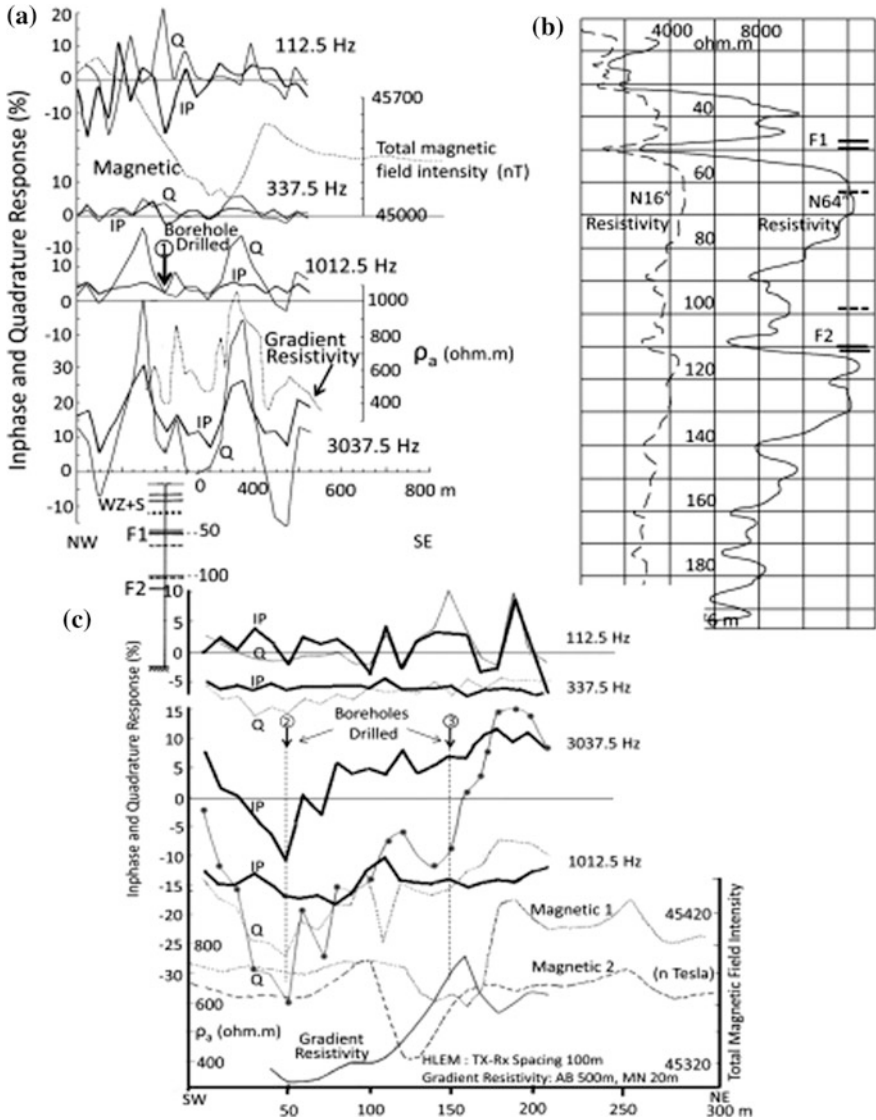
**Fig. 5.1** Ground geophysical surveys (shown as profile AA') for groundwater exploration at site 1 in Chhotanagpur granite gneiss terrain of West Bengal State, India, across coincident aeromagnetic and photo lineament (Chandra et al. 1994). Aeromagnetic data source AMSE, Geological Survey of India

indicated 24-m-thick weathered zone and saprolite with resistivity between 148 and 212  $\Omega$  m. On the basis of these results, drilling sites were selected.

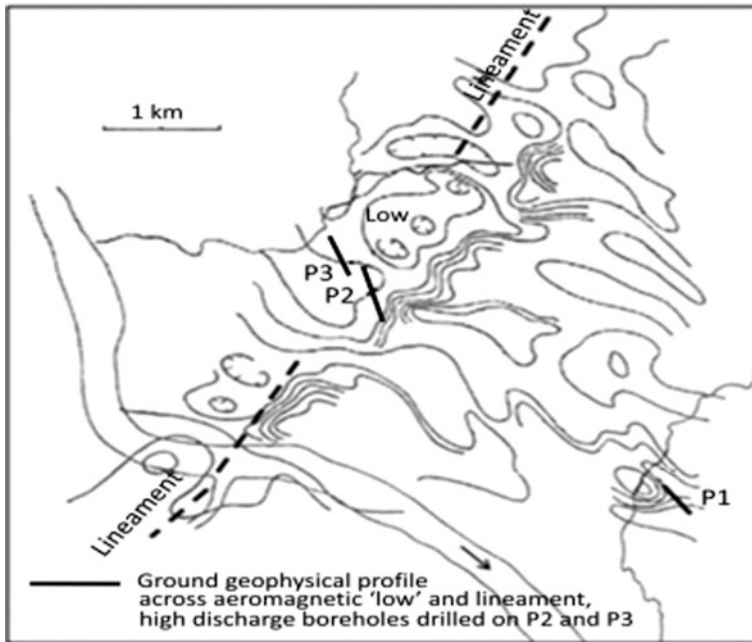
A borehole was drilled up to a depth of 198.76 m on the geophysical anomaly. The borehole encountered weathered zone and saprolite up to 25 m depth and two saturated thin fractured zones, viz. F1 in the depth range 48.36–49.36 m and F2 in the depth range of 110.32–110.53 m (Fig. 5.2b). The yield from the weathered zone was 9.0 m<sup>3</sup>/h and that from F1 and F2 were 7.2 and 10.8 m<sup>3</sup>/h, respectively. The borehole encountered two dry fractures at 63 and 99 m depth. In the electrical resistivity log of the borehole, the saturated fractured zones were picked up as low resistivity zones, dry fractured zones as relatively high-resistivity zones and compact formations with very high resistivity, of the order of 10,000  $\Omega$  m. The borehole drilling and logging results indicated that the thin fractured zones at depths may not get detected individually by resistivity and electromagnetic surveys. However, a reduction in bulk resistivity of the formations due to the presence of saturated fractures can definitely be deciphered.

To select another water well drilling site near site 1, the ground geophysical surveys comprising magnetic, FEM and GRP were conducted along a NE-SW profile in a nearby area. The GRP low and FEM anomaly were coincident (Fig. 5.2c). The FEM responses were enhanced at higher transmitter frequencies. It indicated a thickening of conductive overburden (weathered zone) and possible presence of saturated fractured zone immediately underlying the overburden. The borehole 2 (Fig. 5.2c) was drilled up to 200.82 m depth on this GRP-FEM anomaly. It encountered about 17 m thick weathered zone and a saturated fractured zone at 44.8 m depth. The yield from the weathered zone and saprolite was 5 m<sup>3</sup>/h and that from the fractured zone was 6.9 m<sup>3</sup>/h. To analyse an high-resistivity anomaly in GRP, the test borehole 3 (Fig. 5.2c) was drilled up to a depth of 300.76 m on the GRP 'high' anomaly. The borehole 3 was dry throughout the depth drilled with the only exception that a very small yield of about 0.76 m<sup>3</sup>/h was obtained from 25.47 m thick weathered zone and saprolite. It established the essentiality of geophysical surveys in hard rocks to locate successful water wells.

Like granite gneiss terrain mentioned above, in meta-sediments of Jharkhand, India, comprising schists, quartzites and phyllites, similar ground geophysical survey approach was made to locate water well drilling site (Fig. 5.4). The meta-sediments are highly folded with steeply dipping flanks. A long total magnetic field ground survey profile was placed across the NNE-SSW aeromagnetic lineament coincident with photo lineament, shown in Fig. 5.3. The FEM profiles and GRP (profile P2) were subsequently placed on magnetic anomaly (low). The FEM profiling was conducted at two transmitter frequencies and 100 and 200 m transmitter-receiver spacings. On P2, the low-frequency EM responses for both the spacings are considerable. The high transmitter frequency response for 200 m spacing shows a step-like anomaly with kinks and enhancement of anomaly towards NW. It was attributed to thickening of overburden (weathered zone) and presence of parallel dipping conductors underlying the overburden. A similar step-like GRP anomaly with decreasing resistivity towards NW was observed. The interpretation of VES conducted at this site revealed a 7-m-thick weathered zone of 128  $\Omega$  m resistivity. It

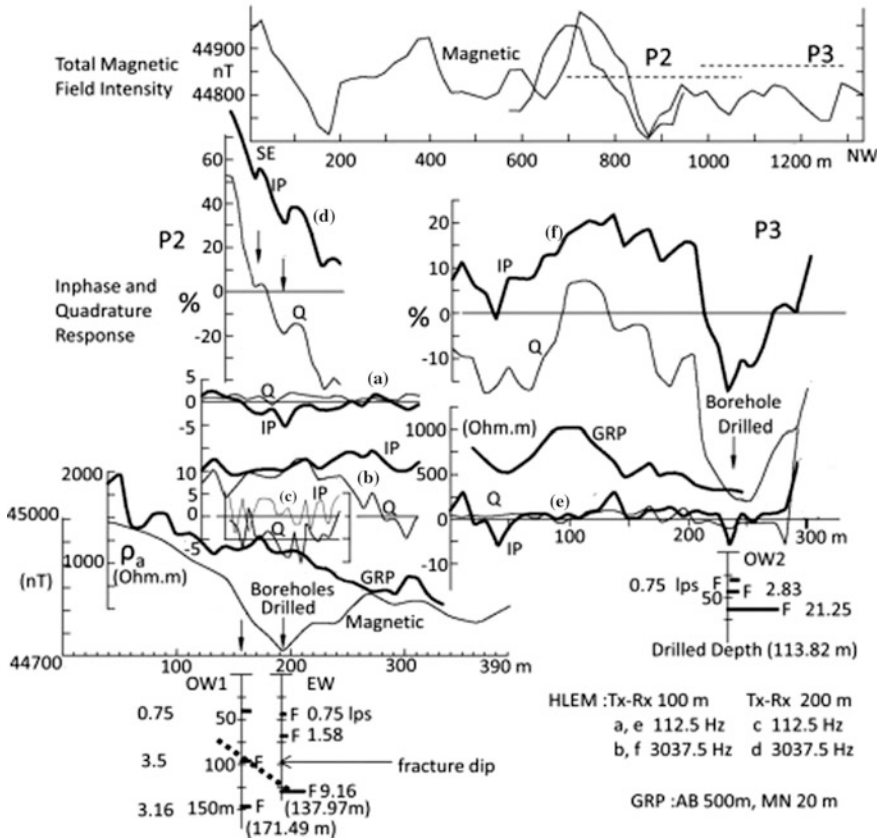


**Fig. 5.2** a Integrated ground geophysical survey profiles along AA' comprising magnetic, gradient resistivity (GRP) and multi-frequency horizontal loop EM profiling (FEM) for site 1 in Chhotanagpur granite gneiss, West Bengal State, India, for locating borehole drilling sites, b N16" and N64" resistivity log of the borehole 1 drilled at site 1; the dry fractured zones at 63 and 99 m depth are shown by dotted lines, and saturated fractured zones are shown by continuous lines; the resistivity log records more than 10,000  $\Omega$  m resistivity for the compact formation; yield from weathered zone and saprolite (WZ+S) was 9 m<sup>3</sup>/h and c ground geophysical survey profiles for borehole 2 and 3; borehole 2 encountered fractured zone at 44.8 m; the borehole 3 drilled on a GRP high was dry. The location of sites is shown on aeromagnetic map in Fig. 5.1



**Fig. 5.3** Ground geophysical surveys conducted (shown as profiles P1, P2 and P3) for groundwater exploration at site 2 in meta-sedimentary terrain of Jharkhand State, India, across coincident aeromagnetic and photo lineament (Chandra et al. 1994). Aeromagnetic data source AMSE, Geological Survey of India

is underlain by 22-m-thick relatively resistive ( $198 \Omega \text{ m}$ ) saprolite. On profile P2, two boreholes were drilled on the basis of FEM anomalies. The boreholes encountered high-yielding fractured zones up to 147 m depth (Fig. 5.4). Since the GRP on profile P2 showed a decreasing resistivity towards NW, another GRP-FEM profile (P3) in NW-SE direction was placed towards NW of P2 over a stretch of 300 m. The GRP on P3 showed lesser resistivity values compared to P2 and a decreasing trend towards NW. The high transmitter frequency FEM profile showed a prominent anomaly towards the NW end of the profile. It indicated a thick conductive overburden (weathered zone). The VES conducted at this site revealed the presence of 6–8 m thick near-surface layer of  $22 \Omega \text{ m}$  resistivity. It is underlain by 35–40 m thick layer of  $60\text{--}70 \Omega \text{ m}$  resistivity. A comparison of the results of VES on P2 and P3 revealed the presence of thick lesser resistive formation on P3. The presence of lesser resistive formation on P3 caused the enhancement in high transmitter frequency FEM anomaly. The borehole drilled towards NW end of profile P3 on GRP-FEM anomalies encountered a very high-yielding fractured zone in the depth range 57.86–68.10 m. The borehole could not be drilled further due to back pressure of water. Comparison of GRP-FEM anomalies of profiles P2 and P3 confirms the enhancement of FEM response due to the thick (35–40 m) relatively less resistive ( $60\text{--}70 \Omega \text{ m}$ )



**Fig. 5.4** Integrated magnetic, gradient resistivity and multi-frequency horizontal loop EM profiling at site 2 in meta-sediments, Jharkhand, India, for locating the boreholes. Location in aeromagnetic map is shown in Fig. 5.3

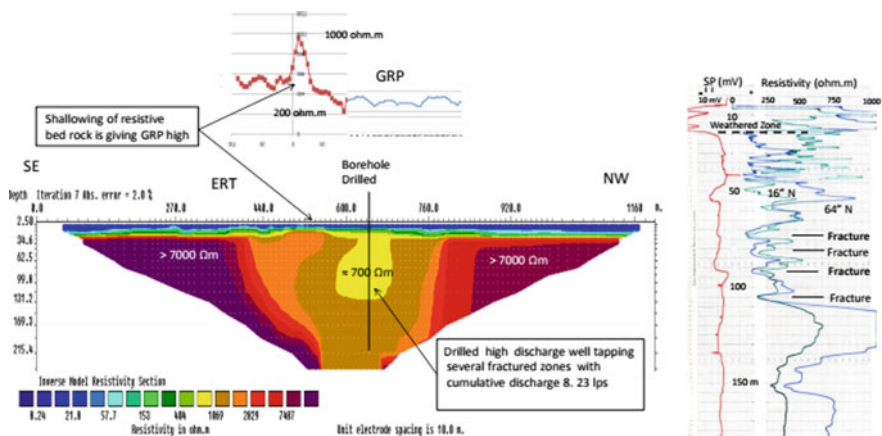
formation and the presence of conductive (or less resistive) fractured zones at depths around 50–70 m. The reduction in GRP resistivity in profile P3 compared to P2 is supported by the reduction in layer resistivities interpreted from the VES conducted on P3. The results of integrated ground geophysical survey in meta-sediments also substantiated its effectiveness in identifying the shallow to moderately deep (within 100 m depth) fractured zone.

These case studies reveal two important aspects, viz. (a) the usefulness of aeromagnetic and lineament maps in narrowing down the area for detailed ground geophysical survey and (b) the integration of electrical resistivity and FEM methods for ground geophysical survey. In case, aeromagnetic maps are not available for the

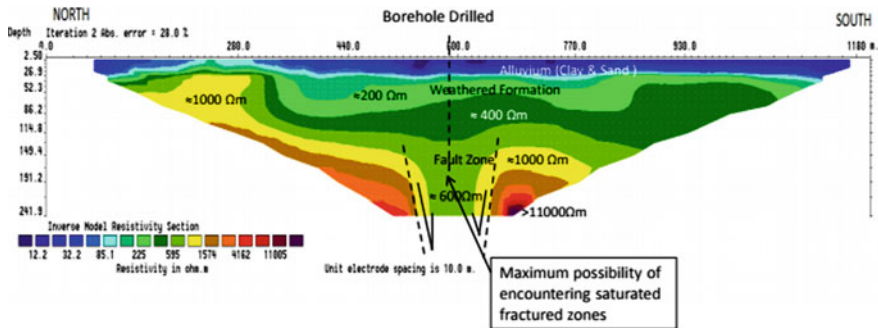


area, at first a long total field magnetic profile is to be placed across the photo lineament and the stretches with magnetic low anomaly across a photo lineament are to be considered for GRP and FEM follow-up surveys. The shape of the total field magnetic anomaly depends on latitude of the location, and corrections are to be applied. The FEM anomalies are to be confirmed by GRP. The GRP resistivity highs are definitely negatives for locating water well drilling site. Wide and contrasting GRP low (resistivity less than 500  $\Omega$  m with the background resistivity of 1000–2000  $\Omega$  m) associated with high transmitter frequency FEM anomaly can be considered for locating a water well drilling site. Though locating high-yielding water wells by geophysical surveys is desired, the efficacy of geophysical methods cannot be judged by well yield alone. In most of the cases, the borehole is drilled on the local best geophysical anomaly which may not be a standard good anomaly.

The case studies 3 and 4 are from Bundelkhand Gneissic Complex where a systematic sequential approach through GRP, VES and ERT was made to map the weathered zone and fractured zone aquifers (WAPCOS 2016). The GRP and ERT are shown in Figs. 5.5 and 5.6. GRP was used to locate the ERT. The ERT finally helped locating the low resistivity zone associated with deeper fractures. It is evident that identifying individual thin fractured zone even by ERT is difficult but the zone which may hold the maximum possibility of fractures can be demarcated. The 200-m deep borehole drilled at site 3 (Fig. 5.5) on the relatively low resistivity (about 700  $\Omega$  m) zone inferred up to about 100 m depth in the central part of the ERT encountered 2 fractured zones at 75 and 93.5 m depths. It is corroborated by the resistivity log of the borehole (Fig. 5.5). The cumulative yield was about 30 m<sup>3</sup>/h. Another ERT conducted to ascertain the extension of a NE-SW trending fault zone, and its suitability for well siting is shown in Fig. 5.6. The borehole drilled in the



**Fig. 5.5** Results of geophysical investigation comprising GRP and ERT and the electrical logging of the borehole drilled at a site 3 in Bundelkhand Gneissic Complex, Uttar Pradesh *Source* WAPCOS 2016



The ERT has confirmed the fault zone and possibility of groundwater saturation in the associated fractured zones

**Fig. 5.6** Results of ERT at a site 4 in Bundelkhand Gneissic Complex, Uttar Pradesh. *Source* WAPCOS 2016

fault zone encountered fractured zones at 34.5, 40.8 and 158.5 m depth. The cumulative yield of the borehole was 12.4 m<sup>3</sup>/h. The combination of GRP and ERT was found quite useful in locating successful boreholes in hard rock.

## 5.8 Managed Aquifer Recharge

The withdrawal of groundwater more than its replenishment results in declining groundwater level. The near-surface weathered zone aquifers, discontinuously available as pockets of limited storage capacity, either get dewatered and dried-up at many places or the water level in them deepens, resulting in a large number of dry wells. This is an alarming issue in the hard rock area of India. According to CGWB (2012), out of the total area under critical and overexploited stages of groundwater development in India, more than 40% area—about 32,000 km<sup>2</sup> under critical and more than 200,000 km<sup>2</sup> under overexploited stages—falls in the hard rocks (Tables 5.4 and 5.5, the limestone and the lateritic terrains are excluded). That is, a huge volume of dewatered weathered zone is available which can be locally recharged. Storing water in the dewatered space to restore or slowdown the declining water level and consequently recharging the connected underlying fractured zones requires intervention known as managed aquifer recharge (MAR) or artificial recharge. According to CGWB (2012), more than 284,000 km<sup>2</sup> hard area is suitable for artificial recharge.

There are several types of artificial recharge methods, of which the dug well recharge, check dam, percolation pond and recharge well are in practice in several States of India. The selection depends on subsurface and surface lithological conditions, terrain, fracture pattern, groundwater conditions and availability of adequate recharging surface water of good quality. Recharge structures are effective in

**Table 5.4** Hard rock area (km<sup>2</sup>) in various states under critical stage of groundwater development

State	Basalt	Granite	Schist	Quartzite	Charnockite	Khondalite	BGC	Gneiss	Total
Andhra Pradesh and Telangana	497	237	76				4414	28	5252
Gujarat	790	119	88	41				17	1055
Haryana				37				4	41
Jharkhand			2		42		438		482
Karnataka	2721		922				9366		13,009
Kerala					6			468	474
Madhya Pradesh	1127		9					15	1151
Rajasthan		139	2	85			13	986	1225
Tamil Nadu		94	122		3724	132	627	4330	9029
Uttar Pradesh				141			620		761
Total	5135	589	1221	304	3772	132	15,478	5848	32,479

Source CGWB (2012)

**Table 5.5** Overexploited hard rock area (km<sup>2</sup>) in various states

State	Basalt	Granite	Schist	Quartzite	Charnockite	Khondalite	BGC	Gneiss	Total
Andhra Pradesh and Telangana	198	1505	77	1675		258	11,943	1	15,657
Delhi				136					136
Gujarat	1059	57						16	1132
Haryana				201					201
Jharkhand		2	344	17			500	56	919
Karnataka	12,575		5323				46,717		64,615
Kerala								266	266
Madhya Pradesh	18,176								18,176
Maharashtra	5001								5001
Rajasthan	7433	12,157	3257	5367	173	74	17,658	15,172	61,831
Tamil Nadu		503	7		13,138	617	2207	18,939	35,411
Uttar Pradesh				11			1356		1367
Total	44,442	14,224	9008	7407	13,311	949	80,381	34,990	204,712

Source CGWB (2012)

areas with permeable soil and weathered zone and in areas with tensional fractures which are open in nature. A minimal rainfall of about 246 mm in red lateritic soil covered granitic terrain and 412 mm in black cotton soil covered basaltic terrain is required for deep percolation (Sharma and Kumar 2008).

In dug well recharge schemes, the dug well is used not only for taking out water but also for recharging the weathered zone and the connected fractures through minor modification. It is quite economical and affordable by individual farmer or group of farmers and benefits can be effectively seen only through mass participation. On an average, the availability of a dug well per hectare (100 m × 100 m area) is minimum 1 and can be utilized for the purpose. However, prior to taking up a dug well for recharge, it is necessary to investigate the subsurface hydrogeological condition around the dug well, the pre- and post-monsoon water level data and its location wise feasibility for getting adequate surface water runoff collected in the agricultural field which can be put into the dug well after sand–gravel filtering. That is, an adequate thickness of permeable weathered zone and a good catchment area should exist around the dug well. Above all, the willingness of the farmers is essential because of the common perception that they may not get the water recharged which may move out of their land (Krishnan et al. 2009). A detailed guideline on dug well recharge is available on CGWB web site.

Percolation tank is another recharge structure constructed in hard rocks over permeable near-surface layer. The rate of recharge from percolation tank varies between 9 and 12 mm/day (Sharma and Kumar 2008). Check dam is the most popular recharge structure in hard rocks. Check dams of different dimensions are constructed across the streams to impound the monsoon runoff. A series of check dams can be constructed across a stream. Muralidharan et al. (2007) indicate that by check dam the natural recharge in granitic terrain can be increased from 5–8% of the rainfall to 27–40%.

## 5.9 Groundwater Quality

Fluoride concentration in groundwater within the permissible limit (<1.5 mg/l) is useful, but its higher concentration in hard rock terrain of India, which is quite common, poses a health issue for drinking water. Nineteen States are affected by high fluoride contaminations (CGWB 2010). The geogenic factors like presence and solubility of fluoride-bearing minerals in the host rock, groundwater contact or residence time and climate control the fluoride concentrations. The higher concentrations of fluoride generally occur in the arid and semi-arid areas with limited flushing. Occurrences of fluoride contaminated high-yielding fractured zone are quite common. Besides, some anthropogenic sources also cause an increase in fluoride concentration above the permissible limit in the shallow zones. The drinking water supply has to be mostly from the overlying fluoride-free weathered zone and from the alluvial capping in some places supplemented by defluoridation of groundwater from the fractured zones. Where better quality surface water is

available, dilution of fluoride concentration through artificial recharge could be a useful option (Muralidharan et al. 2002). The quality of water in weathered zone may vary from that in fractured zones, and also, it may vary from one fractured zone to another. Jayasena (1993) observes that due to flushing and movement of groundwater through fractured zone network, in general, locations with high fractured zone density hold a better quality groundwater, while the structural features and intrusive bodies could also control the quality of groundwater.

**Acknowledgements** Author is grateful to Professor Abhijit Mukherjee, Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur, West Bengal, India, for providing the unique opportunity of writing this chapter. Most of the text and figures in the chapter are taken from the book ‘Groundwater Geophysics in Hard Rock’ by P. C. Chandra, published by Taylor & Francis, The Netherlands, ISBN 978-0-415-66463-9. The author is extremely thankful to Taylor & Francis Group for the kind permission to use the text and figures from the book. Author is thankful to Dr. J. K. Rai, General Manager and Head, GWRDM, WAPCOS Ltd., New Delhi, India, for the permission to use some of the figures of WAPCOS geophysical survey report of Jhansi–Lalitpur districts, Uttar Pradesh.

## References

- Adyalkar PG, Rane VV, Mani VVS, Dias JP (1975) Evaluation of the aquifer characteristics of the basaltic terrain of Maharashtra in India. *Proc Indian Acad Sci Sect A* 81(3):108–117
- Ahmed S (2014) A new chapter in groundwater geophysics in India: 3D aquifer mapping through heliborne transient electromagnetic investigations. *J Geol Soc India* 84(4):501–503
- Central Ground Water Board (2009) Annual report (2008–09). Publication of CGWB, Ministry of Water Resources, Government of India
- Central Ground Water Board (2010) Groundwater quality in shallow aquifers of India. Publication of CGWB, Ministry of Water Resources, Government of India
- Central Ground Water Board (2012) Aquifer systems of India. Publication of CGWB, Ministry of Water Resources, River Development & Ganga Rejuvenation, Government of India
- Central Ground Water Board (2012a) Groundwater studies in Kasai-Subarnarekha River basins. Publication of CGWB, Ministry of Water Resources, Government of India
- Central Ground Water Board (2012b) Ground water information booklet, Kolar district. Publication of CGWB, Ministry of Water Resources, Government of India
- Chandra PC (2015) Groundwater geophysics in hard rock. CRC Press/Balkema, Taylor & Francis Group Publication, The Netherlands, ISBN 978-0-415-66463-9
- Chandra PC, Reddy PHP, Singh SC (1994) Geophysical studies for groundwater exploration in Kasai and Subarnarekha River basins (UNDP project). Publication of CGWB, Ministry of Water Resources, Government of India
- Chandra S, Ahmed S, Auken E, Pedersen JB, Singh A, Verma SK (2016) 3D aquifer mapping employing airborne geophysics to meet India’s water future. *Lead Edge (Special Section: Hydrogeophysics)* 770–774
- Clark L (1985) Groundwater abstraction from basement complex areas of Africa. *Q J Eng Geol* 18 (1):25–34
- Custodio E (2007) Groundwater in volcanic hard rocks. In: Krasny J, Sharp JM Jr (eds) Groundwater in fractured rocks: selected papers from the groundwater in fractured rocks international conference, 15–19 September, 2003, Prague, IAH Selected Paper Series, vol 9. Taylor & Francis/Balkema, The Netherlands, pp 95–108

- Deolankar SB (1980) The Deccan basalts of Maharashtra, India—their potential as aquifers. *Ground Water* 18(5):434–437
- Dev Burman GK, Das PK (1990) Groundwater exploration in hard rock terrain: an experience from eastern India. In: Shamir U, Jiaqi C (eds) *The hydrological basis for water resources management: proceedings of the Beijing symposium, October, 1990*. IAHS Publication. No. 197, pp 19–30
- Dhonde UV (2009) Groundwater information, Nashik district, Maharashtra. 1614/DBR/2009, Central Ground Water Board, Min. of Water Resources, Govt. of India
- Geological Society of India (2008) ‘Drinking water and food security in hard rock areas of India’ and ‘Changing geohydrological scenario-hardrock Terrain of peninsular India’ Golden Jubilee Volumes, ed. Subhrajyoti Das, Geological Society of India Publication
- Ghosh P, Sayeed MRG, Islam R, Hundekari SM (2006) Inter-basaltic clay (bole bed) horizons from Deccan traps of India: Implications for palaeo-weathering and palaeo-climate during Deccan volcanism. *Palaeogeogr Palaeoclimatol Palaeontol* 242(1–2):90–109
- Gustafson G, Krasny J (1993) Crystalline rock aquifers: their occurrence, use and importance. In: Banks D, Banks Sheila (eds) *Hydrogeology of hard rocks: memoires of the XXIV congress of IAH, 28 June–2 July, As, IAH Press, Oslo, Norway*, pp 3–20
- Jayasena HAH (1993) Geological and structural significance in variation of groundwater quality in hard crystalline rocks of Sri Lanka. In: Banks D, Banks Sheila (eds.) *Hydrogeology of Hard Rocks: Memoires of the XXIV Congress of IAH, 28 June–2 July, As, Oslo, Norway, IAH Press*, pp 450–471
- Jones MJ (1985) The weathered zone aquifers of the basement complex areas of Africa. *Q J Eng Geol* 18(1):35–46
- Kale VS, Kulkarni H (1992) IRS-1A and landsat data in mapping Deccan Trap flows around Pune, India: implications on hydrogeological modelling. In: Fritz LW, Lucas JR (eds) *Interpretation of photographic and remote sensing data, technical commission VII, ISPRS archives-vol. XXIX, part B7, proceedings of the XVIIth ISPRS congress, August 2–14, 1992, Washington, DC*, pp 429–435
- Krasny J, Sharp JM Jr (2007) Hydrogeology of fractured rocks from particular fractures to regional approaches: state-of-the-art and future challenges. In: Krasny J, Sharp JM Jr (eds) *Groundwater in fractured rocks: selected papers from the groundwater in fractured rocks international conference, 15–19 September, 2003, Prague, IAH Selected Paper Series, vol 9. Taylor & Francis/Balkema, The Netherlands*, pp 1–30
- Krishnan S, Indu R, Shah T, Hittalamani C, Patwari B, Sharma D, Chauhan L, Kher V, Raj H, Mahida U, Shankar M, Sharma K (2009) Is it possible to revive dug wells in hard-rock India through recharge? In: *Strategic analyses of the National River Linking Project (NRLP) of India series 5, proceedings of the second national workshop on strategic issues in Indian irrigation, International Water Management Institute, New Delhi*. <https://doi.org/10.3810/2010.202>
- Larsson I (1984) Groundwater in hardrocks. Project 8.6 of the IHP, UNESCO, Studies & Reports in Hydrology 33, UNESCO Publication, France. ISBN 92-3-101980-5
- Mahoney JJ (1988) Deccan traps. In: Macdougall JD (ed) *Continental flood basalts* [Online], Kluwer Academic Publishers, The Netherlands, pp 151–194
- Mukherjee A (2018) *Groundwater of South Asia*. Springer Nature, Singapore. ISBN 978-981-10-3888-4
- Muralidharan D, Andrade R, Rangarajan R (2007) Evaluation of check-dam recharge through water-table response in ponding area. *Curr Sci* 92(10):1350–1352
- Muralidharan D, Nair AP, Sathyanarayana U (2002) Fluoride in shallow aquifers in Rajgarh Tehsil of Churu District, Rajasthan – an arid environment. *Curr Sci* 83(6):699–702
- Parchure PK (2010) Groundwater information Ahmadnagar district, Maharashtra. 1645/DBR/2010, Central Ground Water Board, Min. of Water Resources, Govt. of India
- Saha D, Agrawal AK (2006) Determination of specific yield using water balance approach – case study of Toria Odha watershed in the Deccan Trap province, Maharashtra State, India. *Hydrogeol J* 14(4):625–635

- Sharma KD, Kumar S (2008) Hydrogeological research in India in managing water resources. In: Ahmed S, Jayakumar R, Salih A (eds) Groundwater dynamics in hard rock aquifers: sustainable management and optimal monitoring network design, Chapter 1, Springer, pp 1–19
- Singhal BBS (1997) Hydrogeological characteristics of Deccan Trap formations of India. In: Pointet T (ed) Hard rock hydrosystems, proceedings 5th IAHS international symposium April-May 1997, IAHS Publ. No. 241, Morocco, Rabat. Oxfordshire, UK, Institute of Hydrology, IAHS Press, pp 75–80
- Singhal BBS (2008) Nature of hard rock aquifers: hydrogeological uncertainties and ambiguities. In: Ahmed S, Jayakumar R, Salih A (eds) Groundwater dynamics in hard rock aquifers: sustainable management and optimal monitoring network design, Chapter 2, Springer, pp 20–39
- Singhal BBS, Gupta RP (1999) Applied hydrogeology of fractured rocks. Kluwer Academic Publishers, The Netherlands
- Subramanian P (1992) Hydrogeology and its variations in the granites and associated rock formations in India. In: Proceedings of the workshop on artificial recharge of groundwater in granitic terrain, Bangalore, 19 October 1992, pp 1–13
- Surinaidu L, Bacon CGD, Pavelic P (2013) Agricultural groundwater management in the Upper Bhima basin, India: current status and future scenarios. *Hydrol Earth Syst Sci* 17(2):507–517
- WAPCOS (2016) Geophysical survey for aquifer mapping in Jhansi and Lalpur districts, Uttar Pradesh, Report submitted to C.G.W.B., Min. Water Resources River Development & Ganga Rejuvenation, Government of India