MANAGEMENT OF GROUNDWATER RESOURCES

Mathew K. Jose
Scientist D, National Institute of Hydrology, Regional Centre, Belgaum

INTRODUCTION

Despite the importance water assumes in overall human development, it is among the most mismanaged resources, especially in the context of developing countries like India. Neglect of this important resource can result in severe food security problems at the household level and environmental degradation of enormous proportions. Water resources problems, in general, relate both to quantity and, increasingly, to quality. Although the average annual rainfall is high in most parts of the country, its distribution in time and space is highly variable. Rural populations still have no reasonable access to safe water supplies, and usage of contaminated surface water causes a variety of water related diseases. In this context, ground water plays an important role with its unique features like: good natural quality, dependability, wide distribution, and easy-for-development. Ground water is particularly important as a source of drinking water in rural areas, where infrastructure for water treating/ supply does not exist.

It is estimated that more than half the world's population relies on ground water as a drinking water supply. Nevertheless, the supply of ground water is not limitless, nor is it protected from degradation. Growth in industrial, agricultural, and municipal sectors has resulted in increasing utilisation of water, which has caused considerable pressure on the development and sustenance of groundwater reservoirs. Ever increasing dependence on groundwater for various uses has not only triggered environmental hazards like land subsidence, and seawater intrusion in coastal aquifers but depletion of many aquifers too. Groundwater quality is being increasingly threatened by leachates of industrial, agricultural, and urban wastes. Once pollution has entered the subsurface environment, it may remain concealed for many years, becoming dispersed over wide areas and rendering groundwater supplies unsuitable for consumption/ uses.

In the long run, the most effective means for assuring a predictable supply of clean ground water is through the protection and careful management of this valuable resource. Management of ground water resources requires effective institutional arrangements fostered with legal, legislative and community support and needs long-term planning and process. Evidently, it is important to understand the existing aquifer scenarios, the practices and constraints, the problems, feasible solutions/ alternatives, management strategies as well as management tools for adopting a good management approach. The write up has been fashioned by keeping this in view, and attempt is made to include relevant aspects on contemporary developments in the subject area.

Management Scenario in India

In India, access to water, surface or sub-surface, is governed by riparian laws. Though the state is the sole owner and takes the responsibility of water resources development, its role is limited to surface systems only thus leaving the sub-surface systems to private development. Even within the surface systems canal irrigation has been favoured the most, causing neglect of minor systems such as tanks/ ponds. Interestingly, most of the tanks are located in the fragile resource regions, where these surface water bodies can promote percolation recharge to aquifers beneath.

On the other hand, no attempts are being made to strengthen the natural resource storage in terms of replenishing the aquifers. Hitherto, groundwater policies have tended towards encouraging over-exploitation. The existing policies are in the nature of providing incentives for groundwater development such as subsidised credit, and for groundwater exploitation such as subsidised power. The situation of over-extraction and the resultant environmental degradation is a consequence of lack of appropriate and adequate policies/ policy failure for managing the subsurface water resources. While these policies helped in promoting groundwater development in the regions where groundwater development was below potential, they have led to over-exploitation of the resource in fragile resource regions.

In the country, groundwater development and management is mainly left to the private sector and left out of the policy purview, whereas it calls for special policy attention. Groundwater mismanagement could cause irreversible environmental damage. The resulting negative externalities impose enormous social costs. Though there are regulatory mechanisms to control over-exploitation of groundwater, they are grossly ineffective. Recent initiatives in watershed development programmes address this aspect indirectly, as it integrates water bodies development with the watershed development though in a limited way. These initiatives as well as some of the state-level/local initiatives attempt to address the recharge issues rather than management issues. Some States are introducing legislation (like: Water, Land and Trees Act of 2001, GoAP) to check the over-exploitation of water resources. But, many a time such regulations fall short of addressing the equity issues.

In this context, the experience of some NGOs in the country in participatory management of water systems can be looked into. Similarly, the experiences and success stories of other countries (e.g.: South Africa) can also shed some light into viable strategies. Groundwater management approach to the development of groundwater needs to be specifically addressed. Throughout the world, this resource is poorly addressed, and development has, as a result, often resulted in unreliable supply, under- and over-use and damage to the resource. Where groundwater users are in conflict or the environment is threatened, sensitive areas may be declared where notice of intention to drill will be required. Groundwater use must be carried out in the context of an adequate catchment management plan, based on an understanding of the sustainable yield of the local groundwater sources. In sensitive areas, approval of drilling may thus include operating conditions to protect other users as well as the resource itself.

There are no significant policies so far that address the equity and management aspects of groundwater. Though there are regulations on groundwater exploitation, they appear to be ineffective. A viable groundwater management policy should preferably comprise of: a demand-side management approach, an economic approach, an efficient approach, an institutional approach, a decentralised approach and an integrated approach. That is, our water policies should aim at integrating all sources of water in the regional context rather than treating them in isolation.

GROUNDWATER ISSUES

Most groundwater problems are caused by *contamination, overexploitation*, or a combination of these two. An understanding of the nature and extent of such problems essentially forms part of a sustainable management approach.

Contamination:

Basically, all activities carried out on the land surface have the potential to pollute ground water, whether associated with urban, industrial or agricultural land uses. The full extent of damage to aquifers is unknown, but problems are universal and growing. Large-scale, concentrated sources of pollution, such as industrial discharges, landfills and subsurface injection of chemical and hazardous wastes, are obvious sources of groundwater contamination. These point sources of pollution are relatively easy to identify. A much more widespread and pernicious problem is the contamination of groundwater by innumerable dispersed sources such as leaching of agrochemicals and animal wastes in agricultural areas, subsurface discharges from latrines and septic systems in residential areas, and the infiltration of polluted urban runoff in cities. The only effective method for the control of dispersed sources of pollution is through the integration of land use and water management.

Over-exploitation:

In the past, ground water had often been viewed as either inexhaustible or as an extractable resource. Although ground water is a renewable resource, few aquifers can withstand enormous extraction rates indefinitely. Over exploitation of groundwater resources can have severe environmental and social impacts. The philosophy of sustainable development dictates that the rate of groundwater extraction from a given aquifer should not exceed the recharge rate. When groundwater withdrawals exceed the average recharge rates for extended periods of time, aquifers become depleted and many undesirable consequences may ensue, including the drying up of wells, salt water intrusion in coastal aquifers, and land subsidence which is irreversible.

Salt water intrusion:

Salt water intrusion is a common problem in coastal areas. Along the coastlines, unconfined aquifers are usually characterized by an upper zone of fresh ground water that is underlain by denser, saline ground water. The interface between fresh and saline ground water becomes deeper with increasing distance from the sea, forming a wedge-shaped configuration. On small islands, ground water typically occurs as a thin fresh water lens, floating on top of deeper saline ground water. When a well is installed too close to this freshwater-saltwater interface, or is excessively pumped, salt water may be drawn up into the fresh part of the aquifer, rendering it unsuitable for use.

Land subsidence:
Land subsidence occurs when ground water is pumped from a confined sand and gravel aquifer which is overlain by highly compressible clays. As pressures within the aquifer drop, the aquifer materials and the overlying clays gradually become compacted. Land subsidence reflects the consolidation of these materials and may cause structural damage to buildings, roads and other infrastructure.

Salinisation / waterlogging:
Salinisation / waterlogging problems are also known to exist in the northern parts of the country. Irrigated (surface/ ground water) agriculture is practiced especially in arid and semi-arid regions of the country. The applied water tends to evaporate and, depending on the source, will leave behind salts that were originally dissolved in the water. Waterlogging occurs when the water applied builds up in the shallow water table, reaching the root zone, and eventually makes the soil too wet for crops to thrive. The solution to these problems is linked to efficient irrigation water management.

TECHNOLOGICAL SOLUTIONS

Technological approaches to groundwater contamination problems generally involve some combination of source control, aquifer treatment and/or water supply treatment. Some examples of technological measures used to control pollution sources include the lining and capping of landfills, reduction and treatment of industrial and municipal wastes, and construction of sanitary and storm sewers. Once pollution has entered an aquifer, steps can be taken either to isolate the contaminated portion of the aquifer from uncontaminated areas, or to remove and treat the contaminated ground water. Isolation techniques involve manipulation of groundwater flow patterns (by changing pumping rates and/or by creating subsurface hydraulic barriers) within the aquifer, such that contaminated ground water does not flow in the direction of wells. Groundwater problems associated with over exploitation can better be resolved by reducing the overall extraction rates, or redistributing the points of extraction or by augmenting natural recharge through artificial means. Retroactive solutions to problems of groundwater overexploitation and pollution are technologically demanding, extremely expensive and may require many years, if not decades, to become effective (or ineffective!).

GROUNDWATER MANAGEMENT APPROACH

The UN Charter on groundwater management states that: "Governments should formulate and adopt a long-term policy to protect ground water by preventing pollution and overuse. This policy should be comprehensive and implemented at all appropriate levels. It should be consistent with other water-management policies and be duly taken into account in other sectorial policies".

Consequently, as per the UN Charter, a groundwater management strategy should aim at: (i) the sustainable use of ground water and preservation of its quality; (ii) incorporation of groundwater protection plans into the general environmental protection planning; and (iii) protection measures towards prevention of ground-water pollution and over-use. Such protection measures include, inter alia, monitoring of ground waters, development of aquifer vulnerability maps, regulations for industry and waste disposal sites paying due account to ground-water protection considerations, geo-ecological assessment of the impact of industrial and agricultural activities on ground waters, and zoning of ground-water protection areas.

The sustainable management of groundwater resources implies a balance between groundwater development and groundwater protection, and is based on a judicious mix of scientific under standing, informed planning and effective action. The attitude toward, need for and degree of groundwater management varies considerably from region to region. In our country, however, the stakes are high due to the prevalence of water borne diseases in surface waters and the prohibitive costs of remediation. Management can be effectively carried out at the national, regional or local levels. In countries like India, with geologically complex land areas, this function is delegated to State or local bodies, whereas the national agencies typically set guidelines/ standards and monitor the overall situation. The interdependent processes involved in a groundwater management approach are:

(i) the collection and analysis of hydrogeological and other pertinent information;
(ii) the development of a groundwater management plan which articulates priorities, goals and responsibilities; and
(iii) the implementation of this plan through a series of legislative, institutional, regulatory and participatory measures.

GROUNDWATER PLANNING AND MANAGEMENT

Effective groundwater management is based on the setting of realistic priorities, policies and objectives. What are the desired goals of groundwater management? Development of ground water for rural water supplies? The protection of water quality? What degree of protection is practicable? Where efforts should be focused first? The answers to these and related questions may vary widely, depending on such factors as the availability and demand for ground water, the threats, and economic development. The rational management of groundwater resources is difficult without a basic understanding of the distribution and yield of aquifers, their vulnerability to pollution and over draft, and some knowledge of the existing and potential threats to the resource.

Since ground water and surface water are integrally linked, groundwater planning should ideally take place within the broader context of integrated water resources planning. Planning should be based on the natural boundaries of the resource. Aquifers rarely respect administrative or national boundaries. In cases where aquifers cross international boundaries, treaties or other international conventions may be required. Groundwater planning should reflect a coordinated effort between agencies involved in all aspects of ground water. If the goals of groundwater protection and groundwater development agencies are at odds, effective implementation is unlikely. Given that the full protection of all groundwater resources is rarely practicable, priorities must be carefully targeted. Public input and feedback from all sectors of the community is of critical importance in resource management. If public input is not sought early in the planning process, and the plan does not reflect local needs and realities, local cooperation is unlikely. And without the cooperation of individuals, the best planned and technically most advanced efforts will not succeed. Plans should be regularly reviewed and revised to reflect changing needs and up-to-date information. Ultimately, a management plan should define the steps required to achieve the stated goals, identify the entities responsible for each action and establish a time frame for action and review.

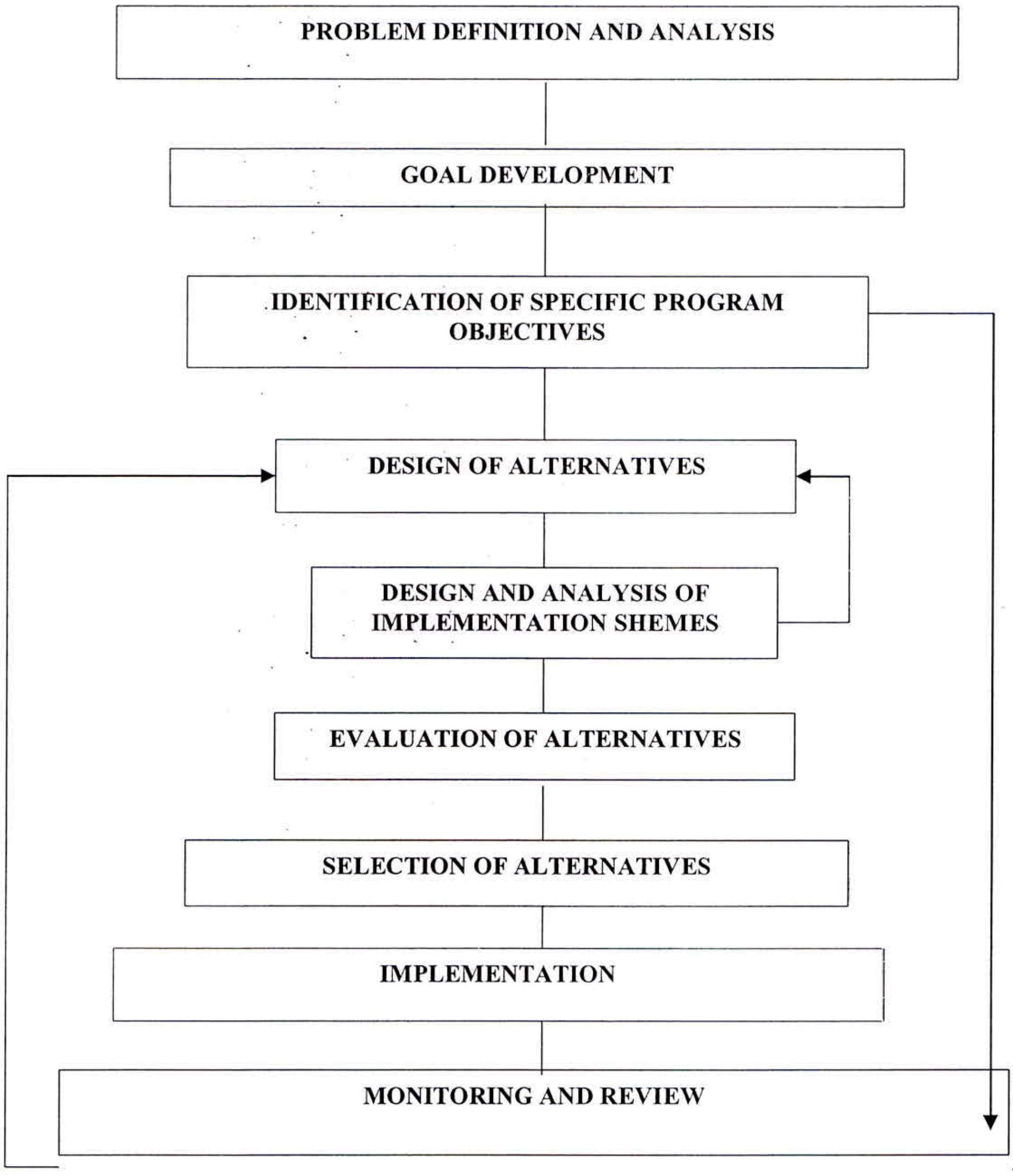

Figure 1: Scheme of an idealised groundwater management program

Regulatory Mechanisms for Groundwater Protection

The usual approach to groundwater protection includes the enactment of national groundwater legislation, the establishment of implementing agencies and the adoption of a variety of regulatory and non regulatory mechanisms. No single recipe will guarantee the successful protection of groundwater resources, however solutions must be tailored to fit the physical characteristics of specific aquifers as well as the goals and resources of a country. The use of legislation as a means of controlling access to water resources dates back to antiquity. In some countries, ground water is incorporated within the context of a basic Water Act which addresses all water resources. In other countries, groundwater protection is achieved to some degree through a wide range of regulations which regulate specific aspects of ground water, such as extraction rates, public health and environmental protection.

To cite a few examples: in India, matters related to water resources are basically handled at the state level. Therefore, primary responsibility for planning and implementation of groundwater development/ management programmes rests with the state governments. At the national level, the Central Ground Water Board/ Authority (Ministry of Water Resources) is responsible for coordinating work related to monitoring surveys, assessment, development, management and regulation of groundwater resources. Similarly, in the US, national legislation mandate the protection of ground water, authorizing the U.S. Environmental Protection Agency (EPA) to protect all water resources. However, much of the responsibility for groundwater protection is delegated to individual states, many of which in turn delegate responsibilities to counties, towns and municipalities. Under the EPA's Wellhead Protection Program, each state is required to design and implement a plan to protect public groundwater supplies from contamination within a framework of EPA criteria. However, groundwater legislation in Thailand brought groundwater activities within designated groundwater areas under government control. Within these areas, permits are required for the drilling of wells, extraction of ground water and subsurface disposal of liquid wastes. Recently, the European Union Water Framework Directive (WFD2000) defines environmental objectives for surface water, groundwater and protected areas. Within this framework, a member country shall implement measures to prevent or limit input of pollutants into aquifers and to prevent deterioration of the status of all groundwater bodies, shall ensure a balance between abstraction and recharge of groundwater, and shall implement steps to reverse any significant and sustained upward trend in the concentration of any pollutant.

A fundamental issue in groundwater legislation is that of ownership. Under many traditional systems of law, property owners were historically entitled to the full use of all resources above and below their land, including ground water. Private ownership of groundwater resources is still the case in many countries. However, ownership does not automatically convey the right to pollute or over exploit the water resources. "Water is the basis of life; it is the gift of nature; it belongs to all living beings on earth. It is not a private property but a common resource for the sustenance of all" (World Water Conference, 2004). In some countries (eg: Indonesia, Australia, Peru) ground water is considered to be a public good, either through legal tradition or through legislation.

Groundwater Protection Areas

Groundwater protection strategies include both quantitative and qualitative considerations: assess aquifer vulnerability and weigh the risks. The vulnerability of a given aquifer to contamination is dependent on a number of factors, including soil type and thickness, the presence or absence of protective clays layers, depth to ground water and aquifer type and permeability. The level of protection needed varies with aquifer vulnerability. Risk assessment balances aquifer vulnerability with actual or potential threats to the groundwater system and can be a useful tool for setting protection priorities. For example, a highly vulnerable aquifer may not require immediate action if it is located in the middle of a nature reserve. However, even a deep, confined aquifer with low natural vulnerability may be at considerable risk if wastes are routinely injected into the subsurface.

Two important functions are served by establishing groundwater protection areas. First, since the protection of all groundwater resources, everywhere, is rarely practicable, the establishment of protection areas is a useful means for setting priorities and focusing efforts on the protection of important aquifers and public water supplies. Second, scientifically determined groundwater protection areas can define the land area which contributes recharge to the resource. Since most groundwater contaminants originate from activities within the recharge area, it is necessary to know the location and extent of this area to effectively control land use activities. Groundwater protection areas can be established for entire aquifers (aquifer protection areas) or for specific water supplies, usually municipal well fields (wellhead protection areas). A pumping well captures ground water, from a subsection of the aquifer, the dimensions of which depend on the well depth, pumping rate and physical properties of the aquifer. In unconfined aquifers, as recharge percolates through the overland area, it carries with it a variety of contaminants leached from the soil which overlie the aquifer.

Well Head Protection Areas

One effective method for protecting the quality of public water supplies is through the delineation and protection of the land that contributes recharge to a specific well. This critical area is termed as the well head protection area (WHPA). Here, it is worth to mention about The Well Head Protection programme established in 1986, and monitored by US Environmental Protection Agency, in the US. To identify WHPAs, methods range from the delineation of circles of arbitrary diameters around a wellhead, to complex modelling procedures through which the velocity and direction of groundwater flow as well as travel time of certain contaminants may be visualized. Aquifer protection area covers the entire recharge area. Different approaches may be required to protect wells in distinct aquifer types. For example, water pumped from a confined aquifer (or a well in a hard rock region) may have originated far from the well site. Therefore, protecting the area in the immediate vicinity of that well may have no appreciable impact on water quality. Further, groundwater flow in fractured bedrock aquifers is difficult to trace, requiring sophisticated delineation methods and/or the protection of very large areas. Once WHPAs have been delineated, a variety of land use controls can be used to limit activities that could potentially contaminate the water supply such as, prohibition of certain land uses (e.g. landfills, industries), sewage discharge, limitations on residential densities and any other appropriate controls.

Where an aquifer is at risk due to over exploitation, the extraction of ground water can be controlled to some degree through regulatory means . Environmental impact assessment is a valuable process for evaluating potential impacts of large projects on groundwater resources, as well as for evaluating the long term effects of groundwater extraction on aquifers and surface water bodies. Within groundwater protection areas, specific land use regulations are often enacted which include restriction of certain activities like clearing of natural vegetation etc. Besides monitoring of groundwater resources is a critical component for effective protection.

GROUNDWATER MANAGEMENT-OPTIMIZATION MODELLING

The development of groundwater simulation models in the seventies provided groundwater planner with quantitative techniques for analysing alternative management strategies. Basically, groundwater models are physically founded mathematical models derived from Darcy's law and the law of conservation of mass. Costs and benefits have been developed for each management alternative so that optimization techniques could be applied to groundwater systems. Thus, groundwater optimization models provide optimal groundwater planning or design alternatives in the context of each system's objectives and constraints.

Optimization models aid decision making in groundwater management by incorporating numerical groundwater flow/ transport models into mathematical programming formulations. The advantage of this approach is that the methods allow expression of management goals explicitly in terms of objective functions that are to be optimized. Since in groundwater management problems usually several objectives are taken into account at the same time, these problems are stated as multiple objectives-optimization problems.

Several groundwater management models have been developed and reported in the literature. They combine optimization techniques with numerical groundwater flow models as well as approaches involving use of transport equation to control water quality. There are a variety of important areas where groundwater management models have been applied such as: water supply management of large regional aquifers, optimization of pumping and infiltration rates, for finding optimal locations of wells, as well as in groundwater quality problems to aquifer restoration design by combining it with a transport simulation model. Further, such optimization models are applicable in the case of conjunctive use of groundwater and surface water for agriculture.

In order to ensure a hydrologically feasible solution, a groundwater model can be included in the set of constraints of the optimization problem similar to other constraints (technical, economic, social or environmental). Well-established linear or nonlinear techniques furnish the decision-maker with the optimal management scheme that satisfies all the constraints and achieves the best value for the objective function. Since the evaluation of groundwater management schemes is inseparable from the decision-makers' judgment, it is necessary to couple groundwater model with the decision aid model, which takes into account the preferences expressed as multiple criteria.

In optimization models, the constraints define a feasible domain in the decision space. Depending on the kind of management problem, the constraints can express restrictions placed on the piezometric heads at any point of the aquifer, the Darcy velocity directions and magnitudes, the hydraulic gradient directions and magnitudes, the pumping rates at any preselected potential well location, and water supply demand on the specified zones or the whole aquifer. In general, any constraints which can be formulated as a function of optimization variables can be incorporated into the management model (for example, budgetary limits on investment or operating costs). For a better appreciation, a specimen set of constraints that could be used in a management optimization model may appear like the following:

(i) The constraints on the piezometric heads are in the form of minimum allowable head to serve for protecting an ecosystem or to keep the water level above a pump elevation or in the form of a maximum admissible value to prevent flooding or to maintain groundwater levels below specified elevations in dewatering problems.

(ii) Darcy-velocity direction and magnitude constraints can be used, for example, to limit saltwater intrusion or to ensure hydraulic containment of contaminant plumes or their desired migration.

(iii) The hydraulic gradient direction and magnitude constraints can be used together with the velocity constraints.

(iv) The constraints on the pumping rates can be used to prescribe a minimum supply demand at a given point or take into account well capacity restrictions.

(v) The constraint of minimal demands on the specified zones or on the whole aquifer are can be used in water supply management.

A "good management" in optimization parlance is conditioned on the management objectives expressed by the decision-maker. They can relate, for example, to maximization of water production from the aquifer, minimization of investment and/ or operational costs of water supply, minimization of the sum of the heads at all pumping locations for maintaining maximum aquifer potential, minimization of total deficit, or minimization of risk related to poorly forecasted groundwater resources etc. In a groundwater management plan, since multiple criteria intervene in determining the final scheme, there is always a compromise between the various criteria. The task of a decision support system is to provide a solution which can be identified as the best compromise solution rather than an "optimal" solution.

SUMMARY

Given the technical difficulties and exorbitant costs inherent in restoring damaged aquifers, the best way to maintain clean and dependable ground water supplies is through the careful management of the resource. Management implies understanding, planning and controlled resource use and protection. A groundwater management approach, that can be implemented, needs to be evolved. It should be done with a perspective on the unique physical conditions, societal/ human needs and available national resources.

Management goals should be specific and achievable, tailored to the technological and financial resources available. Technologically sound tools like optimisation-modelling techniques can be effectively employed to arrive at "feasibly-optimal" management strategies. Besides, regular monitoring and prognostic scenario reviews should be fused into the action plan of an implementable groundwater management scheme. Groundwater should not be treated as an isolated resource, but must be considered as integral component of the national water resources management strategies, community health programmes, agricultural/ industrial development projects, environmental impact assessments etc. In short, an integrated, holistic approach is essential for effective and sustainable groundwater management.

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