INTRODUCTION

Water, like religion and ideology, has the power to move millions of people. Since the very birth of human civilization, people have moved to settle close to water. People move when there is too little of it. People move when there is too much of it. People journey down it. People write and sing and dance and dream about it. People fight over it. And all people, everywhere and every day, need it. We need it for drinking, for cooking, for washing, for food, for industry, for energy, for transport, for rituals, for fun, for life. And it is not only we humans who need it; all life is dependent on water to survive.

But we stand today on the brink of a global water crisis. The two major legacies of the 20th Century - the population and technological explosions - have taken their toll on our water supply. More people lack drinking water today than they did two decades ago. More and more freshwater sources are being used-up and contaminated. Modern technologies have allowed us to harness much of the world's water for energy, industry and irrigation - but often at a terrible social and environmental price - and many traditional water conservation practices have been discarded along the way. Most of the solutions to the crisis must be developed and implemented locally, and always with the view that water is not to be taken for granted, or unjustly appropriated by particular groups for particular needs.

Water is the most important single element needed in order for people to achieve the universal human right to "a standard of living adequate for the health and well-being of himself and his family." (Article 25, Universal Declaration of Human Rights) Without access to clean water, health and well-being are not only severely jeopardized, they are impossible: people without basic water supplies live greatly reduced and impoverished lives - with little opportunity to create better futures for their children.
Access to enough water of sufficient quality is fundamental for all human, animal, and plant life as well as for most economic activity. At the global level, plenty of water is available. But to meet the demand, water has to be supplied where and when it is needed. These spatial, temporal, and qualitative characteristics pose the greatest challenge to meeting the rising demand in all sectors. Water withdrawals are only part of the picture. Almost all uses put something back into the water that degrades it for other users. Water quality and competition between users are therefore critical issues for the future of water use. There is no single “magic bullet” to solve these complex and interrelated problems. Increases in water supplies, and especially storage, are needed, but so is demand management, including not only economic instruments but also education and other efforts to change behavior. Appropriate technologies and institutions must both play a role.

Water is a common chemical substance that is not only essential for the survival of all known forms of life but is in fact crucial for preservation of our natural environment as well as an indispensible resource for the economy. Water in typical usage refers only to its liquid form or state, but the substance also has other state viz.; solid, ice and gaseous state. Water has found place both above and/or below the earth: in the oceans in the form of waves and icebergs, in the air in the form of vapour and clouds, below the earth in the form of aquifers, permafrost etc. water is continuously moving from one form to other form and from one place to another place through the process of evaporation, precipitation and runoff. This continuous movement of water between the atmosphere, lithosphere and biosphere is termed a hydrological cycle or water cycle. This movement of water is an essential process that helps in sustaining life on earth. As the water evaporates by the process of evaporation and/or evapotranspiration, vapors rise and condense to form clouds. As clouds move, precipitation may start and falls in the form of rain, ice or snow. The water falling on the land surfaces may join streams and rivers, and eventually flows back into the oceans where evaporation starts the process anew. A portion of this water infiltrates the soil and is known as the
subsurface water but not all the water percolates down the water table to be termed as groundwater.

Three things can happen basically. In the first case water may be pulled back to the surface by the capillary forces and evaporate to the atmosphere. Secondly it can be absorbed by the plant roots present in the soil and then re-enter the atmosphere by transpiration and lastly some water which may have percolated deep enough can be pulled downwards by the forces of gravity until it reaches the zone of saturation and becomes a part of the groundwater reservoir that supplies water to wells. After joining the body of groundwater it continues to flow horizontally following the hydraulic gradient through the pores of saturated subsurface formations and may reappear at the surface in areas at lower elevation from where it entered the groundwater reservoir. Groundwater discharges naturally at such places in the form of springs and seeps which maintain the flow of streams during dry period. The streams carrying both surface runoff and natural groundwater discharge, eventually joins the ocean and the cycle continues.

Groundwater is not only among the nation’s most precious natural resources, but also permanent and reliable source of water for a majority of the world’s population, especially in the arid and semi-arid regions of the world, where surface water is either scanty or strongly seasonal in occurrence. Groundwater is a major source of water supply for drinking, irrigation and animal husbandry in many states of India, mainly in arid and semi-arid regions. It is also a vital element of groundwater dependent ecosystems such as wetlands. In contrast to surface water changes in quantity and quality are often very slow processes. These changes cannot be determined by simple one-off snapshot surveys alone, and require more elaborate monitoring networks and data interpretation. The primary goal of aquifer management is to control the impacts of groundwater abstraction and contaminant loads, and monitoring aquifer response and quality trends provide key inputs for this goal. Therefore, regular and systematic monitoring
of groundwater resources is necessary for its effective management to support the water needs of the environment and its citizens.

1.1 Monitoring – a prerequisite for a scientific study

Groundwater being an important source of water, for all types of uses viz., domestic, agricultural and other industrial purpose is depleting day by day especially in arid and semi-arid regions of the world mainly due to over exploitation and/or recharge reduction. Degradation in terms of quality (by both natural and anthropogenic sources) is also a serious problem in natural resource management. In arid and semi-arid regions availability of water is extremely low, and the demand is growing manifold because of increase in population and agricultural practices, which can lead to undesired situations. To overcome such situations a rational use of surface and groundwater resources is required which demands systematic collection of ample hydrological data to set supranational, national, regional and local surface and groundwater policies. Further data gathering is required to develop water resource plans, to design water resource systems, to operate the structures that make up these systems and to monitor if the predicted consequences of the implemented systems really occur. Monitoring and management are coined together, and cannot be separated. Thus in order to understand and overcome the water related issues, monitoring systems form the base for management.

Groundwater is an extensive, concealed and inaccessible resource in contrast to surface water. As groundwater is the invisible part of the hydrological cycle, monitoring is a prerequisite to detect and understand changes in quality and quantity of groundwater bodies. Groundwater resource cannot be observed directly, thus measurements are carried out in wells. These wells represent keyholes to aquifers, which allow groundwater pressure and quality measurements to be made and thus furnish information from which the physical condition of the aquifer system can be judged. In
general wells can be categorized into two basic types viz., abstraction wells and observation wells. Although data collected from abstraction well once operational is difficult to interpret because of the changes in water level and quality as it sensitive to drawdown-recovery cycle and mixing of groundwater from different depths and residence times respectively, but can be used for the collection of in-situ data on the groundwater resource and its variation with depth. Data acquired during drilling borehole logging and initial test pumping form key baseline reference information on groundwater quantity and quality. In contrary observation wells are dedicated monitoring stations, sited and designed to detect potential changes in groundwater flow and quality. A suite of observation wells coupled with a selection of abstraction wells normally comprise a monitoring network, which should be designed so as to provide the required access to the groundwater resource. The general monitoring schemes purpose is shown in figure 1 and are specifically designed and operated to:

- detect general changes in groundwater flow and trends in groundwater quality, and bridge gaps in scientific understanding of the groundwater resource base.
- assess and control the impact of specific risks to groundwater.

![Diagram of Groundwater Monitoring](image)

*Figure 1-1: The general monitoring scheme purpose.*
Data are meant to be fed into the management process. They should be interpreted and used to support management decisions. Management decisions in turn have an impact on around water resource. Monitoring will pick up the changes in the resource that result from these decisions. This new information is brought to the attention of decision makers again, who may be prompted to take new decisions. In other words, groundwater management is cyclic and groundwater monitoring is an essential stage in this process. It could also be said in other words as groundwater monitoring means having your eyes in the ground. Its purpose is to understand groundwater resources, and to detect changes and trends in groundwater resources. Figure 1-2 depicts the cyclic nature of groundwater management and the role of monitoring.

![Cyclic nature of groundwater management and the role of monitoring.](image)

Monitoring is of two different types i.e. background monitoring and specific monitoring. Background monitoring is usually carried out before the significant groundwater development occurs. The background monitoring focuses on the characterizing of the initial stage of a groundwater system for the subsequent estimation of groundwater resources and providing information for debating possible over abstraction between water resource managers, environmentalists and conservatists when aquifer is exploited. Generally water use objectives on a national scale need to be explored before
a background monitoring network of groundwater can be designed (Figure 1-3). Existing information on the surface and subsurface should be collected and analyzed to identify groundwater systems, if feasible. In many arid and semi-arid regions the existing data are scarce yet, and system identification cannot be done. In this situation area should be investigated on similarity, which might allow transfer of knowledge to regions to be monitored.

Figure 1-3 Framework of background and specific monitoring. (HAJ Van Lanen 1994)

After the system identification phase, a first groundwater monitoring is designed with the collection of data primarily based on existing wells in that area. After a few years of systematic data collection, the first of the background monitoring network should be thoroughly analyzed and the earlier defined versions of groundwater systems and associated conceptual models
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should be refined. Geostatistics can help to improve the sampling density and frequency. Analysis based on improved knowledge of hydrological phenomenon is likely to lead to adopt the first developed network which better represents the specific characteristics of the groundwater system in the area under consideration. Background monitoring network should be a continuous process of analyzing incoming data, refinement of the description of the groundwater system and subsequent network adoption. Background monitoring in arid and semi-arid area is a long term effort because of higher variability in the hydrological parameters.

Specific monitoring is the monitoring of the aquifer systems in which potential consequences of the significantly exploited groundwater systems are expected. The specific monitoring aims at a) characterizing the transient stage of a groundwater system during groundwater development, b) acting as an early warning system showing over abstraction of a groundwater system, and c) providing information for remedial actions, in case groundwater extraction rates have been decreased after an over exploitation situation. Usually the specific monitoring provides data for state officers and groundwater managers who are responsible to recognize possible over abstraction conditions. Afterwards a specific monitoring network is set up if a governmental body has decided to develop groundwater resources and to design water resource systems for a particular region. The decision is based definitely on the comprehensive analysis of background monitoring data. The conceptual model of the groundwater system is replaced by a numerical model providing scenarios of different abstraction. Subsequently the simulated consequences has to be translated into potential problems which will help in evolving specific monitoring aspects such as boundary of the affected area, type of hydrologic variables to be monitored and the sampling density and frequency.

Groundwater monitoring includes more than only observing the state variables for the saturated part of the subsurface, but recharge and discharge of the groundwater system are monitored as well in order to understand
of monitoring. Geostatistical techniques can be applied to explore the variability of each parameter in the region of interest. Descriptive statistics, i.e. determination of the mean, median, minimum and maximum gave a first impression but generally they offer insufficient information to characterize the spatial and temporal variability. Presently, the spatial correlation is often described with the help of semi-variogram which is based on the fact that observation closer to each other are more likely to be similar than the observations at larger distances. The semi-variogram can be used to interpolate the values at unmeasured location. This procedure which is known as Kriging provides a measure of the uncertainty of the predicted value as well. The specified predicted error can not only serve as a guide to find new locations where the measurement should be carried out but can also serve as a criterion to find out whether the sampling density is already adequate or not.

1.2 Global Groundwater Scenario

“We shall not finally defeat AIDS, tuberculosis, malaria, or any of the other infectious diseases that plague the developing world until we have also won the battle for safe drinking water, sanitation and basic healthcare.”

-Kofi Annan, Former, Secretary-General of the United Nations.-

World population is being increasing exponentially and there has been always uncertainty regarding the sustainability of food in coming years. But it appears that it will be water that will hamper the production of food in future years. Water was considered to be a limitless natural resource but during the past 20 years or so there has been a tremendous pressure on this precious natural resource. Today, we face increasing freshwater scarcity, pollution and water-related disasters. These are affected by population growth, agricultural demand, energy requirements, urbanization, economic growth and industry, globalization, technological and lifestyle changes, recreation and tourism, climate changes and geopolitical changes. It is believed that water related
issues will be the most serious problem of the 21st century whether it concerns environment or cities, health or sanitation, food industry or energy production.

Water is essential for all socio-economic development and for maintaining healthy ecosystems. As population increases and development calls for increased allocations of groundwater and surface water for the domestic, agriculture and industrial sectors, the pressure on water resources intensifies, leading to tensions, conflicts among users, and excessive pressure on the environment. The increasing stress on freshwater resources brought about by ever-rising demand and profligate use, as well as by growing pollution worldwide, is of serious concern. Imbalances between availability and demand, the degradation of groundwater and surface water quality, intersectoral competition, and interregional and international conflicts, all bring water issues to the fore. Symptoms of water scarcity include severe environmental degradation (including river desiccation and pollution), declining groundwater levels, and increasing problems of water allocation where some groups win at the expense of others. A major study, the Comprehensive Assessment of Water Management in Agriculture, reveals that one in three people today face water shortages (Comprehensive Assessment of Water Management in Agriculture, 2007). Around 1.2 billion people, or almost one-fifth of the world's population, live in areas of physical scarcity, and 500 million people are approaching this situation. Another 1.6 billion people, or almost one quarter of the world's population, face economic water shortage (where countries lack the necessary infrastructure to take water from rivers and aquifers). Figure 1-4 shows the distribution of area having physical and economic water scarcity in the world. Areas having abundant water resources relative to use, with less than 25% of water from rivers withdrawn for human purposes fall under little or no water scarcity, while areas where more than 75% of the river flows are withdrawn for agriculture, industry, and domestic purposes (accounting for recycling of return flows) falls under Physical water scarcity region (water resources development is approaching or has exceeded sustainable limits). Approaching
physical water scarcity are those regions where more than 60% of river flows are withdrawn. These basins will experience physical water scarcity in the near future. Economic water scarcity are regions, where water resources are abundant relative to water use, with less than 25% of water from rivers withdrawn for human purposes, but malnutrition exists.

Figure 1-4 Map showing distribution of physical and economic water scarcity regions of the world. (www.worldwaterday07.org)

If all the freshwater on the planet were divided equally among the global population, there would be 5 000–6 000 m$^3$ of water available for everyone, every year. As experts consider that people experience scarcity below a threshold of 1700 m$^3$/person, this global calculation gives an impression of abundance. However, the world’s freshwater resources are distributed very unevenly, as is the world’s population. The areas of most severe physical water scarcity are those where high population densities converge with low availability of freshwater. Many countries are already well below the threshold value. Jordan, like several other countries in the Near East, is an extreme case with less than 200 m$^3$/ person per year.
An increasing number of regions suffer from chronic water shortages. The problem is most acute in the driest areas of the world. Dry lands are home to more than 2 billion people and to half of all poor people. Most countries in the Near East and North Africa suffer from acute water scarcity, as do countries like Mexico, Pakistan, South Africa, and large parts of China and India. Most freshwater used in these areas goes towards irrigated agriculture. In arid and semi-arid regions, where water scarcity is almost endemic, groundwater has played a major role in meeting domestic and irrigation demands. In many regions, massive use of groundwater has been practiced for some time for irrigation. Groundwater mining and the lack of adequate planning, legal frameworks and governance have opened a new debate on the sustainability of the intensive use of groundwater resources.

In the last century, the world population has tripled. It is expected to rise from the present 6.5 billion to 8.9 billion by 2050, before leveling off. Water use has been growing at more than twice the rate of population increase in the last century, and, although there is no global water scarcity as such, an increasing number of regions are chronically short of water. By 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world population could be under conditions of water stress. The situation will be exacerbated as rapidly growing urban areas place heavy pressure on local water resources.

Now a major international issue, climate change is expected to account for about 20 percent of the global increase in water scarcity. Countries that already suffer from water shortages will be hit hardest. Significantly, there will be major increases in water scarcity even if the water impacts of climate change prove to be neutral or even enhancing of the world’s hydrological budget. With neither being reasonably expected to happen, the impact of a changing climate will affect not only bulk water availability but also worsen the extremes of drought and floods. A 2006 study by the UK Meteorological Office
concluded that, with no mitigation of climate change, the severe droughts that now occur only once every 50 years will occur every other year by 2100.

First and foremost, water scarcity is an issue of poverty. Unclean water and lack of sanitation are the destiny of poor people across the world. Lack of hygiene affects poor children and families first, while the rest of the world’s population benefits from direct access to the water they need for domestic use. One in five people in the developing world lacks access to sufficient clean water (a suggested minimum of 20 litres/day), while average water use in Europe and the United States of America ranges between 200 and 600 litres/day. In addition, the poor pay more. A recent report by the United Nations Development Program shows that people in the slums of developing countries typically pay 5–10 times more per unit of water than do people with access to piped water (UNDP, 2006).

The world decided in the year 2000 to launch a concerted attack on poverty and the problems of illiteracy, hunger, discrimination against women, unsafe drinking water and a degraded environment. In September 2000 world leaders from 189 nations agreed and signed the UN Millennium Declaration, binding them inter alia to a global project to decisively reduce extreme poverty in all its key dimensions. While access to safe water and sanitation have been recognized as priority targets through the Millennium Development Goals (MDGs) and the Johannesburg plan of action of the World Summit on Sustainable Development (WSSD), there is increasing recognition that this is not enough. Millions of people rely in one way or another on water for their daily income or food production. Farmers, small rural enterprises, herders and fishing people – all need water to secure their livelihood. However, as the resources become scarce, an increasing number of them see their sources of income disappear. Silently, progressively, the number of water losers increases – at the tail end of the irrigation canal, downstream of a new dam, or as a result of excessive groundwater drawdown. Millennium Development goals and examines a number of vital issues including population growth and
groundwater system adequately. The evaluation of groundwater issues and the implementation of management solutions require hydrogeological data that are in part 'baseline' and in part 'time-variant' in character (Table 1-1)—the collection of the 'time-variant component' is what is usually considered 'groundwater monitoring'. Groundwater monitoring thus comprises the collection, analysis and storage of a range of data on a regular basis according to specific circumstances and objectives. The type and volume of data required will vary considerably with the management issue being addressed, but is also inevitably dependent upon available financial resources (The World Bank, global water partnership associate program, 2002-2006, Briefing Note 9).

<table>
<thead>
<tr>
<th>TYPE OF DATA</th>
<th>BASELINE DATA (from archives)</th>
<th>TIME-VARIANT DATA (from field stations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater Occurrence and</td>
<td>• water well records (hydrogeological logs, instantaneous groundwater levels and quality)</td>
<td>• groundwater level monitoring</td>
</tr>
<tr>
<td>Aquifer Properties</td>
<td>• well and aquifer pumping tests</td>
<td>• groundwater quality monitoring</td>
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<tr>
<td>Groundwater Use</td>
<td>• water well pump installations</td>
<td>• water well abstraction monitoring (direct or indirect)</td>
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<td></td>
<td>• water-use inventories</td>
<td>• well groundwater level variations</td>
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<td></td>
<td>• population registers and forecasts</td>
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<td></td>
<td>• energy consumption for irrigation</td>
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<tr>
<td>Supporting Information</td>
<td>• climatic data</td>
<td>• river flow gauging</td>
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<td></td>
<td>• land-use inventories</td>
<td>• meteorological observations</td>
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<tr>
<td></td>
<td>• geological maps/sections</td>
<td>• observations</td>
</tr>
</tbody>
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Table 1-1: Types of data required for groundwater management.

The classical problem faced at the start, in the designing of monitoring network is the unknown spatial and temporal variability for each of the variable to be monitored. And sometimes lack of knowledge how to interpolate in space and time between measurement points hampers even the beginning
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of monitoring. Geostatistical techniques can be applied to explore the variability of each parameter in the region of interest. Descriptive statistics, i.e. determination of the mean, median, minimum and maximum gave a first impression but generally they offer insufficient information to characterize the spatial and temporal variability. Presently, the spatial correlation is often described with the help of semi-variogram which is based on the fact that observation closer to each other are more likely to be similar than the observations at larger distances. The semi-variogram can be used to interpolate the values at unmeasured location. This procedure which is known as Kriging provides a measure of the uncertainty of the predicted value as well. The specified predicted error can not only serve as a guide to find new locations where the measurement should be carried out but can also serve as a criterion to find out whether the sampling density is already adequate or not.

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the increasing urbanization, changing eco-systems, food production, health, industry and energy, as well as risk management, valuing and paying for water and increasing knowledge and capacity building.

While rain fed agriculture accounts for 80% of the total cropland and irrigated agriculture accounts for 20%, it is this later that contributes to 40% of the total food production. Still, irrigation has strained groundwater and surface water supplies, weakened the quality and resistance of the soil with salt deposits and water logging, and reduced naturally-occurring plant and animal species. It is probably in rural areas that water scarcity affects people most. In large parts of the developing world, irrigation remains the backbone of rural economies. However, smallholder farmers make up the majority of the world's rural poor, and they often occupy marginal land and depend mainly on rainfall for production. They are highly sensitive to many changes – droughts, floods, but also shift in market prices. However, rainwater is rarely integrated into water management strategies, which usually focus exclusively on surface water and groundwater. Countries need to integrate rainwater fully into their strategies to cope with water scarcity. The agriculture sector must take the lead in meeting a challenge that no one can afford to ignore - finding ways to do more with less water and reducing potential damage to the environment.

There will be four main drivers of increasing water scarcity during the coming decades. First, as already mentioned, there is the inexorable growth in population. Second, the world is expected to become increasingly urbanized, focusing the demand for water among an ever more concentrated population. Asian cities alone are expected to grow by 1 billion people in the next 20 years. Third, per-capita consumption, the amount of domestic water that each person uses, is expected to rise as the world becomes more developed. Fourth, while these factors will increase the demand for water, freshwater resources will change as a result of climate change. While the magnitude of this change is still subject to uncertainty and will vary from one region to another, it is recognized that semi-arid regions will probably see an
increase in the variability of precipitations, leading to more frequent periods of
drought. Further, freshwater bodies have a limited capacity to process the
pollutant charges of the effluents from expanding urban, industrial and
agricultural uses. Water quality degradation can also be a major cause of
water scarcity.

As farmers in particular face the challenge of accessing an increasingly
scarce resource, groundwater levels are falling further each year, causing
more rivers to dry up. Water is a major determinant of the health and
productivity of ecosystems, placed in jeopardy in many parts of the world by
reductions in water flows and water quality standards. Increasing water
extraction has threatened the integrity of natural ecosystems, leading to the
loss of significant biological diversity and undermining the ecosystem
productivity on which so many poor people depend. Half of the world's
wetlands disappeared during the twentieth century, many rivers no longer
reach the sea, and fish species are endangered.

1.3 Groundwater Scenario in Indian Context

India is a vast country having diversified geological (rock formations,
ranging in age from Archaean to Recent), climatological (ranging from desert
in the west, to alpine tundra and glaciers in the north, to humid tropical
regions supporting rainforests in the southwest and the island territories), and
topographic set-up (the rugged mountainous terrains of the Himalayas,
Eastern and Western Ghats to the flat alluvial plains of the river valleys and
coastal tracts, and the aeolian deserts of Rajasthan), giving rise to divergent
groundwater situations in terms of occurrence, distribution and movement of
groundwater in different parts of the country. Figure 1-5 shows the distribution
of groundwater in India with yield potential as well as type of formation. India
has a highly seasonal pattern of rainfall, with 50% of precipitation falling in just
15 days and over 90% of river flows occurring in just four months. Throughout
history people have adapted to this variability by either living along river banks
or by careful husbanding and management of water. The topography and rainfall virtually control runoff and groundwater recharge.

Figure 1-5 Hydrogeological map of India with yield potential and formation, (Central Ground Water Board, Ministry of Water Resources, 2006).

Groundwater occurrence in the country is highly uneven due to diversified geological formations with considerable lithological and chronological variations, complex tectonic frame work and also climatological variations. Groundwater exploration in Indo-Gangetic plains has shown existence of potential aquifers down to 1000 m. or more. Annual replenishable groundwater resources of this region are ~200 BCM which is more than 45% of the country. Besides, it also has vast in-storage groundwater resources
down to the depth of 450 m. Deeper confined aquifers get their recharge from distant recharge zone and have groundwater of varying ages. In some of the areas, the deeper aquifers are under auto-flow conditions. The quality of groundwater in these aquifers is also good. These aquifers can support large scale development through both shallow and deep tube wells. The eastern and north eastern parts of the country mainly in the states of Assam, Bihar, West Bengal and UP have huge groundwater resources both in unconfined and confined aquifers. The annual replenishable resources of 165 BCM have been assessed in these states. To the north of this tract all along the Himalayan foot hills, occur the linear belt of Bhabar piedmont deposits, and the Tarai belt. Groundwater in Bhabar zone adjacent to Hills is quite deep whereas in Tarai belt it is shallow. Auto flow conditions have also been observed in some of the tube wells constructed in the area. The groundwater quality in these areas is generally good and within permissible limits for various uses. Terai belt has very productive aquifers and supports high yielding tube wells. Springs and dug wells on the hills and valley fills are the major source of water to meet the requirements and needs to be augmented through percolation tanks, check dams, sub-surface barriers for their sustainability.

Major parts of the states of Andhra Pradesh, Chhattisgarh, Gujarat, Jharkhand, Karnataka, Kerala, Maharashtra, Orissa, Tamil Nadu and part of Madhya Pradesh and Rajasthan are underlain by hard rocks and presence of groundwater is subject to availability of secondary porosity i.e., joints, fractures, fissures and weathered structures. In these rocks, the groundwater occurs in shallow unconfined aquifers in the weathered material and under semi-confined conditions in deeper fracture and joints. Groundwater exploration in granitic/ gneissic terrain has proved existence of water bearing fractures down to 300 m and more. Basaltic terrain covering nearly 40% of the hard rock areas has multilayered aquifer system due to lava flows at places.
The coastal and deltaic tracts in the country form a narrow linear strip around the peninsula. The coastal areas have reasonably extensive multilayered aquifers which have prolific yield potential that can sustain moderate to high capacity tube wells. Enormous fresh groundwater resources are identified in the extensive major delta and coastal tracts, particularly all around the east coast. In the coastal tract of Gujarat generally the unconfined aquifer occurs down to depth of 40 m below ground level (bgl) whereas the semi confined to confined conditions is seen between 30m to 200 m bgl. Due to progressive sea water intrusion the quality of groundwater is steadily deteriorating in the coastal tracts of Kutch and Saurashtra. Thus, in this terrain groundwater withdrawal requires to be regulated so as not to exceed annual recharge and not to disturb hydro-chemical balance leading to sea water ingress.

In India, primary source of fresh water is rainfall (which reaches people mainly at surface) and groundwater. The demand for fresh water in the country has been rising over the years due to increased demand for food production and growing urbanization and industrialization. Currently, total water use (including groundwater) is 634 BCM, of which 83% is for irrigation. The demand for water is projected to grow to 813 BCM by 2010, 1093 BCM by 2025 and 1447 BCM by 2050, against utilisable quantum of 1123 BCM. (The average annual rainfall in the country is 1170 mm (which corresponds to annual precipitation including snowfall of 4000 billion cubic meters), out of which only 1869 BCM appears as average annual potential flow in rivers and further due to various constraints, only 1123 BCM is assessed as the average annual utilisable water ~ 690 BCM from surface water and 433 BCM from groundwater).

Groundwater has become an alternate source for drinking, irrigation and industrial purposes, next to surface water. Exploitation of groundwater in India is very high as it provides about 90 percent of drinking water supplies in rural areas and 40 percent of the irrigation water supply. At the same time
groundwater is generally widespread and easily available without any restriction. As the availability of surface water resources is coupled with rainfall events, in recent time has become an unreliable source for continuous supply. During the past two decades, the groundwater has been trapped extensively. The uncontrolled exploitation of groundwater sources has resulted in the declining of water levels and deterioration in quality, which is clearly evident as base flow to the streams has decreased and large tracts of irrigated land has turned to waste lands. Under the influence of industrial effluents, and over usage of fertilizers, several groundwater basins have become unfit for drinking and irrigation.

Traditionally, India depended on monsoons to meet its fresh water requirements but over the years due to the increasing population and the resulting demand for an increase in food grain production and domestic water supplies, groundwater has been extensively used. This has reduced the country's dependence on monsoons but at the same time has resulted in depletion of groundwater. In several areas of the country like Delhi, parts of Uttar Pradesh, Karnataka, Maharashtra, Tamil Nadu and Andhra Pradesh groundwater levels are perilously low. Clearly, the overall demand will outstrip availability in another 35 to 40 years, while groundwater in particular will come under even greater pressure in the intervening years. The rate of extraction of groundwater is increasing and in many blocks exceeds the rate of recharge, leading to lowered water tables. Twenty-eight percent of the blocks are now semi-critical, critical and over-exploited, stated the report of the Expert Group on Groundwater Management and Ownership, 2007 (Figure 1-6). Out of 5723 assessment units (blocks/mandals/talukas/watersheds), 839 are categorized as "overexploited", 226 blocks/ watersheds are "critical" and 550 are semi-critical units. The remaining, 4078 units are safe and 30 units are saline. The number of dark or over-exploited critical blocks has grown from four percent in 1995 to 15 percent in 2004. Groundwater, in particular, will come under even greater pressure in the intervening years, it added. As groundwater is an open access common property resource, the country is faced with a situation in
which one user tries to maximize his share, lowering the others share. And when groundwater level gets lowered, it increases costs for all, as they need to deepen their wells and require more powerful pumps.

Figure 1-6 Map showing the safe, semi-critical, critical, over-exploited and saline blocks of groundwater resources of India as on March 2004, (Central Ground Water Board, Ministry of Water Resources, 2006).

There is growing concern on deterioration of groundwater quality due to geogenic and anthropogenic activities. The quality of groundwater has undergone a change to an extent that the use of such water could be hazardous. Increase in overall salinity of the groundwater and/or presence of high concentrations of fluoride, nitrate, iron, arsenic, total hardness and few toxic metal ions have been noticed in large areas in several states of India. Groundwater contains wide varieties of dissolved inorganic chemical constituents in various concentrations as a result of chemical and biochemical
interactions between water and the geological materials through which it flows and to a lesser extent because of contribution from the atmosphere and surface water bodies. Groundwater in shallow aquifers is generally suitable for use for different purposes and is mainly of Calcium bicarbonate and mixed type. However, other types of water are also available including Sodium-Chloride water. The quality in deeper aquifers also varies from place to place is generally found suitable for common uses. Only in some cases, groundwater has been found unsuitable for specific use due to various contaminations mainly because of geogenic reasons.

India faces a daunting set of water-related challenges. Unless and until the water management practices are changed in the near future, India will face a severe water crisis within the next two decades and it will be seemingly difficult to build new infra structure and to have enough water need by its growing economy and rising population. We have reached a stage where it is important for us, individually as well as collectively to focus more on the management of the water resources. Management and economics of the available groundwater and fresh water resources will play a vital role in the coming years for the sustainable development. It is high time where the scientist working in this sector should collaborate with the planners and policy makers including the involvement of the local authorities at the village or mandal level to chalk out plans that will ensure stability and security as far as the availability of fresh water is concerned.

1.4 Aim and Objectives of the Proposed Research

Keeping in mind the trend of declining water tables and deteriorating water quality, which of course will lead to scarcity of available water resources in the near future, it has become essential for planners and water scientists to develop sustainable water management strategies. Also at present there are a variety of groundwater resource and contamination problems that involve determining the state of groundwater and detecting or predicting changes in
the groundwater environment. Groundwater being an extensive, concealed and inaccessible resource in contrast to surface water adopts changes in quantity and quality often very slowly. These changes cannot be determined by simple one-off snapshot surveys alone, and require more elaborate monitoring networks and data interpretation.

Groundwater management and groundwater monitoring are two activities, which are not only closely related, but in fact they are inseparable. Sustainable development and management of groundwater resource often requires quantitative as well as qualitative assessment of the resource. Groundwater resource management and planning requires appropriate and accurate data. Without proper groundwater monitoring, effective groundwater management is not possible. Monitoring, recording, assessing and disseminating information on water resources is critically important for achieving the objects of the Act. These data, which can be collected by monitoring networks may contain too little, enough or redundant information. Since the Groundwater monitoring is a costly affair because of the expense involved, in response to this there is a need of vital importance to make the monitoring program as optimal as possible. Optimal groundwater monitoring network makes the program cost effective without losing any scientific information.

This research aims to develop statistically sound methods for groundwater quality and/or quantity monitoring network design using some better estimation techniques then the ordinary statistical ones. Also to review the literature regarding the different interpolation (estimation) methods for groundwater data and to find interpolation methods which have the ability to produce a measure of accuracy of the estimated variable value. The objective was to use different approaches to design observation networks i.e., determination of the number of observation points and their spatial locations according to a specified objective. The sampling sites should be ideal in order to get a representative pattern of groundwater quantity and/or quality data and
should be able to capture the true variability of the parameter under study. The aim of this research was also to develop, by means of a case study, a method to reduce the number of observation points in an existing network according to some well defined and simple criteria, and to rank the relative importance of the different points in the network.

1.5 Overview of the Thesis

The present work is based on the optimization of groundwater monitoring network using geostatistics. For making any kind of study, the first thing to know is its importance and need. Also for developing new methodologies, it is mandatory to select a study area, which could be an ideal representation of such environment where the developed techniques is needed and could be tested and applied.

For making any study it is essential to know the earlier work related to that research. Chapter 2 summarizes the literate related to optimal monitoring network, to get an idea about different techniques available for such study.

Chapter 3 provides the general description of the Maheshwaram watershed, the area selected for this research. The purpose of this chapter is, to provide an introductory sketch of the social, physical and economic characteristics of the study area, and also the water uses, so that groundwater monitoring and related issues can be seen in their regional context. It also includes its geographic location, climate, geomorphology and the physiography and drainage. Geology and the structural features present in the watershed are also discussed to know its representation of true hard rock aquifer in a granitic terrain.

Chapter 4 deals with the basic of geostatistics including variography and estimation theory mainly on ordinary kriging for example. For the spatial variability of any parameter, variographic analysis is essential, that is dealt in
This chapter also explains cross-validation of the variographic models, in order to know that it is able to reproduce the true data. Emphases are given to bring out the practical approaches to these techniques.

The chapter 5 includes the theoretical developments of the Geostatistical optimization techniques applied for designing the groundwater monitoring network. It then illustrates the case studies which have been carried out in the watershed and their results. It includes evaluation of groundwater monitoring network for parameters like water level, rainfall and fluoride. The major part of this chapter explains one comparative study, which in brief describes the result of optimizing the monitoring network by two different ways and advantages of each method.

As stated earlier in the present scenario where the demand supply gap is increasing, it is necessary to have an assessment of the available groundwater resources in terms of quality as well as quantity. The chapter 6 deals in detail with the optimization of groundwater quality monitoring network using geostatistics. Since the groundwater quality is involving a number of parameters, a multivariate statistical technique is used which reduce the number of variables to a small number of indices, while attempting to preserve the relationships present in the original data. This chapter thus explains the application of multivariate statistical and geostatistical approaches for developing an optimal monitoring network. Lastly it explains the result of the validation of the optimal monitoring network evolved using the above mentioned approach.

A brief summary and conclusion for this research, accompanied by some recommendations for future work are presented in last Chapter followed by reference.