*International Conference "Water, Environment, Energy and Society" (WEES–2009)*
*New Delhi, 12–16 January 2009*

# Development *versus* Sustainable Development of Ground Water Resources in Indian Context

**S.N. Rai**[1]
National Geophysical Research Institute
Hyderabad - 500 007, INDIA
E-mail: snrai@ngri.res.in

**ABSTRACT:** The accelerated growth in population, industries and agriculture has brought about many fold increase in the water supply. Groundwater contributes significantly to meet the ever increasing demand of water supply. Massive withdrawal of ground water in India commenced from late sixties since the onset of nationwide green revolution. Till late eighties, the main aim of so called ground water development in Indian context was restricted to the delineation of ground water resources and their exploitation without paying due attention towards its effects on quantity and quality of ground water. All these years, ground water development has been carried out and still continuing by private operators, who mostly do not have adequate understanding about the prevailing hydrogeological conditions and the dependencies and linkages of ground water with other constituents of hydrological cycles. For most of them, ground water is unlimited source, which is otherwise a limited source annually replenished by rain water. During all these years, inappropriate development of ground water resources has caused several kinds of problems such as declining of ground water level leading to failure of wells and ground water pollution, water logging and soil salinity in canal command areas. Since last 10–15 years attention has been paid in some areas by government institutions and NGOs towards achieving the goal of sustainable development by linking the management and governance policies to the development program. Sustainable development rejects all policies and practices which leads to quantitative and qualitative deterioration of ground water resources by fulfilling present needs ignoring the future requirements. This paper describes the impacts of development and sustainable development with the help of case studies to highlight the necessity of integration of management and governance schemes with the development programs.

## INTRODUCTION

Ground water is being used for domestic purposes world wide from immemorial time because of presence of its vast volume geographically distributed all over the globe. Later on it's use was extended to agriculture sector followed by industrial sector. In India, till early sixties, dug wells and ponds were the only source of water supply from ground water resources. Penetration of these dug wells and ponds were more or less restricted to the water table zones in alluvial formations and weathered zones in hard rock terrains, both lying at shallower depths. These zones are getting replenished annually during rainy seasons between June to September. Thus, dug wells and ponds serve two objectives: first as a source of water supply and second as an infrastructure for conservation of surface water in to ground by arresting run off. Since the residence period of this replenished water happens to be a year or so, it is less mineralized and more or less free from any kind of pollution in the absence of human intervention or natural sources of pollutants. In general, cases of groundwater pollution were not heard as long as ground water from these zones was in use. Then, the era of nation wide green revolution commenced from late sixties. With this the demands of water supply from ground water resources started escalating day by day and the water supply from dug wells and ponds were not sufficient to meet the ever increasing demands. Then the use of borewells, facilitated by improved well drilling and pump technologies started picking up at a faster rate and with the passage of time the significance of dug wells and ponds started fading away from the minds of users as well policy makers. There is a misunderstanding among majority of the people that the quality of ground water improves with depth. This misunderstanding led them to go for deep borewells at more cost even though ground water is available at shallower depths. They are ignorant of the fact that the main source of ground water is precipitation only which first infiltrates to the shallow aquifers. Deeper aquifers receive water from the shallow aquifers only with the passage of time. During its movement from shallow aquifers to deeper aquifers it passes through different geological formations and getting mineralized by dissolution of substances present in that formation

[1]Conference speaker

through which it passes. In many cases these substances are of hazardous nature polluting the fresh ground water. Presently, instead of promoting the construction of new dug wells and ponds as a source of water supply and water conservation and keeping the old structures in usable conditions, we have allowed these structures to fall into disuse. In the beginning ponds and dug wells are being used as a waste disposal site and later on when their waters become polluted then they are being treated as a source of pollution. It provides an excuse to the land grabbers or even local administration under pressure from local people to fill it. At this stage, because of ulterior motives, no body is willing to pay any attention towards their restoration. Instead, these sites are being filled with municipal/ industrial wastes containing hazardous substances and later developed in the form of parks, community centers, places of worships or in other form of personal properties. This practice is reducing the potential infrastructures of ground water recharge. This story is alike in rural as well in urban areas. Thus, on one hand the magnitude of ground water recharge is on reducing trend while on the other hand magnitude of ground water withdrawal is on increasing trend due to increasing number of borewells. This ever growing disparity between recharge and withdrawal of ground water is the main cause for the present day ground water related crisis. This reflects that the present crisis is not due to scarcity of physical water but due to mismanagement of its resources. In the following sections a scenario of ground water development and its consequences will be discussed. This is followed by discussion on sustainable development and its advantages.

## GROUND WATER DEVELOPMENT AND ITS CONSEQUENCES

In India, groundwater rights are attached to the landownership such that a land owner can extract as much water as he desires. Because of invisible character of ground water resources there is widespread lack of awareness among majority of stakeholders about limitation of water storage capacity of aquifer systems, their links with the other constituents of hydrological cycle, ways and means of their replenishment, possible sources of their pollution, changes in quantity and quality under prevailing hydrological stresses and hydrogeological environment. Development activities of ground water resources are mostly confined to the delineation of ground water resources and their exploitation to meet the present requirements without paying attention to their sustainability to meet the demands of future generation. Before 1960, the total numbers of borewells in the country were less than 1 million. During last four decades since the commencement of green revolution in late sixties several thousands of farmers have drilled their own borewells numbering over 19 millions, at their own expenses and risk in order to make use of the advantage of low cost, high quality and drought-resilient groundwater based irrigation. Development works have been executed mostly by engaging private operators whose knowledge is mostly restricted to drilling operation only and their main concern is business which is linked to the borewell depth. This practice has been carried out since past four decades and still continuing in uncontrolled manner and without any scientific basis.

Ground water resources are subjected to change in space and time domains due to both, natural and anthropogenic causes. Hence, periodical monitoring of its quantity and quality conditions are essential to identify the groundwater regime in terms of quality and quantity on the day of observation, identification of problems, if exist, ascertaining the causes influencing its present status, assessment of socio-economic effects on users, selection of suitable management scheme to cope up with the prevailing ground water related problem, etc. For these purposes, ground water levels are being regularly monitored four times a year during January, April/May, August and November by CGWB through a network of about 15,000 observation wells located all over the country in different hydro-geological environments. In addition to that 1200 digital water level recorders have been installed at selected wells to acquire high frequency water level data so as to monitor short term changes in ground water regime. Samples are collected through these observation wells once a year during the month of April/May to know the status of ground water. These data are being analyzed for each assessment units in the form of Blocks, Mandals, Talukas, Districts, Districts valley etc. Block is considered as assessment unit in Punjab, Haryana, Rajasthan, Uttaranchal, Uttar Pradesh, Bihar, Jharkhand, Madhya Pradesh, Chhattisgarh, Orissa, West Bengal, Kerala, Tamil Nadu, Manipur, Mizoram, and Tripura; Mandal in Andhra Pradesh; Taluk in Goa, Gujarat, Karnataka and Maharastra; District in Arunachal Pradesh, Assam, Delhi, Meghalaya and Nagaland; District's valley in Himanchal Pradesh and Jammu and Kashmir. According to Romani (2006), out of 5723 assessed units, 839 units are characterized as overexploited where withdrawals exceed annual replenishment, 226 units are critical where groundwater development has reached high level of development and 550 units are semi-critical. Remaining 4067 units are found safe. The State's wise total number of assessed units, overexploited units and critical units are given as :Andhra Pradesh (1231, 219, 77) Tamil Nadu (385,142, 33), Rajasthan (237, 140, 50), Punjab (137, 103, 5), Karnataka (175, 65, 3), Haryana (113, 55, 11), Uttar Pradesh (803, 37, 13), Gujarat (223, 31, 12), Madhya Pradesh (312, 24, 5), Maharastra (318, 7, 1), and Delhi (9, 7, 0). More details on state-wise ground water resources availability, their utilization and stage of development are also given in Romani (2006). From ground water availability point of view situation in the entire hard rock regions of Maharashtra, Gujarat, Madhya Pradesh, Andhra Pradesh, Karnataka, and Tamil Nadu states which occupy almost two third surface areas of the country is very alarming. In these states, weathered zones which are the main sources of ground water because of their presence at shallower depths, amenability to natural replenishment and high permeability are almost devoid of ground water. Limited quantity of water is left over only in cracks and joints of deeper crystalline basement rocks which get replenished during a long span of time and are considered strategic reserves. Presently mining of ground water from strategic reserves is going on due to non-availability of ground water in the weathered zones. Just to give an idea of inappropriate development of ground water resources, an example is given here from Maheshwaram watershed, located 35 km south of Hyderabad and covering an area of 53 sq. km in R.R. District of A.P. This watershed is a representative of south Indian catchments in term of geology, over-exploitation of aquifers, climate (semi-arid), cropping pattern, rural socio-economic context (Dewandel *et al.*, 2007). This watershed was having only two tube well in 1975. This figure rose to 10 in 1985, 100 in 1995 and by 2002, the number of borewells rose to 935. Out of which 228 borewells are dried up due to intensive withdrawal of ground water in excess to existing recharge. Lowering of ground water level leads to many kinds of socio-economic problems like reduction in water supply, failure of tube wells, increase in pumping cost etc. Because of high development cost, failure of borewells, and inability to pay the loan, several hundreds farmers have committed suicide. Such things will continue to happen in future also if the ground water related problems are not handled amicably.

Urban areas are also facing scarcity of ground water supply due to rapid population growth and spatial expansion of cities. More and more surrounding areas are brought into city limits. These surrounding areas were having several surface water bodies in the form of lakes, ponds, large diameter dug wells etc. to meet the domestic and irrigational demands of that region before becoming a part of the city. After integration into city limits, these surface water bodies are also being sold for construction purpose. Such practice has reduced the potential facilities of ground water recharge leading to man made water scarcity. Because of no further scope for creation of new surface water bodies due to either non availability of land or fund, the share of water supply from surface water bodies remains the same from several past years. Therefore, ever increasing demand of water supply is being met through inappropriate development of ground water resource by drilling closely spaced large numbers of borewells, mostly privately. Very often, especially during summer, these borewells go dry due to non-availability of ground water. On the other hand, now a days, merely two hours of continuous rainfall is sufficient to create flood in major cities like Mumbai, Delhi, Chennai, Kolkota, Hyderabad etc. Flooding is not due to increase in rainfall intensity or inefficiency of drainage systems but due to lack of infrastructure for water conservation such as percolation tanks and rooftop rainwater harvesting structures. Thus, the precious fresh water is allowed to flow into drains which are linked to near by streams or rivers. In the absence of infrastructures of water conservation, good amount of rainfall is also unable to increase ground water recharge and the ground water resources of the places where rain falls remains deprived of fresh ground water. In spite of government orders issued for many cities majority of people have not made arrangements for rooftop rain water harvesting. Therefore, government alone cannot be blamed for water scarcity during dry period and flooding during rainy period, but each individual citizen and institutions who failed in their responsibility to develop infrastructure for rooftop rain water harvesting in their compounds. One should remember that rainfall is the only source of fresh water available either in surface water bodies or within the Earth in the form of ground water.

Withdrawal of groundwater in excess to recharge not only causes the lowering of the water table but also changes the flow path of groundwater which is otherwise in a state of local/regional water balance. This led to the movement of pollutants from nearby regions into fresh water zones. Earlier in the era of ground water withdrawal from weathered zones in hard rock regions, the pollution due to fluoride was reported from few pockets. But in recent years due to ever increasing mining of ground water from deeper aquifers, fluoride led ground water contamination is reported from different parts of the country, especially from hard rock regions spread over in Karnataka, A.P., Maharastra and M.P. Around 62.5 million people are suffering from disorder of teeth or bones through fluorosis, which is due to unknowingly consumption of fluoride rich water (Susheela, 1999). Hydrogeological investigations carried out in the rural parts of Yavatmal district of Maharastra State reveal high fluoride concentration in water from deeper aquifers compared to water from shallow aquifers. A comparison of fluoride concentration between borewell water from deep aquifers and dug well water from shallow aquifers is presented in Table 1. Physicochemical conditions like decomposition, dissociation and subsequent dissolution along with long residence time are stated to be reasons for leaching of fluoride into ground water. (Madhnure *et al.*, 2007). In this region, ground water from shallow aquifers only is being recommended for drinking. Geochemical investigation of ground water from 58 selected fluoride rich areas in different parts of the country that include eight districts has been carried out to deduce the chemical parameters responsible for the dissolution activity of fluoride in ground water (Saxena and Ahmed, 2003). The origin of high fluoride in a regional alluvial aquifer system under water stress in the North Gujarat-Cambay Region is investigated. This region is severely affected by endemic fluorosis due to ingestion of ground water containing excessive fluoride (Gupta *et al.*, 2005). Certain sub-aquifer zones have been identified within the Cambay basin where ground water contains relatively high fluoride concentration. Alternating belts of low and high fluoride concentration are ascribed to ground water recharge during the past wet and arid climatic phases, respectively. Concentration of fluoride in the ground water of south eastern part of R.R. District is reported in the range of 0.7 to 4.8 mg/l and from 0.4 to 4.20 mg/l during the pre and post monsoon seasons, respectively (Sujatha, 2003). Fluoride in ground water from Anantpur district has been investigated by Subba Rao and Devadas (2003).

Arsenic (As) led contamination of ground water due to inappropriate ground water resources development is another major problem in Indian sub-continent and is reported from several places in India, Nepal, Bangladesh and Pakistan. In India, As problem in ground water was first reported from only seven districts in Bhagirathi-Ganga Delta and Damodar fan delta of West Bengal in late eighties (Acharyya *et al.*, 1993, Mandal *et al.*, 1996). Now, as contamination of ground water is reported from larger areas of Bhagirathi-Ganga Delta, Damodar fan delta and recently from Middle Ganga Plain and Brahmaputra basin. As on today elevated concentrations of As exist in ground water of nine districts of West Bengal, namely Malda, Murshidabad, Nadia, North and South 24 Paraganas, Bardhman, Howrah, Hugli and Kolkatta. Around 50 million people in West Bengal alone living in 3200 villages covering 38865 $Km^2$ are exposed to drinking water containing As above the permissible limit fixed at 50 mg/l in India (Singh, 2006). WHO has suggested only10 mg/l as a permissible limit. Narrow As contaminated tracts have been delineated from the Middle Ganga flood plains covering Bhagalpur, Bhojpur and Buxar districts of Bihar, Shahebgunj district of Jharkhand and Ballia and Ghazipur districts of UP (Acharyya, 2005, 2006).

**Table 1:** Fluoride Concentration in Ground Waters (BW-Borewell; DW-Dugwell) (after Madhnure *et al.*, 2007)

| *Sample Location* | *Source* | *F (mg/l)* | *Sample location* | *Source* | *F (mg/l)* |
|---|---|---|---|---|---|
| Chikhaldara | DW | 0.48 | Ganeshpur | DW | 0.78 |
| | BW | 1.21 | | BW | 2.84 |
| Mohadari | DW | 0.34 | Wai | DW | 0.47 |
| | BW | 0.95 | | BW | 3.02 |
| Runjha | DW | 0.61 | Oatpari | BW | 2.91 |
| | BW | 4.81 | Pimpri | DW | 0.86 |
| Khatara | DW | 0.88 | | BW | 0.90 |
| | BW | 3.03 | Gevrai Munch | DW | 0.66 |
| Sonurli | DW | 0.56 | | BW | 4.81 |
| | BW | 7.22 | Marathwakdi | DW | 0.72 |
| Karanji (Phul Pod | DW | 0.56 | | BW | 1.0 |
| | BW | 2.45 | Ohoki | DW | 1.77 |
| Wadhona (Bk) | DW | 0.58 | | BW | 1.09 |
| | BW | 5.76 | Shushri | DW | 0.55 |
| Wadhona (Kh) | BW | 5.75 | | BW | 5.95 |
| Sakhi (Bk) | DW | 0.64 | Pendhari | BW | 2.88 |
| | BW | 0.98 | Tembhi | BW | 1.58 |
| Oharna | DW | 0.58 | Warha | BW | 1.77 |
| | BW | 13.41 | Arli (Bk) | DW | 0.61 |
| Sakhra | BW | 11.9 | Pimpershenda | DW | 0.47 |
| Nilzai | DW | 0.45 | | BW | 1.01 |
| | BW | 3.50 | Karegaon | DW | 0.30 |

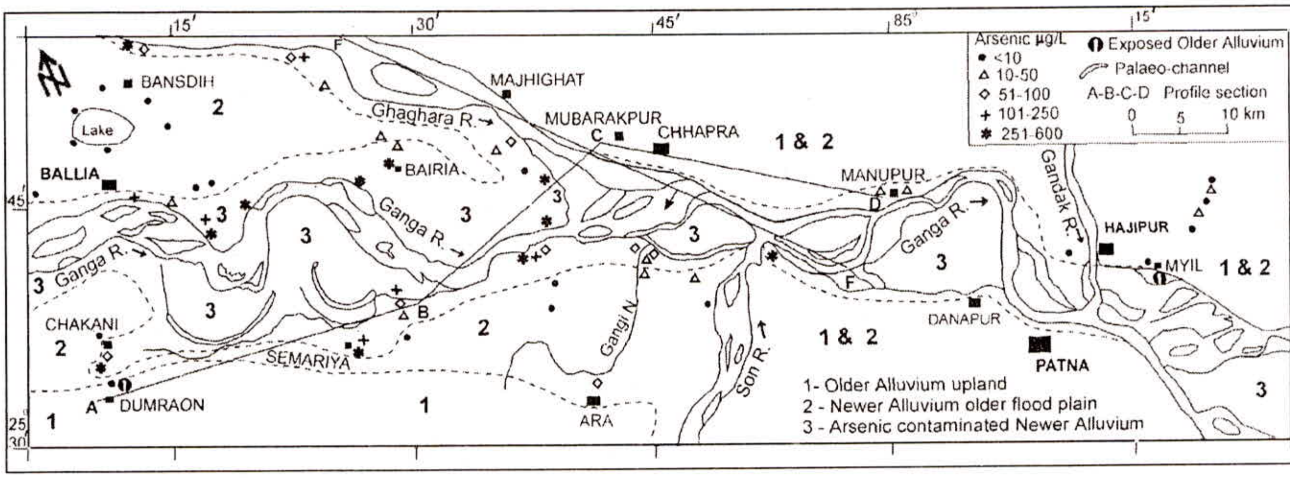


**Fig. 1:** Site locations of Arsenic pollution in middle Ganga Plain (after Acharyya, 2006)

It is reported that the As contaminated aquifer are restricted to the newer alluvium deposits and confined within narrow entrenched flood plains and meandering channels of the river Ganga and Ghaghara (Figure 1). The northern bank area of the river Ganga, East of Ballia, is severely As polluted. But Ballia town itself located on the older alluvium or shallow newer alluvium is free of As problem. Arsenic concentrations in borewell water from Chayan, Chhapra and Bajroha villages are 950 and 1450 mg/l, respectively. In Simeria village of Bhojpur district, deeper borewell water is As contaminated while dug well water is As safe. A narrow belt along the southern bank of the river Ganga from its confluence with the Son River to Chakhani area is also found to be As contaminated. In Bhagirathi-Ganga Delta and Damodar fan Delta As occurs absorbed on Hydrated-Iron-Oxide (HFO). HFO occurs as coating on sediment grains such as quartz, clay and other ferromagnesian minerals. Most As affected alluvial areas are preferentially located close to abandoned or present channel meanders, which are perennial or seasonally water filled and sites of biomass accumulation. Ground water flow, particularly during recharging of aquifer, brings dissolved organic carbon, contributed either by recently accumulated biomass and/or derived from organic aquifer sediments, in contact with HFO promoting their bio-mediated reductive dissolution. This results in release of absorbed As to ground water (Acharyya, 2005, 2006; Acharyya and Shah, 2007). Dug well water because of its oxidizing nature is generally As safe, even in areas with strong As contaminated borewells. In northeastern India, As has been detected in 21 of the total 24 districts of Assam, three districts in Tripura, six districts in Arunachal Pradesh, two in Nagaland, and one in Manipur. All these above mentioned areas mainly belong to Ganges-Brahmaputra basin. This is a very serious problem because majority of Indian population lives in this basin. Intensive mining of ground water from deeper aquifer in excess to their replenishment disturb the regional water balance which is stated to be one of the reasons for ground water pollution (Singh, 2006). Withdrawal of ground water from deeper aquifers allows the passage of ground water of good quality from shallow aquifers to deeper aquifers and getting contaminated while passing through the formations having As materials. Arsenic has been reported from Ambgarh Chowki Block in Rajnandgaon district of Chhattisgarh State also. Borewells in some areas of this Block record As concentration over 50 mg/l and often reach 100 mg/l, whereas dug wells water has As concentration $<10$ mg/L (Chakraborti *et al.*, 1999, Acharrya *et al.*, 2005). Concentration of As in hair samples of some persons from Raipur in Chhatisgarh and from Choube Chapra in Bihar were found to be 6310 and 4790 ppb, respectively against the normal concentration of As in human hair in the range of 50 to 250 ppb (CSE report, 2005).

India has coastline of 7516 kms running from Gujarat coast in the West to West Bengal coast in the East. Inappropriate development of ground water resources in many coastal regions and island environment have also lead to the ingression of saline sea water in to fresh ground water zones. Ground water quality assessment of shallow aquifer using GIS in part of Chennai City, Tamil Nadu has been carried out. From the higher TDS and $Cl/HCO_3$ ratio, it is inferred that the sea water has intruded into a considerable area adjoining the coast due to over exploitation of ground water (Singh and Lawrence, 2007). In many coastal regions of Orissa, Andhra

Pradesh, Tamil Nadu, and Gujarat, the intrusion of sea water towards inland fertile soils has been reported mostly due to over development of coastal aquifers. The effect of sea water intrusion up to 3 to 4 km within inland along the entire coast line of Gujarat has been reported. In the Minjur area of· Thiruvallur district of Tamil Nadu the range of sea-water intrusion is 2 to 9 km (Romani, 2005). Sea-water ingression due to inappropriate development of ground water resource is also reported from coastal aquifer of Vakadu Mandal of Nellore District in A.P., Kavarati island of Lakhdweep islands group (Singh and Gupta, 1999), Potharlanka in Krshna Districts of A.P. (Saxena, *et al.*, 2003).

## SUSTAINABLE DEVELOPMENT

Most of the above mentioned ground water level declining and contamination problems are mainly because of inappropriate development practices being presently adopted by ground water user communities. It goes against the ethics of sustainable development which rejects all policies and practices that led to the depletion and contamination of ground water resources by fulfilling present needs and leaving future generation unable to meet their demands. Sustainability contains both, the more restricted concept of security and survivability. Objectives of sustainable development can be achieved by integrating appropriate management and governance measures to the development programs. In broader sense, management measures are aimed to ensure the maintenance of sustainable water supply and assuring the longevity of the resources for future generation. Governance measures deal with the legislations and administrative set up to control and regulate the development practices and management measures. Many experts strongly feel that present ground water crisis is mainly a crisis of management and governance. Therefore, ground water related policies need a major shift from presently adopted development practices to management and finally to governance mode in order to achieve the preset objectives of sustainable development. The integrated management and governance strategies should take in to account the functional behavior of two systems: (1) the human system which influences the quantity and quality of ground water by resorting to inappropriate development activities and (2) the ground water system which is the source of water availability. Recently government organizations and some NGO have changed their development policies of delineation and subsequently exploration/exploitation of aquifers to delineation and assessment of their potential before passing on recommendations for their sustainable development. This is mostly done by integrating geological, geophysical, geochemical and remote sensing data and by application of GIS analyses. Management and governance schemes are being either implemented or planned in several problematic areas. Some examples are described in the following section.

Ground water resources have been estimated for the Koyana River basin for the catchment downstream of the Koyana dam (area 1082 sq km) on the basis of water table fluctuation method (Naik and Awasthi, 2003). Based on this study construction of about 500 additional dug wells has been recommended in the command areas alone to make the best utilization of the available ground water resources. A detailed hydrogeological investigation was carried out in parts of the Central Ganges Plain with the objective of assessing the aquifer frame work and its resource potential (Umar, 2006). Electrical resistivity, ground water level, borehole and remote sensing data have been integrated in the GIS analysis for hydrogeological zoning in the piedmont zone of Himalayan foot hills region of Uttaranchal (Israil *et al*., 2006). An integrated study was carried out in Bairasagara watershed in Karnataka to investigate the sub-surface conditions in hard rock environment with the aim of identifying zones with ground water potential (Subhash Chandra *et al.*, 2006). Studies are carried out using hydrological, hydrogeological, and geophysical methods in various islands of Lakshadweep for deciphering the complex hydrogeological environment of islands. This has been done to develop a prognostic model of fresh ground water lenses so that a sustainable management of the freshwater resource could be planned for the islands (Varma, 2006). Hydrogeomorphological, hydrogeological, and geophysical investigations were carried out in the Pageru River basin of Cuddapah district of Andhra Pradesh for assessment of ground water potential (Sreedevi *et al.*, 2003, 2005). An integrated investigation comprised of geoelectrical survey, remotely recorded data and pumping test data was made to delineate ground water potential zones in crystalline terrain of Guntur district, A.P. (Subba Rao, 2003). An attempt has been made for delineation of aquifer geometry and surface and sub-surface fault in Ganges Plain by integrating remote sensing and well log data. (Samdder *et al.*, 2007). Sea water ingression study along the Guhagar coast of Maharastra with reference to the harmonious water resources development has been carried out. The pros and cons of constructing engineering structures for preventing sea water ingression and strategy to enhance groundwater recharge for increasing freshwater column in the lower reaches of

Creeks, tidal inlets and their tributaries, without causing harm to the delicate ecosystem of mangrove have been analyzed (Umrikar and Thigale, 2007). Evaluation of sustainable ground water development prospect in the Kadalundi Basin in Malapuram district of Kerala has been done by analyzing the pattern of water level fluctuation in different physiographic regions, the depth to water level and saturated thickness in different seasons, the hydrogeological properties of the rocks within the basin, the ground water assessments, the ground water quality etc. (Narasimha Prasad *et al.*, 2007). An assessment of ground water availability and impact of sea level rise on the aquifer of Kavarathi and Bengaram islands have been carried out by making use of Ghyben-Herzberg equation and Brune's rule, respectively (Sunderesan, 2006). An integrated water management scheme with four components viz, ground water, rooftop rain water harvesting, desalinisation using waste heat produced by diesel generators, and solar salinization is proposed to meet the fresh water demands of Lakshadweep islands (Najeeb, 2007).

A management strategy for managing a part of a shallow aquifer through a systematic well-schedule that is based upon the characteristics of the aquifer and their variability in space through community participation is proposed. This strategy is being tried in Neemkheda village from the tribal dry lands of Bagli Tehsil in Dewas district of Madhya Pradesh (Kulkarni *et al.*, 2004). The Indo-French Center for Ground Water Research at N.G.R.I., Hyderabad has developed a Decision Support Tool (DST) for assessing the impact of changing cropping pattern and ground water development scenarions on ground water resources under variable agro-climatic conditions (Dewandel *et al.*, 2007). This tool is useful in making judicious selection of sustainable cropping pattern in accordance to the availability of ground water. This tool is used to study the ground water problem of Maheshwaram watershed. Based on this study it is estimated that with the existing pattern of agriculture and ground water development practices, if no solution of ground water level declining is quickly found then by 2010 declining trend of ground water level will entail the loss of about 50% of the borewells with all the accompanying serious socio-economic consequences. This DST is entirely an interactive software, where the farmers, with expert's assistance, could analyse the outcome of various options of cropping pattern and select a suitable one. In following sections some important management and governance measures useful for sustainable development of ground water resources without causing adverse effects on it are discussed.

## Awareness

Worldwide some 2 billion people depend on ground water uses. It is guessed that > 80% of illness is only due to lack of quality water supply. People of developing nations are most affected. Hence, scarcity of supply of good quality water not only affects the economic growth but primarily to the health of the people. It has been observed that because of unawareness about the quality of ground water and subsurface location of aquifers with fresh ground water, As and fluoride contaminated ground water from deep borewells are used for drinking purposes whereas safe water from dug wells is being used for other purpose. As above mentioned, around 50 million people in West Bengal alone are exposed to drinking As contaminated ground water and around 62.5 million people in India are suffering from disorder of teeth or bones due to unknowingly consumption of fluoride rich water. These are few examples of people's sufferings due to unknowingly consumption of polluted ground water. Therefore, awareness about the qualitative and quantitative status of ground water resources under prevailing hydrological stresses (withdrawal and recharge), hydrogeological conditions, advantages and disadvantages of their uses and misuses, their links with the other constituents of hydrological cycle, ways and means of replenishment, possible sources of their pollution, remedial measures of water purification etc. help in convincing the policy makers and users about the need of management and governance schemes to be adapted to achieve the objectives of sustainable development. Awareness can be created mostly either through education or through electronic and print media. It is a global tragedy that in spite of significant contributions of ground water in socio-economic benefits to the majority of population, ground water science is not given its due share in the present educational system (Dickerson and Callahan, 2006). In India, formal education of ground water starts from graduation level while majority of the students leave their study from high school level or even before. Hence, a majority of population remain deprived from the knowledge of ground water science. Therefore, efforts should be made to starts the education of ground water science from early stages (Primary or at least Junior High School level), exclusivelv as a part of Earth Sciences and not as a part of any other subjects. Syllabus on groundwater in Earth Science courses of universities and colleges are inadequate and mostly confined to exploration aspects. Management and governance aspects are mostly missing. There is an urgent need for an up-gradation of these age old courses by integrating recent advancements made in this subject.

Mass contact, electronic and print media are very effective measures for creating awareness among peasants about the functioning of groundwater resources and ways and means of their beneficial uses. Awareness related programs should be implemented in large scale in local languages to reach maximum number of people. The CGWB has been organizing mass contacts programs throughout the country and provides training to different sections of stakeholders on management and governance of groundwater resources. Similar awareness programs have been conducted by NGRI and other organizations. Through mass contact programs only, Tarun Bharat Sangh has effectively created awareness among villagers from more than 1500 villages in drought prone Arawali region and other adjoining regions in Rajasthan State about the significance of conservation of water into aquifer systems, execution and monitoring of demand driven self made management and governance measures to make best use of available water. Their development, management and governance policies and practices are framed and monitored by committees of local people keeping aside any kind of interference from Government or any other outsider. In addition to this, several training courses sponsored by Government Departments like Department of Science & Technology, Ministry of Water Resources etc. have been organized at various centers to train the groundwater professionals in the field of development and management of groundwater resources. Lecture notes of these courses containing basics of ground water science and case studies of ground water resources development, management and governance have been published for the benefit of students, teachers and ground water professionals (Rai, 2004; Suresh Babu *et al.,* 2005; Palanisami *et al.,* 2005; Ghosh and Sharma, 2006). So for roles of electronic and print media in propagation of programs and policies of ground water conservation and it's optimal use remain negligible. They prefer to telecast mostly sensational news. The reason could be lack of sponsorship for this kind of knowledge based programs. Government should take initiative in utilizing services of televisions and radios in telecasting and broadcasting programs on limitations of ground water resources, ways and means of water conservation and their importance, economic ways of water uses for domestic, agricultural and industrial purposes, sources of ground water pollution and its effects on environment in general and human health in particular, etc. with the help of case studies.

## Ground Water Recharging

Ground water recharging (natural/artificial) is the most effective measure to overcome from the problem of water scarcity, if suitably implemented in a large scale. Water requirement of the large sections of the people living in regions away from any potential river basins and canal networks and depending only on rain water can be effectively fulfilled by this measure. It is non-controversial, cost effective and environment friendly measure compared to the river linking like mega project and has the potential to reverse the declining trend of ground water level and to protect its quality from encroachment of pollutants from surrounding regions. The best way of recharging is to impound as much rain water as possible where it falls. Suitable structures such as percolation ponds, check dams, bunds, injection wells and rooftop rain water harvesting structures are used for arresting runoff and diverting it into the aquifers. It should be practiced by every section of water users from rural and urban areas in large scale. Only government's effort is not enough to achieve the goals of sustainable development. Efficacy of this measure has been demonstrated by several experiments conducted in different terrains by many governments and non government organizations such as Central Ground Water Board (CGWB), State Ground Water Departments, National Geophysical Research Institute (NGRI), several NGO, etc. During the 9th Five Year Plan (1997–2002), the CGWB has completed 69 artificial-recharge projects which include construction of 25 percolation tanks, 32 check dams, 68 recharge wells, 236 recharge shafts, and 10 subsurface dykes (Romani 2005). Recharge structures have been constructed by several State Groundwater Departments. For example, in Uttar Pradesh, so far 9314 ponds have been rejuvenated/constructed in rural areas whereas in urban areas 140 ponds have been rejuvenated for the purpose of groundwater recharge. In total 16,634 check dams of various dimensions have been constructed on different streams. An ambitious groundwater scheme named as Adarsh Jalashay Yojana has been launched in the State. In the present financial year 2006–07, 52002 ponds would be rejuvenated/constructed, one in each Gram Sabha (Arya *et al.*, 2006).

Artificial-recharge experiments have been carried out by NGRI scientists at Seelaiagaripalli village in the Chittoor district, Wailpally watershed in the Nalgonda district (Muralidharan, 2005/06) and NGRI Campus (Muralidharan *et al.,* 2007). All the three sites are located in hard rock terrains. In these recharge experiments rainfall run-off is diverted in to aquifer with help of check dams constructed at higher elevation of the sloping surface. At lower side recharged water is collected into dugwells/borewells for water supply (Figure 2). Figure 3 presents hourly recorded rainfall and consequent ground water level growth during 8th September to 29th November, 2005 in borewell adjacent to the check dam in NGRI campus. Maximum water level rise of 5.151 m is registered. Water level is measured from the level of measurement point and is mentioned as B.M.P. (below measurement point) in the figure. Recharge experiment at Wailpally has not only increased the ground water reserve but has brought down the fluoride concentration below permissible limit and is able to provide safe drinking water to about 10,000 villagers. Recharge experiments have been reported from three regions, namely Kolwan Valley in Maharastra, Satlasana in Gujrat and Coimbatore in Tamil Nadu (Gale, *et al.*, 2006). Like surface runoff, ground water also leaves the river basin as base flow, if it is not harnessed. Four Subsurface dams in the Swarnmukhi river basin, which is essentially a semi-arid tract in Chittoor district of A.P. State, have been constructed at Tandlam, Jeepalem, Munagalaplem, and Bandarupalle to harvest the base flow going in sandy alluvium and thereby to increase ground water potential (Raju *et al.*, 2006). The sub-surface dams were constructed with puddled clay 0.9 m thick which has been keyed into a hard end connection on either side of the river bank. The top of subsurface dams has been limited to 1 m below river bed level to allow excess flow downstream to flush the salts accumulated and to leave unaffected the reparian rights of the farmers downstream (Figure 4). Well hydrographs for piezometers upstream (TU) and downstream (TD) of Tandlam subsurface dam is presented in Figure 5 to illustrate the efficacy of sub-surface dam in raising ground water levels on upstream as well as down stream side after construction of dams. Around 1.5 m growth in ground water level is found after construction of check dam. Similar results have been observed at other three sites of sub-surface check dams. This measure of water conservation has improved base flow and increase the storage capacity at sub-surface dams and ultimately facilitated the rejuvenation of the river to the extent of becoming a perennial one.

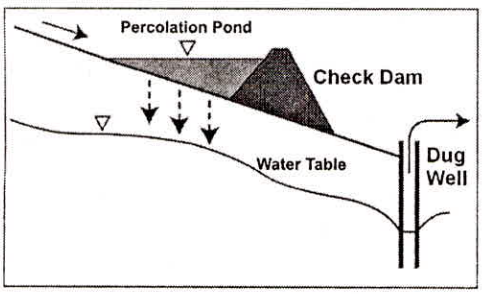


**Fig. 2:** Percolation ponds behind check dam

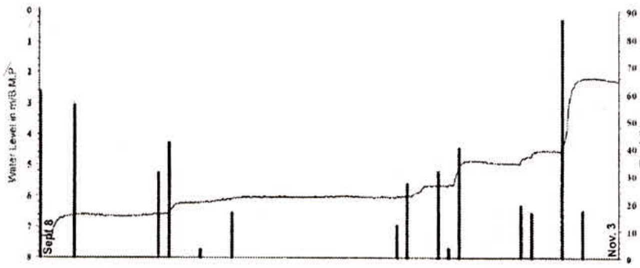


**Fig. 3:** Hydrograph of borewell for September 8 to November 3, 2005 along with rainfall (after Muralidharan *et al.*, 2007)

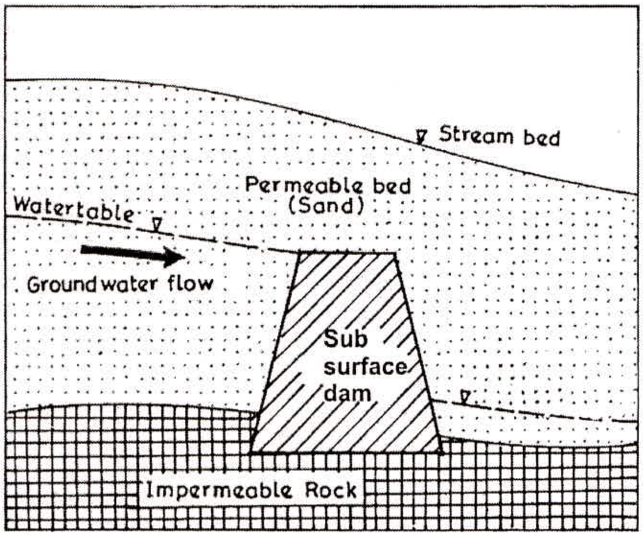


**Fig. 4:** Schematic diagram of subsurface dam (after Raju *et al.*, 2006)

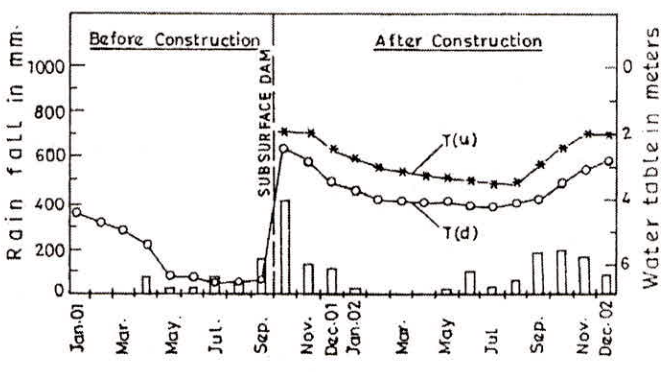


**Fig. 5:** Well hydrographs for Piezometer upstream, T(u) and downstream, T(d) of Tandlam subsurface dam (after Raju *et al.*, 2006)

Another case study of revival of both surface and ground water reservoirs by rainwater harvesting through percolation tanks and Johads is from dry watershed areas of Arwari river located in Alwar district of Rajsthan. Tarun Bharat Sangh (TBS) has played crucial role in reviving the traditional practice of water conservation in Alwar district of Rajasthan by promoting construction of Johads (a kind of check dam) with the help of villagers. As a result of these efforts availability of groundwater has improved to such an extent that it is not only sufficient to fulfill the local demands of water supply but also in converting Arwari river in to perennial river that had nearly dried up (Singh, 2002, 2006). This experiment has been extended to the neighboring Jaisalmer, Ajmer, Udaipur and Bharatpur districts. Over 5600 Johads have been so for constructed.

In general, urban areas lack open space for development of infrastructures for the purpose of ground water recharging. Roof-top rain water harvesting is very effective measure not only to recharge ground water but also to prevent intermittent flooding in urban areas. This measure requires connecting the outlet pipe from roof top to divert rain water to either existing wells or other ground water recharging structure or to storage tank for direct consumption (Figure 6). Conservation of roof-top rain water in to storage tank for direct consumption is practiced in Lakshadweep islands which receive average monthly rain fall more than 40 mm for 8 months a year from May to December. Just at the inlet point to the storage tank, a filter bed composed of coir, fibre, charcoal, fine sand, and gravel is provided. The water from the first rain after a long dry period is let out by means of a diversion so that the dust and aerosols accumulated on the roof are washed out (Najeeb, 2007).

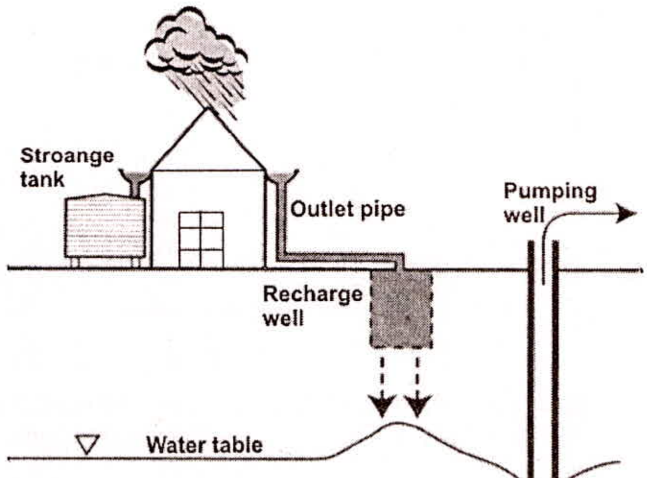

**Fig. 6:** Roof top rainwater harvesting

## Fresh Ground Water Skimming Systems

In coastal regions, pumping from the installation of shallow as well as deep borewells are constrained with shallow depth of good quality ground water lenses floating over the saline water in deeper aquifers. For example, consider the case of Andhra Pradesh where water table is found at shallow depth in the range of 0.5 to 3 m spread over in 1.74 lakh hectare area in the form of 10 km wide and 972 km long strip along the coast extending from Ichapuram in Srikakulam district in the north to Tadain in Nellore district in the south. Excessive pumping of fresh ground water in such environment of coastal areas and inland irrigated water logged area with saline water in relatively deeper aquifers by means of conventional vertical borewell leads to gradual deterioration in pumped fresh ground water quality due to up-coning of relatively more saline ground water of deeper aquifers to within the domain of abstraction wells at shallower depths,. Under these circumstances, it is imperative not to disturb the saline water but to selectively skim fresh water accumulated over the native saline ground water through some modified form of pumping. A thin layer of fresh water that cannot yield sufficient discharge through vertical tube wells without up-coning of saline water could possibly be exploited by radial collector wells. Radial collector wells involve shallower penetration than a single vertical well operating at the same discharge rate. These wells have two components: a circular vertical collector well of 3–5 meter diameter for storage of water and horizontally laid slotted radial drains close to the collector base to collect and carry groundwater from the aquifer to the collector (Figure 7). The collector wells have large yields under low pumping rates. Since the radial drains collect water from shallow depth, up-coning of saline water from lower depth is prevented. This arrangement of ground water withdrawal is known as "Sub Surface Fresh Water Skimming System" (SSFWSS). This system is suitable for water pumping in coastal sandy alluvium. According to a report by Raghu Babu *et al.*, (1999), 42 collector wells are operational at 15 places, namely Baptla (10), Vedullapalli (3), Reddypalem (7), Mutthaipalem (2), Herthivaripalem (1), Kavuru (1), Bavanamvari palem (1), Rambatlavari palem (1), Padison peta (4), Kajipalem (1), Dammanavaripalem (10), Manubroluvari palem (6), Kothapeta (2), Chinamatlapuri (1), and Akkayaplaem (1). On system can meet irrigation demand for 104 ha area. Experiences show that each system can supply sufficient good quality water to meet crop demands of 3 hectare area during Rabi using sprinklers or 4–5 hectares of plantation crops through drip irrigation system. The entire system may cost between Rs. 65,000 to Rs. 80,000 depending on installation depth of collector lines. The cost include Rs. 35,000 to 45,000 for installing SSFWSS, Rs. 18,000 for Oil engine/electric motor and Rs. 22,000 for sprinkler unit. Kamra (2001) has described some other skimming systems also for abstraction of fresh water floating over saline water zone in inland irrigated water logged area such as in Haryana, Punjab, Uttar Pradesh, Rajasthan etc.

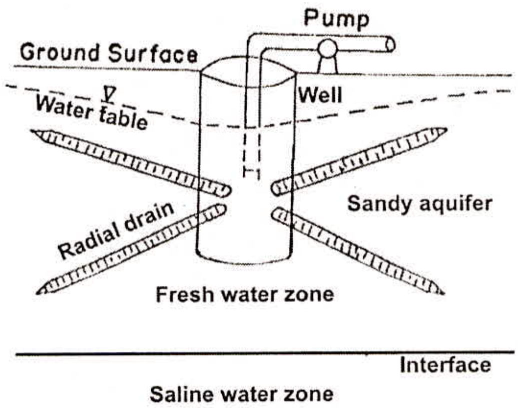


**Fig. 7:** Radial collector well

### Alternative Source

For water supplies to be sustainable, the rate at which water is withdrawn from ground water sources needs to be in balance with the rate of renewal or replenishment of these sources. Earlier the emphasis of waste water treatment was only on pollution control to safeguard the public health and prevention of environmental degradation through removal of biodegradable materials, nutrients and pathogens. But in the recent years the potential for recovering water from the waste water has been recognized. Technological advances in physical, chemical and biological processing of waste water led to the era of waste water reclamation, recycling and reuse water recycling and reuse, in conjunction with conservation, efficient management and use of existing water resources results in a sound and integrated approach to water resources management. Improved quality of recycled water can be a reliable source of water supply through out the year. Water supply in Singapore from recycled water is one such example. In many cities, waste water treatment plants are operating and many more are proposed. For example four treatment plants in Hyderabad city located at Langar houz, Mir Alam tank, Safilguda lake and Saroor Nagar lake are already functioning and some more are proposed. Usefulness of reclaimed water produced from treatment plants operating in Hyderabad city is visible. Domestic/ industrial waste waters are being treated and thereafter stored in to percolation tanks for ground water recharging through out the year. This water can be directly used for gardening and industrial uses. Table 2 presents comparison between pre and post treated qualities of water collected from Langer houz plant.

Desalinization of saline water provides other alternative source of water supply in coastal regions and other inland and islands regions having surface and sub-surface sources of saline water. This measure not only helps in mitigating water supply problem, but also reduces the stress on ground water system. For example, Alicante city of Spain derive major share of it's water supply from the desalinized sea water. In India also, a desalinations plant is operational in Lakshdweep. Another plant is proposed for the Chennai. According to a news report appeared in "Swatantra Varta" on 25th January, 2007, The Bhabha Atomic Research Centre(BARC) is working on a project in which excessive heat produced by Nuclear Reactors to be built in future will be used for desalinization of sea water. The BARC is already constructing desalinization plants at Kalpakam in Tamil Nadu, Trombay in Maharastra and Badmer in Rajsthan. This is a very bold and welcomed initiative towards mitigation of water scarcity.

**Table 2:** Water Quality Before and after Treatment; Date of Collection 29–09–2005

| *Parameter* | *Unit* | *Desired Value* | *Influent Quality* | *Effluent Quality* |
|---|---|---|---|---|
| pH | – | 6.5 to 8.5 | 7.04 | 7.10 |
| Total suspended solids | mq/l | <5 | 198 | 4 |
| Total nitrogen as N | mq/l | <10 | 23 | 4.48 |
| Nitrates as $NO_3$–N | mq/l | – | 4 | 9.0 |
| Total phosphorous as P | mq/l | <1 | 3.8 | 0.9 |
| COD | mq/l | <50 | 278 | 20 |
| $BOD_3$ at 27°C | | <5 | 130 | 3 |

(*Source:* Report of Sewage treatment plant at Langer houz, Hyderabad)

### Reduction in Ground Water Use

It is apparent that ground water crises are due to increase in water supply demand. Demand can be reduced by adopting many technical, social and economic measures. One such example could be the judiciously use of groundwater for irrigation by using many modern gadget like sprinklers and drip irrigation pipes. Irrigation by these gadgets requires much less quantity of water than that by flood irrigation. Experiences show that crop yield by use of these modern irrigation techniques is more than that by use of the conventional flooding technique. Hence, farmers should adopt modern irrigation techniques to minimise ground water uses. Cropping pattern should be changed in accordance to the availability of ground water. Sugarcane, wheat and paddy like high water consuming crops should not be allowed to grow in water scarcity areas of arid/semi-arid regions away from any river basin or canal command areas. Instead crops like Ragi, Jowar, Bajra, Corn, Ground nut etc should be encouraged (Radhakrishna, 2003) Medically, it has been proven that these food grains are more nutrient than wheat and rice. Essential quantity of wheat, rice and sugar can be transported in these regions from other region at relatively low cost of production.

### Mathematical Modeling

An understanding of the quantitative and qualitative changes in ground water system because of existing and proposed hydrologic stresses is prerequisite for their proper management. Mathematical models are used for assessing the future behaviour of ground water in terms of both quantity and quality in response to various operational or proposed development schemes related to recharging, pumping, waste disposal etc and in making judicious selection of a sustainable development scheme out of many proposed scheme without resorting to expensive field experiments. A 3D mathematical model is developed to simulate ground water flow in the Lower Palar Basin in Tamil Nadu (Senthilkumar and Elango, 2004). The aquifer modelling study was carried out for estimation of canal seepage to the ground water system in Ganga-Kali sub-basin, a part of central Ganga basin (Ala Eldin, *et al.,* 2006). Numerical mathematical models have been developed to simulate ground water flow and solute transport in and around Gujrat refinery, Vadodara (Gurunadha Rao, 2006a) Hindalco-belgaun works watershed (Gurunadha Rao, 2006b), Patancheru industrial area in Nakkavagu watershed near Hyderabad, (Gurunadha Rao, 2006c) Upper Palar basin, Tamilnadu (Gurunadha Rao, 2006d, Solid waste disposal site in Hyderabad (Gurunadha Rao *et al.,* 2006), Ravada watershed, A.P. (Vinod Rao and Gurunadha Rao, 2006), Lower Tandava River Basin in East Godavari district of A.P. (Vinod Rao and Gurunadha Rao, 2006), Wagarwadi Watershed in Parbhani District, Maharastra (Gore and Gurunadha Rao, 2006). Aquifer modelling and hydrogeologic system analysis have been carried out in Gadchandur in Maharastra (Singh, *et al.,* 2004). A new generation of analytical mathematical models have been developed by Manglik *et al.,* 2004 and Rai *et al.,* (2006) to simulate water table fluctuations in the presence of time varying recharge, pumping and seepage from any number of recharge basins, wells and leakage site of different dimensions. Time varying recharge and withdrawal have been approximated by use of linear elements of different lengths and slope depending on the nature of variations of these processes (Rai and Singh, 2005). Although application of analytical models are restricted to ground water flow in homogeneous flow systems having boundary of simple geometrical shapes, their application is fast and simple in comparison with numerical models. Analytical models are used for the analysis of the effects of various controlling parameters such as intensity and duration of recharge/withdrawal rates, shape, size and positions of recharge basin/wells, changes in aquifer parameters, pollutants spreading etc. on the state of ground water system.

## GOVERNANCE

Necessity of governance was felt because of failure of implementation of sustainable development and management schemes due to selfish motives of stakeholders which is a common thing in a democratic set up like in India. Governance encompasses political, social, economic and administrative systems that are in place to regulate the development and management of ground water resources and provisions of water related services at different levels (Rogers, 2006). Roles in the legislative and executive processes need to be clear. Each of the concerned institution must explain and take responsibility of what it does. The rules of the game need to be clearly spelled out, as should the consequences for violation of the rules, and have built-in arbitration enforcing mechanisms to ensure that satisfactory solution can still be reached when seemingly irreconcilable conflicts arise among the stakeholders. Policies must deliver what is needed on the basis of demand, clear objectives, an evaluation of future impact, and, where available, of past experience.

The Central Ground Water Board (CGWB) has been constituted as Central Ground Water Authority (CGWA) by the Ministry of Environment and Forest in the pursuance of the Hon'ble Supreme Court order with the mandate to regulate and control the groundwater development and management programs in the country. Its main objectives are:

- Regulation of indiscriminate boring and withdrawal of ground water in the country and to issue necessary regulatory directions with a view to preserve and protect the ground water.
- Notify an area where over-exploitation, sanity hazard, etc. have been observed.
- Resort to the authorized penal provisions against defaulter.

According to the Indian constitution water is a State subject. Therefore, planning and implementation of programs for sustainable development of ground water resources is their responsibility. For this purpose, many States have constituted their own Ground Water Authority (GWA) to achieve the objectives of sustainable ground water development outlined by Central Ground Water Authority. The state GWA can adopt those programs and policies which suit the requirements of the respective State.

## CONCLUSIONS

Deteriorating condition of ground water resources of the country indicates their inability to sustain the present level of water supply in pace with the growing demands unless they are properly managed under stipulated governance policies. The solution to this problem lies only in the sustainable development of ground water resources guided by appropriate management and governance measures. Therefore, to cope up with the present ground water crises, the national ground water policies should integrate appropriate management and governance measures to development activities to achieve the goal of sustainable development which stands for survivability of ground water resources and security of safe water supply. Emphasis should be given towards increasing ground water conservation facilities in large scale, economize the use of ground water resources by adopting modern techniques of irrigation, increasing the use of reclaimed water, change in crop pattern in accordance to the availability of water supply and other alternative sources of water supply. Presently the number of infrastructures for ground water recharging is much less than its withdrawal infrastructures. This gap should be minimized. This is possible only by active participation of the users, policy makers, political and administrative set-up. For this purpose, there is an urgent need for launching mass movement on the pattern of green revolution to implement and practice the sustainable development schemes of groundwater resources. For this purpose, services of local administrations which are in direct touch with the user communities such as Block Development Office in rural areas and Municipalities in urban areas should be availed. Here, it is worth to mention that Block Development Offices had played a decisive role in the success of green revolution. The same experiment can be repeated in case of sustainable development of ground water resources. These offices should have facilities to monitor quantity and quality of ground water resources and should be empowered to take penal action against the defaulter. No region should be considered safe unless its water quality is tested, both for shallow and deeper sources. People should be informed regularly through mass contact programs, electronic and print media about the existing quality of ground water and its effect on health and environment, measures to be taken to improve quantity and quality of ground water resources. These activities should be implemented and monitored by an expert of the subject attached to the local administrative offices.

## ACKNOWLEDGEMENTS

Author is grateful to Dr. V.P. Dimri, Director, National Geophysical Research Institue for his permission to publish this paper. Thanks are also due to Dr. S. Thiagarajan for his help in it's preparation.

## REFERENCES

Acharrya, S.K. (2005). "Arsenic levels in ground water from Quaternary alluvium in the Ganga Plain and the Bengal Basin, Indian subcontinent: insight into influence of stratigraphy". *Gondwana Res.*, 8, 1–12.

Acharrya, S.K. (2006). "Arsenic contaminated ground water from parts of Indian subcontinent: insight in to influence of geological settings and bio-geochemical processes". *Souvenir of the 31st annual convention of Indian Geophysical Union*, 6–12 November, Hyderabad, 21–39.

Acharrya, S.K., Lahiri, S., Raymahashay, B.C. and Bhowmik, A. (1993). "Arsenic toxicity of ground water in parts of the Bengal basin in India and Bangladesh: the role of Quaternary straightigraphy and Holocene sea level fluctuation". *Environ. Geol.*, 39, 1127–1137.

Acharrya, S.K., Shah, B.A. Ashiya, I.D. and Pandey, Y. (2005). "Arsenic contamination in ground water from parts of Ambagarh-Chowki Block, Chhatisgarh, India: source and release mechanism ". *Envi. Geol.*, 49, 148–158.

Acharya, S.K. and Shah, B.A. (2007). "Arsenic contaminated ground water from parts of Damodar fan delta and west of Bhagirathi River, west Bengal, India". *Env. Geol.*, 52, 489–502.

Ala Eldin M.E.H, Umar, R. and Gurunadha Rao, V.V.S. (2006). "Estimation of canal seepage to the groundwater system in Ganga-Kali sub-basin, a part of Central Ganga Basin". *In: Groundwater flow and mass transport modeling* (Ed. T. Vinoda Rao*),* Allied Publ., New Delhi, 186–199.

Arya, A., Ansari, M.M., Tribhuwan and Sinha, R.S. (2006). "Ground water governance in Uttar Pradesh-issues, initiatives and actions". In *Groundwater Governance (appended paper;* Eds.: S. Romani, *et al.*), Capital Publ. Comp., New Delhi, pp. 1–9.

Chakraborti, D.K., Biswas, B.K., Roychowdhury, T., Basu, G.K., Mandal, B.K., Chowdhury, U.K., Mukherjee, S.C., Gupta, J.P., Chowdhury, S.R. and Rathore, K.C. (1999). "Arsenic ground water contamination and suffering of people in Rajnandgaon district, Madhy Pradesh". *Current Sci*., 77, 502–505.

CSE. (2005). "Nctar to poison", Cntre for Science and Environment, New Delhi, pp. 3–10.

Dewandel, B., Gandolfi, J-M, Zaidi, F.K., Ahamed, S. and Subrahmanyam, K. (2007). "A decision support tool with variable agro-climatic scenarios for sustainable ground water management in semi-arid hard rock areas". *Current Sci*, 92(8), 1093–1102.

Dickerson, D. and Callahan, T. (2006). "Groundwater is not an educational priority". *Groundwater*, 44, 323.

Gale, I.N., Macdonald, D.M.J., Callow, R.C., Newman, I., Moench, M., Kulkarni, H., Mudrakaratha, S. and Palanasami, K. (2006). "Managing aquifer recharge: an assessment of its role and effective in watershed management". *Report of DFID KAR project R8169,* British Geological Survey, Keyworth, Nottinghan, pp. 77.

Ghosh, N.C. and Sharma, A. (2006)."Groundwater governance: few pertinent issues relating to availability and possible threat". In*: Groundwater Governance (*Eds. S. Romani *et al.),* Capital Publ. Co., New Delhi, 297–310.

Gore, K.P. and Gurunadha Rao, V.V.S. (2006). "Assessment of impact of water harvesting structures on groundwater resources in Wagarwadi watershed, Parbhani District, Maharashtra". In: *Groundwater flow and mass transport modeling* (Ed. T. Vinoda Rao), Allied Publ., New Delhi, 200–205.

Gupta, S.K., Deshpande, R.D., Agarwal, M. and Raval, B.R. (2005). "Origin of high fluoride in ground water in the north Gujrat-Cambay region, India". *Hydrogeol. J*., 13, 596–605.

Gurunadha Rao, V.V.S. (2006a). "Assessment of ground water contamination around Gujarat Refinery, Vadodara". In *Ground water flow and mass transport modeling* (Ed. T. Vinod Rao). Allied Publ., New Delhi, 242–249.

Gurunadha Rao, V.V.S. (2006b) "Impact of red mud stacking on groundwater regime in the HINDALCO-Belgaum works Watershed, Karnataka". In: *Groundwater flow and mass transport modeling* (Ed. T. Vinoda Rao), Allied Publ., New Delhi, 250–255.

Gurunadha Rao, V.V.S. (2006c). "Prediction of groundwater contamination migration from Patancheru IDA in Nakkavagu Watershed, A.P". In: *Groundwater flow and mass transport modeling* (Ed. T. Vinoda Rao), Allied Publ., New Delhi, 267–275.

Gurunadha Rao, V.V.S. (2006d). "Groundwater pollution due to tannery effluents in Upper Palar basin, Tamilnadu". In: *Groundwater flow and mass transport modeling* (Ed. T. Vinoda Rao), Allied Publ., New Delhi, 276–280.

Gurunadha Rao, V.V.S., Sankaran, S. and Mahesh Kumar K. (2006). "Assessment of likely impact of hazardous solid waste disposal site (Hyderabad - TSDF) on groundwater: Mass transport modeling". In: *Groundwater flow and mass transport modeling* (Ed. T. Vinoda Rao), Allied Publ., New Delhi, 281–287.

Hooja, R., Shriniwas, V. and Sharma, G. (1995). "Water logging and salinity problems in IGNP, Rajsthan". Proc. natl. symp on *Reclamation and management of water logged saline soils* (Eds. K.V.G.K. Rao *et al.* (Eds.), Hissar, 141–159.

Israil, M., Al-hadithi, M. and Singhal, D.C. (2006). "Application of a resistivity survey and Geographical Information System (GIS) analysis for hydrogeological zoning of a piedmont area, Himalayan foothill region". *Hdrogeol. Jour*., 14, 753–759.

Kamra, S.K. (2001). "Skimming structures for abstracting fresh water overlying saline ground water"..Proc.of the first NATP workshop on "*Technologies for skimming and recharging fresh water in saline ground water region*; 9–10 August, Bapatala, A.P., 1–11.

Kulkarni, H., Vijay Shankar, P.S., Deolankar, S.B. and Shah, M. (2004). "Ground water demand management at local scale in rural areas of India: a strategy to ensure water well sustainability based on aquifer diffusivity and community participation". *Hydrogeol. Jour*., 12, 184–196.

Madhnure, P., Sirsikar, D.Y., Tiwari, A.N., Rajan, B. and Malpe, D.B. (2007). "Occurrence of fluoride in the ground waters of Pandharkawada area, Yavatmal district, Maharastra, India". *Current Sci*., 92(5), 675–678.

Mandal, B.K., Roy Choudhury, T., Samanta, G., Basu, G.K., Chowdhury, P.P., Chandra, C.R., Lodh, D., Karan, N.K. Dhar, R.K., Tamili, D.K., Das, D., Saha, K.C. and Chakroborti, D. (1996)." Arsenic in ground water in seven district of West Bengal, India—the biggest arsenic calamity in the world". *Current. Sci.*, 70, 976–986.

Manglik, A., Rai, S.N. and Singh, V.S. (2004). "Modelling of aquifer response to time varying recharge and pumping from multiple basins and wells". *Journal of Hydrol*. 292, 23–29.

Muralidharan, D. Deshmukh, S.D., Rangrajan, R., Satyanarayana, U., Udaykumar, C.M., Shankar, G.B.K., Andrade, R., Janakiraman, L, Mohan Reddy, A. and Sathiah, B. (2005/06). "Water harvesting and artificial recharge: Wailapally watershed in Nalgonda district representing granites terrain". *NGRI annual report*, 44–45.

Muralidharan, D., Andrade, R. and Rangarajan, R. (2007). "Evaluation of check dam recharge through water table response in ponding area". *Current Sci.*, 1350–1352.

Naik, P.K. and Awasthi, A.K. (2003). "Ground water resources assessment of the Koyana river basin, India". *Hydrogeology Jour.*, 11, 582–594.

Najeeb, K. Md. (2007). "Integrated water management schemes for Lakshadweep islands". *J. Geol. Soc. of India*, 69, 1005–1010.

Narashimha Prasad, N.B., Shivraj, P.V. and Jegatheesan, K.S. (2007). "Evaluation of ground water development prospect in Kadalundi river basin". *J. Geol. Soc.of India*, 69, 1103–1110.

Palanisami, K., Thangrajan, M. and Sinha, A.K.(eds) (2005). "Ground water flow and mass transport modeling for assessment and management of aquifers". *Lecture note volume of a training course;* 13–30 October, Coimbatore, p. 470.

Radhakrishna, B. P. (2003). "Linking of major rivers of India – Bane or boon". *Current. Sci.*, 84(11), 1390–1394.

Raghu Babu, M., Prasad, P.R.K, Subaiah, G.V., Khan, M. and Minhas, P.S. (1999). "Subsurface fresh water skimming system. : Improved Doruvu technology", *Bulletin no. 1/99*, CSSRI, Karnal, pp. 19

Rai, S.N. and Singh, V.P. (2005). "Artificial recharge of unconfined aquifer". In: *Water Encyclopedia-Groundwater* (Eds.: Jay Lehr, Jack Keeley, Janet Lehr and Thomas B. Kingery III), John Wiley & Sons, 11–17.

Rai, S.N. Manglik, A. and Singh, V.S. (2006). "Water table fluctuation owing to time varying recharge, pumping and leakage". *Jour. of Hydrology*, 324, 350–358.

Rai, S.N. (ed.) (2004). *Role of mathematical modeling in groundwater resources management*, Lecture notes volume of a DST training course, Hyderabad, pp. 448.

Raju, N.J., Reddy, T.V.K. and Munirathanam, P. (2006). "Subsurface dams to harvest rain water—a case study of the Swarnamukhi River Basin, Southern India". *Hydrogeol. J.*, 14, 526–531.

Rogers, P.P. (2006). "Water governance, water security, and water sustainability". In: *Water crisis: myth or reality* (Eds.: P.P. Rogers, M.R. Llmas, and L. Martinez Cortina), Taylor and Francis/Balkema, Great Britain, 3–36.

Romani, S. (2005). "Groundwater management—a key for sustainability". In: Lecture notes volume of DST course on *Numerical Simulation of groundwater flow and mass transport for effective management of aquifers* (Eds. :D.S. Suresh Babu *et al.*), 413–424.

Romani, S. (2006). "Groundwater management—emerging challenges". In: *Groundwater Governance* (Eds. S. Romani *et al.*), Capital Publ. Co., New Delhi, 1–18.

Samadder, R.K., Kumar, S. and Gupta, R.P. (2007). "Conjunctive use of well-log and remote sensing data for interpreting shallow aquifer geometry". *Jour. Geol. Soc. India*, 925–932.

Saxena,V. K. and Ahmed, S. (2003). "Inferring the chemical parameters for the dissolution of fluoride in groundwater". *Envi. Geol.*, 43, 731–736.

Saxena,V. K., Singh, V.S., Mondal, N.C. and Jain, S.C. (2003). "Use of hydrochemical parameters for the identification of fresh groundwater resources, Potharlanka Island, India". *Envi. Geol.*, 44, 516–521.

Senthil Kumar, M. and Elango, L. (2004). "Three-dimensional mathematical model to simulate ground water flow in the lower Palar Basin, Southern India". *Hydrogeol. Jour.*, 197–208.

Singh, A.K. (2006). "Chemistry of arsenic in ground water of Ganges-Brahmputra basin". *Current Sci*, 91(5), 599–606.

Singh, D.A.H. and Lawrence, J. F. (2007). " Groundwater quality assessment of shallow aquifer using Geographical Information System in part of Chennai City, Tamil Nadu". *Jour. Geol. Soc. India,* 1067–1076.

Singh, V.S. and Gupta, C.P. (1999). "Feasibility of ground water withdrawal in coral island". *Hydrol. Sci. Jour.*, 44, 173–182.

Singh, V.S., Maurya, A.K. and Singh, A.K. (2004). "Aquifer modeling and hydrogeologic system analysis in limestone terrain, Gadchandur, Maharastra". *NGRI-04-GW-460.*

Sreedevi, P.D., Subrahmanyam, K. and Ahmed, S. (2005). "The significance of morphometric analysis for obtaining groundwater potential zones in a structurally controlled terrain". *Envi. Geol.*, 47, 412–420.

Sreedevi, P.D., Subrahmanyam, K. and Ahmed., S. (2003). "Integrated approach for delineating potential zones to explore for ground water in the Pageru River basin, Cuddapah district, Andra Pradesh, India". *Hydrogeol. Jour.*, 534–543.

Subba Rao, N. (2003). "Groundwater prospecting and management in an agro-based rural environment of crystalline terrain of India". *Envi. Geol.*, 43, 419–431.

Subba Rao, N. and Devadas, D.J. (2003). "Fluoride incidence in groundwater in an area of Peninsular India". *Envi.Geol.*, 45, 243–251.

Subhash Chandra, Rao, V.A., Krisnamurthy, N.S., Dutta, S. and Ahmed S. (2006). "Integrated studies for characterization of lineaments to locate the ground water potential zones in hard rock region of Karnataka, India'. *Hydrogeol. Jour.*, 14, 767–776.

Sujatha, A. (2003). "Fluoride levels in the groundwater of the south-eastern part of Ranga Reddy district, Andhra Pradesh, India". *Envi. Geol.*, 44, 587–591.

Sundaresan, I. (2006). "Groundwater perspectives of small islands-Lakshadweep islands, India". In: *Groundwater Governance* (Eds. S. Romani *et al.*), Capital Publ. Co., New Delhi, 125–132.

Suresh Babu, D.S., Thangrajan, M. and Sinha, A.K. (Eds) (2005). *Numerical simulation of ground water flow and mass transport for effective management of aquifers*; Lecture notes volume of a training course, 1–20 August, Thiruvananthpuram, pp. 534.

Susheela, A.K. (1999). "Fluorosis management programme in India". *Current Sci.,* 77(10), 1250–1256.

Swatantra Varta (2007). "Atomic reactor will make saline sea water potable". 25th January, Published from Hyderabad, p. 2.

Umar, R. (2006). "Hydrogeological environment and ground water occurrences of the alluvial aquifers in parts of the Central Ganga Plain, Uttar Pradesh, India". *Hydrogeology Jour.*, 14, 969–978.

Umrikar, B. and Thigale, S. (2007). "Sea water ingress study along the Guhagar coast of Maharashtra with reference to the harmonious water resource development". *Jour. Geol. Soc. India*, 933–942.

Varma, R.A. (2005). "Characteristics of coral island aquifer systems – An example of Lakshadweep", In: *Numerical simulation of groundwater flow and mass transport for effective management of aquifers* (Eds. D.S. Suresh Babu *et al.*), 331–362.

Vinoda Rao, T. and Gurunadha Rao, V.V.S. (2006). "Groundwater recharge process model of Ravada watershed, Andhra Pradesh, India.", In: *Groundwater flow and mass transport modeling* (Ed. T. Vinoda Rao), Allied Publ., New Delhi, 314–321.

Vinoda Rao, T. and Gurunadha Rao, V.V.S. (2006). "Mathematical model of Lower Tandav River basin, East Godavari District, Andhra Pradesh, India". In: *Ground water flow and mass transport modeling* (Ed. T. Vinoda Rao), Allied Publ., New Delhi, 322–329.