CHAPTER X

SUMMARY AND CONCLUSIONS

This Chapter embodies the summary of the observations and conclusions made on the basis of field and laboratory investigations carried out in the research area which includes a part of the plains of Ambala District (1302 sq. km.) confined to the Pinjore, Raipur Rani and Naraingarh blocks and the adjoining Siwalik Hills of Haryana and Himachal Pradesh.

The Alluvial plains consist of the Intermontane valley/Bhabar and Tarai zones whereas the Siwalik Group is composed of the Lower and Upper Siwalik formations. The two formations are separated by the Jansu Thrust. The Middle Siwalik rocks are not exposed in the research area.

The Lower Formation is composed of alternating well bedded sequence of sandstones and clays. The sandstones are hard and compact whereas the clays are friable. The Upper Siwalik sequence is composed of two types of sedimentary facies; viz. sandstone facies and conglomerate facies. The sandstone facies is dominantly composed of sandstones, sandy clays and shales. The conglomerate facies comprises well indurated pebble- to boulder-sized fragments interbedded with lenses and beds of sandstones, sandy-clays and shales. The Upper Siwalik rocks contain more of clay content as compared
to rocks of the Lower Siwalik sequence. The order of superposition of the various lithological units in the two formations indicates coarsening upward sequence. The Siwalik sequence in the research area attains a maximum thickness of 1012.5 m and is devoid of fossils of marine organisms and salt cubes, glauconite and gypsum which are usually formed in marine environment. The common fossil finds include remains of fresh water vertebrate and invertebrate organisms and petrified/carbonised vegetable matter.

The various sedimentary structures noticed in the Siwalik rocks of the research area include bedding, cross-bedding, graded bedding, imbrication, and mud cracks, ripple marks, parting lineations, organic markings, slump structures concretions and nodules, and colour banding. The orientation of the various sedimentary structures including foreset beds and the fabric analysis of megaclasts indicates southerly to southwesterly flow of paleocurrents.

The various rock types identified in the Siwalik Group include quartz arenites, arenites calcareous cement, arenites ferruginous cement, quartz wackes, lithic wackes and siltstones/clays/shales. Quartz arenites and quartz wackes are absent in the Upper Siwalik Formation exposed in the research area. Petrographic studies of the Siwalik rocks
reveal that the percentage frequency distribution of monocrystraline quartz decreases from the Lower Siwalik Formation to the Upper Siwalik Formation whereas the frequency of quartz grains with more than 3 crystals per grain increases in the corresponding lithostratigraphic units. Majority of the quartz grains of the Siwalik rocks show undulose extinction. The frequency of such strained quartz grains is more in the Lower Siwalik as compared to that in the Upper Siwalik Formation. A large proportion of the quartz grains in both the units bear regular, irregular, acicular and globular inclusions. Feldspar content in the Siwalik rocks is low and the mineral grains in the Lower Siwalik rocks are usually altered. The rock fragments which represent varied types of parent rocks constitute a higher percentage of modal composition in the Upper Siwalik Formation than in the Lower Siwalik rocks. Volcanic rock fragments are observed in the Upper Siwalik Formation only. The various diagenetic features such as disrupted framework, etching of quartz grains, development of reaction rims, bending of mica flakes, incipient development of micaceous components in clay matrix, presence of veins and filling of cracks by cement are frequently noticed. Development of authigenic overgrowth in quartz grains is not very common except in the case of quartz arenites, where it has resulted in the reduction of pore spaces. Kaolinite
and illite dominate the clay mineral assemblage of the Siwalik Group, followed by montmorillonite and chlorite. Vermiculite is absent in the clays of the Siwalik Group.

The size and shape analyses indicate that Siwalik rocks of the area are composed of medium to very fine sand size grains and most of the samples have unimodal population. The mode, median and mean size of the detritus show gradual coarsening of sediments from the Lower to the Upper Siwalik Formation. More than 75% of the log probability plots are composed of 3 to 4 segments. The overall sorting values of the detritus show well sorted to moderately well sorted nature. Some of the samples from the Upper Siwalik Formation are poorly sorted. The degree of roundness of the detrital grains decreases from the Lower Siwalik to the Upper Siwalik Formation. The sand sized detrital grains exhibit low to moderate degree of sphericity. However, sphericity values of the Upper Siwalik Formation are slightly lower than those of the Lower Siwalik Formation.

The Upper Siwalik Boulder Conglomerates are dominated by equant and elongate classes of the megaclasis which exhibit intermediate values of roundness ratio.

The southward flow of paleocurrents in the research area indicates the derivation of the sediments constituting the Siwalik sequence from the rising Himalaya located to the North of the research area. The orientation of the
foreset beds and the fabric analysis of the megaclasts of the Upper Siwalik Boulder Conglomerate also indicate the prevalence of northeasterly currents during the Upper Siwalik time and the derivation of the Siwalik sediments from the rocks located to the North and Northeast of the research area. Various workers including Parkash and Bajpai (1970), Bhushan (1973), Sharda et al. (1977), Chaudhri and Gill (1979), Gill (1983b; 1985a; 1986), Tandon et al. (1984) and others have also worked out the southerly and southwesterly flow of paleocurrents in the Siwalik rocks.

The presence of quartz arenites and quartz wackes in the Lower Siwalik Formation and their absence in the Upper Siwalik Formation signifies a change in paleotectonic set up in the distributive province with the passage of time. The appearance of Boulder Conglomerates in Upper Siwalik Formation supports this contention. The newly upheaved sedimentary, metamorphic and volcanic rocks were exposed to denudation and supplied megaclasts of the Upper Siwalik Boulder Conglomerates.

Several workers including Bokman (1952), Blatt and Christie (1963), Conolly (1965), Blatt (1967), Blatt et al. (1972), Harrel and Blatt (1978), Friedman and Sanders (1978), More (1979), Turner (1980), Gill (1983b, 1986) and others
have used crystallinity of quartz as a criteria for provenance determination. Blatt, Middleton and Murray (1972) opined that polycrystalline quartz of plutonic origin has 2 to 3 crystals per unit, whereas polycrystalline quartz having more than three crystals per grain has metamorphic source. Basu et al. (1975) also made similar observations. The characters of polycrystalline quartz in Siwalik sediments are indicative of contribution of the detritus from metamorphic and plutonic rocks. The higher percentage frequency distribution of polycrystalline quartz in the Upper Siwalik horizon may be attributed to the coarser nature of the Upper Siwalik rocks and an increased supply of sediments from metamorphic source. Conolly (1965) also observed that polycrystalline quartz in clastic rocks is a function of grain size and increases with increase in size of the detritus.

Dominance of monocrystalline quartz in the Siwalik sediment is attributed to fine to medium size of the detritus. Bokman (1957b) attributed the source of fine to very fine grained monocrystalline quartz grains to metamorphic source. According to Friedman and Sanders (1978) about 50% and 40% of monocrystalline quartz grains are derived from granites and schists, respectively; whereas 22% to 25% are contributed by gneisses.
According to Mackie (1896) inclusions of regular and acicular types are more common in quartz grains derived from gneissose and schistose rocks whereas irregular and globular inclusions are more frequent in quartz grains derived from granitic rocks. Krynine (1940) observed that inclusions in metamorphic quartz are more acicular than those in plutonic quartz. Friedman and Sanders (1978) noted that fluid inclusions are particularly abundant in quartz grains derived from quartz veins. A review of Table 10 showing the percentage frequency distribution of quartz grains bearing various types of inclusions reveals that majority of the quartz grains of the Lower and the Upper Siwalik formations have been derived from metamorphic and plutonic rocks. The quartz grains bearing globular inclusions may have been derived from quartz veins and granitic rocks.

A number of workers including Krynine (1940), Tuttle (1952), Bailey et al. (1958), Hubert (1960), Folk (1961), Blatt and Christie (1963), Gilbert (1965), Blatt et al. (1972), Pettijohn, Potter and Siever (1973), Basu et al. (1975), Friedman and Sanders (1978), and others have discussed the importance of undulosity of quartz in decipherment of provenance.

Basu et al. (1975) indicated that quartz grains derived from plutonic rocks show undulose extinction on
less than $5^\circ$ rotation of the microscope stage, whereas the mineral grains derived from low-rank metamorphic source rocks show undulose extinction on more than $5^\circ$ rotation of the stage. Table 11 and Fig. 14 reveal that majority of the quartz grains of the Lower and the Upper Siwalik formations of the research area show undulose extinction on more than $5^\circ$ rotation of the stage, indicating thereby the derivation of a significant proportion of the sediments from metamorphic source rocks.

The quartz grains showing undulosity on less than $5^\circ$ rotation of the stage indicate the derivation of a part of the sediments from plutonic rocks; whereas the non-undulose quartz grains must have been derived from sedimentary and volcanic source rocks.

The fragments of undecomposed parent rocks provide direct evidence regarding the source of the sediments. Presence of such type of rock fragments as quartz arenites, arenites calcareous cement, arenites ferruginous cement, quartz wackes, siltstones/clays/shales; carbonaceous matter, chert, limestones, various types of schists and polycrystalline quartz indicates the derivation of a significant proportion of the detritus constituting the Siwalik sediments from sedimentary and metamorphic source rocks. Appearance of fragments of trap rocks in the Upper
Siwalik Formation indicate that volcanic rocks were exposed in the distributive province. The presence of fragments of fragile rocks like siltstones/clays/shales, and various types of schists indicate their derivation from source rocks situated close to the basin of sedimentation. Cameron and Blatt (1971) also observed that schist fragments do not survive more than 25 km of transport. A significant proportion of the Siwalik sediments are of first cycle origin as indicated by dominance of rock fragments. This contention is also supported by the angularity of the detrital grains.

The overall medium to fine sand size of the detritus signifies the derivation of a major part of the sediments of the Siwalik sequence from sedimentary and metamorphic rocks. The dominance of subangular to subrounded shape and low to moderate degree of sphericity of a significant proportion of the detrital quartz grains indicate their first cycle origin and short transport.

The megaclasts of the Upper Siwalik Boulder Conglomerate also indicate exposure of different types of source rocks. The pebbles, cobbles and boulders are dominantly made up of fragments of sedimentary rocks. Frequency of very equant and very elongate classes and disc shaped and rod-like fragments indicates short distance of transport of the detritus.
A review of the petrographical, mineralogical and textural characteristics of the detritus constituting the lower and the Upper Siwalik formations as discussed above indicates their derivation from metamorphic, sedimentary and volcanic rocks. The works of Babu and Dehadrai (1958), Misra and Valdiya (1961), Raiverman (1968), Kharkwal (1969), Chaudhri (1970a and 1970b, 1972), Tandon (1972a), Shukla and Verma (1976), Sahay and Verman (1977), Chaudhri and Dhanoa (1980), Chaudhri and Gill (1981), Gill (1983b) and others also support these observations.

The paleogeography of the Indian Subcontinent indicates that the Peninsular Shield comprising Precambrian plutonic and metamorphic rocks and Paleozoic and Mesozoic sedimentary rocks was reduced to low elevation at the end of the Mesozoic, whereas the Himalaya composed of crystalline, metamorphic and sedimentary rocks was upheaved in different phases and was exposed to denudation. A number of workers including Medlicott (1864), McMahon (1883), Auden (1934), Krishnan (1953), Chaudhri (1966, 1971c, 1975), Pande (1966), Pande and Saxena (1968), Saxena (1973), Gill (1983b) and others support the view of the rise of the Himalaya during Pre-Neogene time.

The basic concepts of erosion and sedimentation indicate the derivation of a major part of the Siwalik
sediments from the rising Himalaya rather than from the Peninsular Shield which by that time had attained near peneplanation stage.

The various lithostratigraphic units constituting the Punjab and the Kumaon Himalaya (Table 43) and exposed to the Northeast of the research area served as source rocks of the Siwalik sediments. The southerly flowing rivers from the rising Himalaya carried the detritus to the basin of sedimentation located parallel to the foot of the mountain chain.

<table>
<thead>
<tr>
<th>Stratigraphic Unit</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sirmur</td>
<td>Sandstones, shales and limestones</td>
</tr>
<tr>
<td>Tal</td>
<td>Quartzites, Sandstones, Shales and limestones</td>
</tr>
<tr>
<td>Krol</td>
<td>Limestones, Sandstones and Shales</td>
</tr>
<tr>
<td>Infra-Krol</td>
<td>Bleached and carbonaceous shales, and sandstones</td>
</tr>
<tr>
<td>Blaini</td>
<td>Limestones and Shales</td>
</tr>
<tr>
<td>Jaunsar</td>
<td>Conglomerates, Sandstones and Shales</td>
</tr>
<tr>
<td>Simla</td>
<td>Shales and Sandstones</td>
</tr>
<tr>
<td>Deoban, Shali and Tejam</td>
<td>Limestones, quartzites and shales</td>
</tr>
<tr>
<td>Chail</td>
<td>Quartzite, phyllites and schists</td>
</tr>
<tr>
<td>Jutoghh</td>
<td>Quartzites, limestones, carbonaceous and mica schists and basic intrusives</td>
</tr>
</tbody>
</table>
The environment of deposition of the Siwalik Group has been a topic of debate for quite a long time. The views vary from marine to the freshwater sedimentation environment. The name of the basin in which the deposition took place has also been differently termed by different workers. The field and laboratory studies reveal that the basinal conditions as also the paleoclimate and paleogeography had been fluctuating in time and space during the Siwalik sedimentation.

Quartz arenites in the Lower Siwalik Formation signify prevalence of comparatively stable paleotectonic conditions. The coarsening of the detritus and appearance of conglomerates in the Upper Siwalik Formation indicate gradual shallowing up of the basin with the passage of time and disturbed balance between sedimentation and subsidence towards culmination of the Siwalik sedimentation.

the decipherment of environments of deposition. The purple colour of the Lower Siwalik Formation reflects warm and humid climate where chemical decomposition of the parent rocks took place at a relatively slow pace. The abundance of ferruginous cement and presence of hematite and limonite support the observation. The purple/red pigment also suggests oxidizing environment at the time of deposition of the Lower Siwalik sediments.

In the Upper Siwalik Formation, red pigment is subordinate as a result of absence of chemical weathering and dominance of mechanical fragmentation of the parent rocks. Presence of cross-bedding indicates turbulent waters and shallow to moderate depth of the basin. Ripple marks also suggest shallow depth. Well developed imbrication pattern in the megaclasts of the Upper Siwalik Boulder Conglomerate also indicates deposition in shallow turbulent water. Presence of mud cracks in the Siwalik rocks is also an evidence of deposition of the sediments in shallow water flood plain environment. Graded bedding in the Siwalik rocks is attributed to rapid sedimentation from dense suspension. Fast rate of settling is also revealed by such sedimentary structures as convolute bedding and slump structures. Presence of concretions in the Lower Siwalik Formation is attributed to diagenetic redistribution of
calcareous matter. Sahay and Verma (1973) also assigned a post-depositional origin to the concretionary features in the Siwalik rocks of Garhwal Himalaya.

The development of reaction rims at the contact of quartz and carbonate cement, etching of quartz grains, disrupted framework of the rocks and bending of mica flakes is suggestive of deep burial of the sediments.

The presence of illite in the Lower as well as in the Upper Siwalik Formation is attributed to the stable nature of the mineral. Kaolinite, montmorillonite and chlorite tend to change into illite during diagenesis. Genesis of kaolinite is attributed to alteration of potassium feldspar and mica flakes under warm-humid climate. Presence of kaolinite indicates prevalence of freshwater conditions (Keller, 1970). The presence of montmorillonite and illite is indicative of temperate climate where weathering has not been intense (Forth and Truck, 1973). The total absence of vermiculite may be attributed to its unstable nature.

The well sorted to moderately well sorted nature of the Siwalik sediments signifies deposition of the detritus in shallow to moderately deep waters where rate of sediment supply kept pace with that of subsidence. The moderately to poorly sorted nature of the Upper Siwalik sediments suggests...
dominance of fluvial environment. The near-symmetrical, fine-skewed and strongly fine-skewed distribution of the Siwalik sediments also support fluvial sedimentation environment.

The log probability curves are made up of two to four segments. Majority of the plots, however, contain four segments indicating thereby that the sediments were transported by traction, saltation and suspension. These processes are common in fluvial environments. The two segment plots generally have the break at cumulative frequency of less than 85%, the character partially developed in fluvial deposits (Visher, 1969).

The sphericity data of the sand-sized quartz grains of the Lower and the Upper Siwalik Formation as well as the roundness ratio, intercept sphericity and shape of the megaclasts of the Upper Siwalik Boulder Conglomerate indicate short transport and deposition of the detritus near the source.

To sum up, the Siwalik sediments were deposited in fresh water basin located transverse to the main Himalayan drainage. The southerly and southwesterly flowing rivers from the rising Himalaya debouched their load in the basin at the foot of the mountain chain. During the early stages of sedimentation, the pace of erosion and sedimentation was
slow to moderate. At the close of Pliocene, the balance 
between erosion and sedimentation was disturbed. Rapid 
erosion and short transportation during this period 
resulted in the accumulation of pebble-, cobble- and 
boulder- sized fragments as fan deposits which now constitute 
the Upper Siwalik Boulder Conglomerate.

The various hydrogeological characters of the 
research area have been studied with the help of surface 
and sub-surface geological investigations. The aquifer 
characteristics in the alluvial plain areas have been 
inferred from the subsurface geology as well as analysis 
of pumping test data. The Siwalik rocks in the North and 
subsurface samples from the Bhabar and Tarai region in the 
South have been subjected to various field and laboratory 
analyses. From the knowledge of surface lithology of the 
Siwalik sequence and the subsurface lithological correlation 
sections of the Indo-Gangetic alluvial plains, it has been 
found that the Siwalik sediments constitute the bulk of 
the deposits filling the depressions of the Intermontane 
valley, the Bhabar and the Tarai zones. Pandey et al. 
(1968), and Rao (1973) also made similar observations in 
other parts of the Indo-Gangetic alluvial plains.

Field observations and petrographical studies 
(Chapter V) indicate that the Siwalik sequence is composed
of well indurated to moderately indurated clays/shales/
siltstones, sandstones, granules, pebbles, cobbles and
boulders. The varied lithology of the Siwalik Group and
texture of the constituent rocks result to the occurrence
of moderate to poor aquifers. The thin section study of
the Siwalik sandstones reveals the presence of calcareous,
ferruginous and argillaceous cementing materials and deve­
lopment of overgrowth on some of the quartz grains which
further decrease the permeability and porosity of the rocks.

The well indurated nature of the rocks and steep
slopes of the Siwalik hills prevent much of the meteoric
water to percolate down to the substratum. This water
flows down slope in the form of surface runoff and contributes
to the ephemeral streams of the region.

The subsurface correlation sections (Figs. 79(i)
and 79(ii) reveal that much variation does not exist
between the subsurface lithology of the Intermontane valley
and the Bhabar zone, except for the marked topographical
variations and occurrence of thin beds of sandy clays at
shallow depths. The Intermontane valley deposits consist
of recent alluvial fill. The Bhabar zone is characterized
by steep slopes composed of gravels and boulders embedded in
sands. The subsurface lithological sections of the Indo-
Gangetic alluvial plains indicate that aquifer lithology in
the Intermontane valley and Bhabar zone comprises large
boulders, pebbles, gravels and sands which form good aquifers. The Bhabar aquifers vary in thickness from 15 m at Dera to 167 m at Toka. The aquifer materials are uniformly graded. The Bhabar beds have high porosity, high hydraulic conductivity and high absorptive character which result in rapid infiltration underground and percolation up to the water table of most of the water received in the zone from rainfall and by seepage from emerging ephemeral streams of the Siwalik rocks. Superficially, the Bhabar zone is devoid of water except after the rains, but has large subsurface water storage capacity.

The Tarai zone consists of fine to medium grained unconsolidated alluvial sands, silts, sandy-clays, clays and occasional gravels and pebbles. The subsurface correlation sections indicate that the Tarai aquifers generally vary in thickness from 3 m to 8 m (Shazanpur-Azampur areas) and consist of sands and gravels which are overlain by impermeable clay and sandy clay beds (Figs. 79(i) and 79(ii)). The thickness of the clays vary from 3 m to 55 m in the Tarai zone. The sandy-clays, clays and silts of the Tarai zone are highly porous and absorb large quantities of water which are retained by molecular attraction.
The aquifer beds taper down from the Bhabar zone towards the Tarai zone, whereas the clay and sandy clay beds increase in thickness towards the Tarai zone in the South and also with increase in depth (in the Tarai zone). The Bhabar aquifers intermingle and form a continuous sequence with Tarai aquifers (Figs. 79(i) and 79(ii)) and most of the groundwater of the Bhabar zone is received by downward percolation and lateral flow in the Tarai zone. The Bhabar zone forms the recharge zone while the Tarai zone forms the discharge zone.

The zone of interception of the thick aquifer beds of the Bhabar zone and the predominantly thick clay beds of the Tarai zone is marked by conspicuous lithological changes and emergence of springs along the 'spring line'; which marks the boundary between the Bhabar and the Tarai zones. Landsat imagery studies of the research area have also helped in decipherment of the Bhabar-Tarai boundary along the spring line (Fig. 80b).

Pumping test data has revealed that transmissivity and hydraulic conductivity values of aquifers in the research area decrease from the Bhabar zone/Intermontane valley areas towards the southern Tarai zone (Map 7, Table 26). This character is attributed to the increased thickness of the clay beds in the Tarai zone. The transmissivity values in the research area vary from 733 m²/d at Naraingarh.
to 4992 m²/d at Fatehpur II (Map 7, Table 26) indicating that well yield in the region can be adequate for industrial, municipal and irrigational purposes. Generally, the discharge of the wells decreases from the Bhabar zone towards the Tarai zone.

The subsurface lithological correlation sections and storativity values of the aquifers (pumping test data) reveal that groundwater in the Bhabar zone and parts of the Intermontane valley mainly occurs under water table conditions. However, local flowing conditions occur in the Intermontane valley areas. Sluice valves should be used on some of these flowing wells as to minimize wastage and economise the utilization of groundwater. In the Tarai zone, groundwater occurs under confined and semi-confined conditions. Local variations, however, exist in both the Intermontane valley/Bhabar zone and the Tarai zone.

Depth to water level maps for Pre-monsoon and post-monsoon periods (Map 9) of the research area, indicate that water table occurs at great depths (up to 42.99 m at Manakpur) in the Intermontane valley/Bhabar zone, but occurs at shallow depths varying from 1.63 m to 14 m below ground level in the southern Tarai zone (Table 27). The high water table condition in the southern Tarai zone is attributed partially to the low hydraulic conductivity of the aquifer materials and predominance of clay beds in the
Tarai zone. As a result of small sub-surface outflow in these clay beds, compaction and capillary effects force pore water to rise rapidly out of fine clay beds through worm holes, fissures and minute cavities in clay beds.

Groundwater flow direction in the area is from northeast to southwest except in the northwestern part of the Pinjore Intermontane valley where the flow is from southeast to northwest (Map 10). Groundwater flow in the region is generally influenced by topography, lithology, and quantity of water flowing in the river. The hydraulic gradient of water table varies from 2.1 metres per kilometre to 3.02 metres per kilometre in the Intermontane valley/Bhabar zone and gradually flattens to about 0.76 metres per kilometre in the Tarai zone.

Groundwater level fluctuations in the Intermontane valley/Bhabar and Tarai zones exhibit peculiar characteristics (Figs. 86 to 88) and are influenced by variations in effective precipitation, hydraulic conductivity of the soils and evapo-transpiration. Water level fluctuations are large in the Bhabar zone as compared to the Tarai zone. Maximum water level fluctuations (up to 5.6 m) were observed in the Intermontane valley/Bhabar zone. Water level elevation in the area, is maximum in the month of October when
infiltration becomes abundant following rapid saturation of the soil water zone with rainfall; but sink to lowest depths in the summer month of June when groundwater runoff exceeds afflux (Fig. 86).

Study of water level data of the past few years reveals that the declining trends in water level in the research area occur during years of less rainfall (Tables 28 and 29) and that the continuous decline in water level in the Tarai zones of Raipur Rani and Naraingarh, particularly in the latter, has been contributed by groundwater overdrafting due to heavy pumpage of groundwater for agricultural and domestic purposes, and by rapid evapo-transpiration in the shallow water table zones.

Chemical analysis of water samples reveal that Total dissolved Solids (TDS) and Electrical Conductivity (EC) values increase from the Bhabar zone to the southern Tarai zone away from the recharge zone on account of length of flow and residence time of groundwater in the aquifers; and rapid evapo-transpiration from higher water table in the area (Tarai zone) which concentrates dissolved salts. Groundwater in the Bhabar zone is rich in alkali earths ($Ca^{2+}, Mg^{2+}$), alkalies ($Na^+, K^+$) and weak acids ($HCO_3^-, CO_3^{2-}$) whereas in the Tarai zone, groundwater is rich in alkalies and weak acids. Groundwater in both Intermontane valley/ Bhabar and Tarai zones has no secondary salinity and is inordinately soft.
The groundwater in the Intermontane valley/Bhabar zone belongs to sodium-calcium-bicarbonate-chloride-sulphate-facies with calcium-magnesium occurring in dilute solutions, whereas sodium-calcium-bicarbonate-hydrochemical facies dominate the groundwaters of the Tarai zone with high concentration of sodium in the Tarai than in the Bhabar zone. Higher sodium concentration in the Tarai zone is due to weathering of clay minerals and plagioclase feldspars.

The chemical characteristics of groundwater in the research area reflects combined effect of chemical activity related to the lithology and groundwater flow pattern within the aquifer of the zones.

The suitability of groundwater in the research area for various uses has been discussed in the light of percent - sodium, sodium hazards, bicarbonate hazards, total dissolved solids and electrical conductivity; in addition to the concentration of various cations and anions in consonance with recommended standards of the U.S. Salinity Staff (1954), U.S. Geological Survey (1974), Indian Council for Medical Research (1975), Haryana Agricultural University, Hissar (1979), U.S. Department of Health Education and Welfare (1962) and absolute World Health Organisation Standards (1961), etc. The above results and
discussions of chemical analysis indicate that the groundwater of the Bhabar and most of the groundwater of the Tarai zones of the research area are fresh and fit for irrigation, domestic and industrial purposes.

The annual module of natural recharge in Intermontane valley/Bhabar zone is higher (varying from 8 to 22 l/sec/km\(^2\)) than in the Tarai zone (2 to 8 l/sec/km\(^2\)) in relation to the lithological characteristics and geological location of the zones (Chapter IX; Table 33, Map 12). Similarly, natural groundwater storage (Static groundwater resource) for the Intermontane valley/Bhabar zone \((5544.84 \times 10^6 \text{ m}^3)\) far exceeds the storage in the Tarai zone \((924.456 \times 10^6 \text{ m}^3)\) (Table 34). Groundwater recharge in the research area is principally from precipitation which contributes 94.65% of the total recharge. Other sources of recharge include return flow of irrigation water (5.30%), and from ponds/tanks (0.05%). Groundwater discharge is mainly as a result of withdrawal of groundwater for irrigation purposes through tubewells and dugwells and these account for 85.22% and 3.62% of the gross draft respectively. Groundwater is also discharged in the region through evapo-transpiration and effluent losses in springs and streams etc. (unrecoverable losses) which contributes 11.23% of the total draft. The Intermontane valley/Bhabar zone has some potential of exploitable groundwater resources.
whereas the Tarai zone (Raipur Rani and Naraingarh areas, particularly the latter) is suffering from groundwater depletion. Heavy duty wells including deep tubewells should be installed in the Intermontane valley/Bhabar zone as to tap groundwater from the deep aquifers of the zone.

Kharif and Rabi season crops are grown in the research area. The Tarai zones of Raipur Rani and Naraingarh form the main agricultural areas of the region and groundwater utilization in the Tarai for irrigation and domestic uses is in excess of replenishment. The groundwater in the Naraingarh Block and parts of the Raipur Rani Block in the Tarai zone, is overexploited, hence the declining trend in water level has been observed as mentioned earlier.

Detailed studies based on crop pattern versus soil yield per hectare should be undertaken in the research area to assess hectare-centimetre requirements of water for individual crops and the acreage under command. This may help minimise excessive and wasteful pumpage and thus reduce overdrafting in the region. It is also suggested that artificial recharge measures as described in Chapter IX may be employed to check the depletion of water levels in parts of the region suffering from groundwater overdraft.
It has been observed that the rivers Ghaggar and Markanda have constant flows which are considerably reduced during the summer season whereas all the other rivers in the research area are dry for most of the year except during the monsoon season when the flows in them are charged with mud. Infiltration experiments carried out during the present investigation (Chapter IX) along the Rivers Patiali Rao, Ghaggar, Dangri, Begna and Markanda show high infiltration rates along the river beds, thus indicating the suitability of artificial recharge by river bed method as a measure to combat the progressive lowering of groundwater levels due to overdrafting in parts of the research area. The flows of the rivers Ghaggar and Markanda, especially during the dry season when the water is clean and contain sediment load of less than 20 mg/l can be utilized without further cleaning as a source of artificial recharge by "River Bed Method" or by developing "induced well fields". It is, therefore, strongly recommended that artificial recharge by the river bed method be employed in the research area. If the water in the rivers/streams in the region can be cleaned, especially during the monsoon when all the rivers/streams in the region are under flood, artificial recharge by river bed or basin method can be accomplished on large scale by diverting stream flow for recharge through series of basins
that can be constructed parallel to the natural stream channel. It is recommended that the organisations/agencies concerned with groundwater resources/irrigation in the region should in future investigate the costs involved in treatment of the floodwaters of the rivers in the research area during monsoon for reducing the sediment load so that these waters may be utilized for artificial recharge.

Other artificial recharge measures like flooding of the natural depressions and ravines for augmenting recharge of aquifers, trench method and injection method through large diameter wells may be employed in the region.

Tubewells based on induced recharge well fields may be constructed along the Ghaggar and the Markanda rivers parallel to river bed. However, as the floodwaters of these rivers are laden with suspended sediments, the aquifers may be clogged if penetrated by floodwaters at high infiltration rates. The river bed deposits have higher permeability and will correspondingly give high infiltration rates. As such, it is suggested that the tube wells may be installed at reasonable distances (150-200 m) from the river bed as to check the clogging of the aquifers.
It is hoped that the present work will help towards proper management of groundwater resources in the area and in solving the groundwater problems existing in the region. It will also form a basis for future investigations regarding the relationship of various sedimentological parameters with the hydrogeological regimes.