Optimal Network Design for Groundwater Monitoring

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INTRODUCTION

Groundwater is a major source of water supply for drinking, irrigation and animal husbandry in many countries, especially in arid and semi-arid regions. It is also a vital element of groundwater dependent ecosystems such as wetlands. Groundwater supports different functions and uses. Available groundwater resources are being exploited at a large scale for urban, industrial and agricultural uses. During the last decades, the demand for groundwater of good quality has grown rapidly and consequently a continuously increasing quantity of the groundwater resources is exploited. One result is that many groundwater resources are being over-exploited with water being abstracted at unsustainable rates. Furthermore, falling groundwater levels may result in ecological deterioration and in land subsidence which could damage foundations and buildings in certain urban areas. At the same time, in many coastal areas in the world, over-pumping has caused groundwater quality problems due to saltwater intrusion. Groundwater pollution has increased as a result of human activities, the consequences of high population density, continuously growing industrialisation and intensive agriculture. Regular and systematic monitoring of groundwater resources is necessary for its effective management to support the water needs of the environment and its citizens.

Monitoring of groundwater is one of the tools used in groundwater management to obtain the information which is required for the assessment of the groundwater system and the groundwater management issues. To establish an effective monitoring system, a proper design procedure should be applied that starts with the specification of the information needs.

A prerequisite for monitoring and assessment of groundwater resources is the preliminary characterisation of the relevant aquifer systems and the actual condition of groundwater flows. After a preliminary characterisation of the groundwater systems, further monitoring should provide information about the aquifer dynamics such as seasonal variations and changes of the groundwater flow system and about the effects of measures and other anthropogenic influences. Therefore, groundwater quality, groundwater levels and groundwater abstractions have to be monitored as well as the surface water systems which form the boundaries of the groundwater flow systems.

According to a world-wide inventory of groundwater monitoring compiled by the International Groundwater Resources Assessment Centre (IGRAC), in many countries systematic monitoring of groundwater quantity or quality, even at a regional scale, is minimal or non-existent. Lack of monitoring may result in undiscovered degradation of water resources either due to over-abstraction or contamination, leading to the following scenarios:

- Declining groundwater levels and depletion of groundwater reserves;
- Reductions in stream/spring base flows or flows to sensitive ecosystems such as wetlands;
- Reduced access to groundwater water for drinking water supply and irrigation;
- Use restrictions due to deterioration of groundwater quality;

- Increased costs for pumping and treatment;
- Subsidence and foundation damage.

A number of factors that contribute to the lack of monitoring can be identified. Lack of financial resources and lack of technical capacity to implement monitoring are perhaps the major factors. Other factors that may contribute are a lack of clear institutional responsibilities and legal requirements for monitoring. Even where monitoring programmes are operating, they may fail to provide adequate information to support effective management because:

- The objectives are not properly defined;
- The programme is established with insufficient knowledge of the groundwater system;
- There is inadequate planning of sample collection, handling and storage;
- Data are poorly archived and not readily accessible in the type of formats that can be used to support management and inform other stakeholders.

GROUNDWATER MONITORING

Groundwater monitoring can be defined as the scientifically-designed, continuing measurement and observation of the groundwater situation. Groundwater monitoring is the collection of data, generally at set locations and depths and at regular time intervals in order to provide information which may be used

- to determine the state of groundwater both in quantitative and qualitative sense,
- to provide the basis for detecting trends in space and time and
- to enable the establishment of cause-effect relationships.

Within a monitoring programme, data on groundwater are to be collected as far as possible at set locations and regular time intervals. Although the legal basis, institutional framework and funding situation will impose their own objectives and constraints, still the underlying scientific or technical objective is to describe the groundwater situation in space and time.

The requirement for continuity and stability in the monitoring programme emphasizes:

- the need for long-term planning and commitment of staff and budgets;
- the need to understand the hydrogeological and hydrological setting
- the need to ensure uninterrupted access to sampling points.

As a general principle, the area to be monitored should be defined on hydrological or hydrogeological criteria rather than political ones. Even if political or administrative boundaries determine institutional responsibility for monitoring, the interpretation and assessment should be made on the basis of physical units. The river basin, groundwater flow system or aquifer should always be the scale for which monitoring programmes are designed. This provides the basis for an integrated hydrological approach, in which surface water and groundwater and their interactions, and their potential links to estuarine and coastal environments are all considered together. An early step in the preliminary stages of planning and implementation of a monitoring programme is to define the information needed as a basis for managing the quantity and quality of groundwater (Table 1).

Table 1: Essential questions concerning information needs

Information needs - questions	Illustrative examples of answers
Who wants to be informed?	Governments, environmental regulators, water users, health authorities, the public, international agencies (EU, EEA, UNEP)
What types of information?	Groundwater level and quality status and trends, ancillary data for interpretation, DPSIR framework
For what purpose?	Reconnaissance, regulation, compliance, effectiveness of measures, public information
How accurate?	Time and spatial scale of observations, data aggregation, analytical results
How fast?	Weekly/monthly control, periodic reports
In what format?	Reports, maps, internet

Type of Monitoring

Monitoring may come under two categories:

1. Background monitoring to characterising the initial stage of a system,
2. Specific monitoring to deal with systems where significant exploitation has taken place. This functions as an early warning system and provides information for remedial action.

Background Monitoring

Background monitoring commences with inventory of existing information like land use, topography; extent, thickness, structure of the geological units and their hydraulic properties. Based on the analysis of the data, different ground water systems can be identified. These are defined by the occurrence and types of aquifers and aquitards, positive and negative boundaries, and areal distribution of recharge, heads, leakage and seepage areas, flow direction and general chemical composition. Ground water monitoring at this stage may be based on existing observation wells only. After a few years of monitoring, the data should be thoroughly analysed. Geostatistics may help to improve upon the sampling density and frequency. The analysis will lead to adoption of the first network version, which bring only the general characteristics of the ground water system in the area.

The background monitoring data may be used to

- Conceptualise the groundwater system and recharge process.
- Provide estimates of aquifer properties, recharge and discharge.
- Provide historical data for detailed resource assessment and design of specific monitoring network.
- Provide baseline information regarding spatial variations in water quality.
- Understand potential development constraints and benefits.

Background monitoring is a long term effort, because a key factor i.e. ground water recharge and withdrawal is likely to be variable over time and space. The background monitoring in the present context is akin to the regional monitoring of ground water regime being adopted in our country.

Specific Monitoring

Based on information of the background monitoring data, the specific monitoring system is designed. The specific monitoring aims at study of the following two most important features:

- Hydraulic features like overall well field performance, individual well performance, induced recharge, over exploitation, water logging, saline water intrusion;
- Hydrochemical changes affecting water use and well installation.

The knowledge of well field performance requires a thorough understanding of the groundwater distribution and head changes, consequent to abstraction. The monitoring wells network should be so designed as to provide; (i) transient drawdowns over the forecast cone area in dedicated piezometers, both in the aquifer systems as also in aquiclude layers within system, and in the bounding layer below the operative aquifer, and in any juxtaposed aquifer unit that may be affected by cone development; (ii) changes in spring discharge, base flow vis a vis recharge inputs; and also (iii) quality changes consequent on development. The numerical model so developed will act as an early warning system showing over-exploitation of a ground water reservoir; and providing information for remedial action.

Loaiciga et al. divide the objectives of groundwater quality monitoring programs into: ambient monitoring, detection monitoring, compliance monitoring, and research monitoring. Ambient monitoring establishes an understanding of characteristic regional groundwater variations over time. Detection monitoring has the primary function of identifying the presence of targeted contaminants when their concentrations exceed background or established levels. Compliance monitoring is enforced to verify the progress and successof groundwater clean up and remediation works in disposal facilities. Research monitoring consists of groundwater quality sampling tailored to meet specific research goals.

Stages in Groundwater Monitoring

In the development of groundwater monitoring, networks of different types, size and functions can be distinguished. With respect to the size of groundwater monitoring networks, one can distinguish between large "regional" (sub-national) networks and "local" networks. Regional monitoring networks are usually designed to characterise and monitor regional groundwater systems of large extent and importance while local networks focus on more detailed observation of the local groundwater situation, such as around well fields or point sources of pollution such as landfills or industrial sites.

In the early stage of groundwater assessment, when information regarding the groundwater resources is still very scarce, assessment and monitoring will usually be aimed at regional assessment of groundwater resources and their potential for development. When financial resources are limited, groundwater observation or sampling will usually be done at any suitable observation point available. Hence the initial network often has an improvised set-up.

Improvements to the initial network for regional monitoring can be achieved by selecting suitable observation points from the initial round of data collection and by adding new points in gaps of the network where additional information is crucial. In this way large capital costs can still be avoided. Such a large-size groundwater monitoring network, primarily aimed at monitoring the status and trends of regional groundwater systems can be referred to as a *"general reference monitoring network"*.

In a later stage of groundwater development, a reference monitoring network may be further upgraded to a "primary network", which is a dedicated tool for overall observation of regional groundwater bodies. At that stage the groundwater potential becomes sufficiently well known and when the economic returns of monitoring become more obvious, more investments are justified to increase the level of detail. Primary monitoring networks may be combined with local "secondary networks" designed for specific needs or local detail. At that stage, the components of the monitoring programme (selected parameter sets, the network of monitoring wells and the frequency of observation) can be optimally adjusted to specific tasks, using detailed knowledge of the hydrologic and geochemical processes as well as sophisticated statistical techniques.

Design of a monitoring programme is a complex exercise that requires knowledge and experience. Even with sufficient knowledge and experience available, designing a monitoring programme will be an iterative process in which the final result will usually be reached after considering and weighing different options. If experience with groundwater monitoring is limited, it may be wise to develop the monitoring programme by starting with some practical unit. A gradual approach will provide insight in the labour and costs involved in the final design and realization of the monitoring programme.

Groundwater Monitoring Attributes

Groundwater is a dynamic system. The groundwater variables required to be monitored are water level or head, quality and temperature. All these variables are subjected to changes due to manmade or natural causes. The zones of aeration and saturation play important roles in groundwater recharge and water level fluctuations and groundwater quality. The monitoring of the groundwater regime is not confined only to water levels, quality or temperature, but also involves monitoring of spring discharges and its quality and base flow to rivers.

Groundwater level monitoring

The configuration of the water table depends upon by topography, geology, climate, water yielding and water bearing properties of rocks in the zones of aeration and saturation which control ground water recharge. The upper surface of the zone of saturation is the water table. In case of wells penetrating confined aquifers the water level represents the pressure or piezometric head at that point.

The piezometric level is dependant on:

- static or time-independent topographical features and also
- dynamic or time dependant variables. The time independent features also include aquifers and their characteristic parameters like transmissivity and hydraulic conductivity. The dynamic variables include precipitation, evaporation, seepage from surface water bodies ground water extraction and outflow.

Ground water level represents the storage position of the reservoir. The difference over a period of time in the input and output components of the storage equation is reflected as change in storage. Ground water inflow includes recharge from rainfall and surface water bodies, canal seepage, return flow of irrigation and sub surface inflow from adjacent areas. Ground water outflow accounts for ground water discharge to streams, evaporation loss from the capillary fringe, evapotranspiration loss of ground water from phreatophytic vegetation, extraction by pumping and flowing wells, as also sub surface outflow. Water levels reflect the cumulative effects of natural recharge discharge conditions and withdrawal by pumpage. The principal factors controlling water level fluctuations are recharge groundwater withdrawal and specific yield of the aquifers.

Groundwater quality monitoring

Monitoring of ground water quality is an effort to obtain information on chemical quality through representative sampling in different hydrogeological units. Ground Water is commonly tapped from phreatic aquifers through dugwells in a major part of the country and through springs and hand pumps in hilly areas. The main objective of ground water quality monitoring programme is to get information on the distribution of water quality on a regional scale as well as create a background data bank of different chemical constituents in ground water.

Ground water quality evolves through interaction of the recharge water with the host rocks in the zones of aeration and saturation. The chemical constituents in solution may be broadly classified as major (1 to 1000 milligrams per litre (mg/l), secondary (0.01 to 10 mg/l), minor (0.0001 to 0.1 mg/l) and trace elements (less than 0.001 mg/l).

Quality monitoring is a pre-requisite for establishing groundwater pollution. The major sources of pollution are pesticide and fertiliser leachate in agricultural fields, untreated sewage wastes, industrial effluent, nuclear wastes and disturbed hydrodynamic equilibrium between salt water and fresh water in the coastal areas. The degree and extent of pollution depends upon the quantity and concentration of pollutants, the porosity, hydraulic conductivity and gradient, depth to water table, storage capacity of the aquifer and time factors. The pollutants are dispersed in a broad front in the direction of ground water flow. Water table or piezometric surface maps are useful in tracing the source and direction of movement of pollutant.

The temperature of ground water is largely dependant on the atmospheric temperature, terrestrial heat, exothermic and endothermic reactions in the rocks, infiltration of surface water, thermal conductivity of rocks, rate of movement of ground water and interference of man with the ground water regime. Proper analysis of temperature data may give useful clues about the source of recharge and direction of groundwater movement and geothermal field.

Spring discharge monitoring

Monitoring programme in ground water must necessarily include observation on baseflow and spring discharge. The annual recharge to ground water reservoir finds its natural discharge through various outlets like baseflow in rivers and spring discharge. Baseflow is an indirect measure of recharge as it represents drainage of ground water from the aquifer storage after the recharge has occurred. It follows an exponential decay and is directly related to the heads governing the flow.

Spring discharge may vary from a trickle to concentrated flow which is not constant over time. It is also dependent on the ground water heads in the basin and exhibits an exponential decay. In a monitoring programme, it is essential to include major and medium springs and their discharges must be measured atleast once in a month either using a container or by float method. In the case of very small springs, narrow channel is made and 'V' notch is used for flow measurements.

Making Use of Existing Data

The strategy for designing a monitoring and assessment programme should take adequate account of existing information. At an early stage inventories should bring together information that is available but often distributed between different agencies and institutions or their various departments. Inventories should cover the major aspects that are relevant to identification and analysis of issues. These include for example: water uses and water needs, groundwater levels, groundwater quality, landuses and non-point pollution sources from land use, such as fertilisers and pesticides. Water quality surveys are intended to give a first insight into the functioning of the aquatic ecosystem and the occurrence of pollution and its impacts on groundwater systems. The availability of existing groundwater level and quality records should also be taken into account when designing the monitoring network and selecting sites as maintaining long-term series is likely to be an important monitoring objective.

Criteria for selection of an existing well as a network station

While it is desirable to have custom built structures economy can often be achieved by monitoring existing dugwells or tubewells as part of the network. The structures selected for the purpose should conform to the following conditions:

- It should be representative of the hydrogeological situation in the area.
- It should be in good condition, without being silted up. The parapet at curbing provided must be stable and must not collapse.
- The aquifer tapped should be identifiable.
- The well must be in use, but only sparingly. It should not be subjected to heavy withdrawal so that rest water level can be obtained.
- It should have sufficient water column so that it does not dry up in summer.
- It should be accessible in all seasons.
- Well should be located in areas of environmental hazards like over exploitable or water logging in canal command to bring out the response of ground water regime in these areas.

Prioritizing Monitoring Efforts

No monitoring programme can provide the data needed for all actual or potential issues related to groundwater management and protection. Low budgets will very often be a major limiting factor for groundwater monitoring. Also lack of institutional embedding, mandates, manpower, experience, etc. may stand in the way of very ambitious monitoring programmes. Differentiation of monitoring programmes and setting priorities will then be needed to achieve a sound balance between the value of data collected and the labour and costs involved in collecting them.

One way of setting priorities is by making use of risk assessment. Concerning groundwater quality, the long-established and widely adopted approach of defining and mapping the vulnerability of aquifers to pollution can be used to prioritize monitoring activities. Based on the physical and chemical properties of the soil and the geological materials above the water table, the potential for pollutants to be retarded and attenuated is evaluated and mapped. Where such maps exist, they can be used to help focus monitoring to areas where groundwater has important uses and where it is most vulnerable.

Differentiation of the monitoring programme is also possible by reducing ambitions. This can be done in many different ways, for instance by monitoring pilot areas, selecting indicative points or by using a lower frequency of observation. A lower ambition level will often lead to a reduced level of information, but that level may still be acceptable for the users.

Presentation of Results

Investments in the monitoring programme will only be guaranteed if the data from the monitoring network meet the objectives and needs of the users. So, the data gathered and the information presented should be considered a major factor in convincing that continued support is necessary. Non-deliverance of the required information may be a reason for decreasing interest and investment, in the worst case leading to the complete elimination of the monitoring programme.

GROUNDWATER MONITORING IN INDIA

India maintains extensive networks of wells for monitoring groundwater levels and water quality. As part of the International Hydrological Decade Programme the erstwhile Ground Water Divisions of the Geological Survey of India, established a network of observation wells in 1969 for monitoring water levels and quality of ground water. Initially the number of observation wells stood at 410, the criteria adopted being one well in each prevalent litho unit in each degree sheet, covering about 11,600 sq. kms area. Since the merger of Ground Water Wing of the Geological Survey of India with the Central Ground Water Board in 1972, the number of network observation wells has been progressively increased by establishing new observation wells, and also with the accession of wells monitored under various ground water projects of the Board. There were 1617 monitoring stations by the end of 1976. Subsequently the number of observation wells has been steadily increased filling up the data gaps in the process. Now, the CGWB operates a network of 15640 monitoring wells nationwide (Table 2). Groundwater entities attached to various state-level departments operate other networks. Water is a state matter under India's constitution but the central government provides much of the financing for groundwater development. Historically, most of CGWB-maintained wells were open dug wells (generally used for drinking-water). However, a substantial number of isolated piezometers have been installed over the past five years and the number is increasing. Aside from a limited selection of piezometers and key wells that are monitored more frequently, most wells in the CGWB network are monitored four times a year, including once before and once after the monsoon.

Groundwater data collection and monitoring by organizations at state level is relatively similar in design to the CGWB network but varies substantially in relation to the attention given to it. Some states have developed extensive groundwater departments attached to major line organizations such as the Public Health Engineering Department. Other states maintain small units as adjuncts to marginally related mining or geology organizations. Most states monitor a network of 1 500-2 000 wells although some have many more (Rajasthan monitors more than 6000 wells). Groundwater levels in state networks are generally monitored twice a year, before and after the monsoon. As with the CGWB, state monitoring networks are dominated by open dug wells supplemented by a small number of piezometers. Some are moving to strengthen their networks through the installation of piezometers (Rajasthan being a prime example). However, most of these piezometer networks are only a few years old.

Until recently, data collection by both the state organizations and the CGWB was organized on the basis of blocks, local-level administrative units between the *panchayat* (local government) level and the major districts into which each state is subdivided. Recently, some states have transferred the focus of groundwater data collection and monitoring to hydrological units. Recent revisions in groundwater evaluation methodologies by the Ground Water Resource Estimation Committee (GWREC) recognize the importance of hydrological units and recommend that monitoring and evaluation be based on watersheds (GWREC, 1997). Regardless of the base unit, groundwater conditions in most states are reported on the basis of administrative blocks.

Table 2 Network of 15640 nationwide monitoring wells by CGWB

Sl. No.	Name of the State/U.T.	Number of NHNs as on						
		31.3.85	31.3.95	31.3.98	31.3.02	31-3-03	31.3.06	31.3.09
1	2	3	4	5	6	7	8	9
STATES								
1	Andhra Pradesh	309	1042	1028	1013	970	981	981
2	Arunachal Pradesh	7	17	18	19	19	19	19
3	Assam	195	371	365	379	379	381	381
4	Bihar	173	599	569	365	373	373	373
5	Chhattisgarh	-	-	-	484	477	516	516
6	Delhi	76	61	82	87	100	87	87
7	Gujarat	267	974	1045	1116	986	966	966
8	Goa	17	53	53	53	53	53	53
9	Haryana	434	521	550	552	539	426	426
10	Himachal Pradesh	71	78	79	81	86	85	85
11	Jammu & Kashmir	110	162	203	217	201	206	206
12	Jharkhand	-	-	-	208	208	208	208
13	Karnataka	257	1349	1311	1132	1132	1499	1499
14	Kerala	187	651	731	864	864	864	864
15	Madhya Pradesh	412	1350	1343	1323	1307	1325	1325
16	Maharashtra	475	1409	1289	1456	1456	1496	1496
17	Manipur	6	25	25	25	25	25	25
18	Meghalaya	24	37	35	38	38	38	38
19	Nagaland	4	8	8	17	17	17	17
20	Orissa	200	1122	1122	1068	1068	1214	1214
21	Punjab	383	497	485	413	399	261	261
22	Rajasthan	597	1414	1456	1337	1337	1373	1373
23	Sikkim	0	0	NA	NA	N.A	N.A	N.A
24	Tamil Nadu	265	766	765	1039	1010	906	906
25	Tripura	26	37	37	37	42	42	42
26	Uttar Pradesh	636	1514	1477	1210	1232	1218	1218
27	Uttarakhand	-	-	-	-	-	44	44
28	West Bengal	303	836	831	721	726	909	909
TOTAL STATES		5434	14893	14907	15254	15044	15532	15532
UNION TERRITORIES								
1	Andaman & Nichobar Island	4	29	29	-	N.A	63	63
2	Chandigarh	21	14	14	21	22	16	16
3	Dadra & Nagar Haveli	2	7	7	10	10	10	10
4	Daman & Diu	0	6	5	6	4	4	4
5	Lakshadweep	0	30	30	-	N.A	N.A	N.A
6	Puducherry	0	16	20	22	21	15	15
TOTAL U.Ts.		27	102	104	59	57	108	108
TOTAL ALL INDIA		5461	14995	15012	15313	15101	15640	15640

Sources : Central Ground Water Board, Hydrology Project, Ministry of Water Resources.

Because 'level of development' was the main criteria for allocating groundwater development financing, the focus of groundwater monitoring was to collect the water-level fluctuation data necessary to drive the methodology. As a result of this dynamic, pre- and post-monsoon water levels are available as the core data set with state groundwater organizations and the CGWB.

Although some wells have been monitored since the mid-1970s, most of the monitoring began in the 1980s after the GWREC report. Staff from the CGWB and state groundwater organizations take measurements manually. Most of the wells selected are dug wells because tubewells are often blocked by pumps. Where possible, wells used for drinking-water rather than irrigation have been selected. This selection rests on the assumptions that drinking uses will result in less extraction and that the well will provide a more accurate measure of water-table conditions than more heavily utilized wells. However, many state networks contain a significant number of irrigation wells where use levels may be high. This is also true of the CGWB network (although this network contains a significant number of piezometers). Data from the national and state networks are currently being compiled electronically and as part of the Hydrology Project, which is supported by the World Bank.

Central Ground Water Board has been monitoring the chemical quality of ground water in the country since 1974. The chemical quality of shallow ground water is being monitored by Central Ground Water Board once in a year (April/May) through a network of 15640 observation wells located all over the country.

Water Quality Monitoring Programme by CPCB

Water quality monitoring is an important exercise, which helps in evaluating the nature and extent of pollution control required, and effectiveness of pollution control measures already in existence. It also helps in drawing the water quality trends and prioritising pollution control efforts. In order to perform the functions specified under the Water (Prevention and Control of Pollution) Act, 1974, Central Pollution Control Board (CPCB) and State Pollution Control Boards/Pollution Control Committees (SPCBs/PCCs) need adequate knowledge on nature and extent of pollution control required in different parts of the country. Also they have to evaluate performance of the pollution control efforts. To achieve this, a continuous water quality monitoring is required. Realising this CPCB in collaboration with concerned SPCBs/PCCs established a wide network of water quality monitoring. The water quality monitoring is performed with following main objectives in mind.

- For rational planning of pollution control strategies and their prioritisation;
- To assess nature and extent of pollution control needed in different water bodies or their part;
- To evaluate effectiveness of pollution control measures already is existence;
- To evaluate water quality trend over a period of time;
- To assess assimilative capacity of a water body thereby reducing cost on pollution control;
- To understand the environmental fate of different pollutants.
- To assess the fitness of water for different uses.

Keeping these objectives in mind the Central Pollution Control Board (CPCB) has established a network of monitoring stations on rivers across the country. The present network comprises of 1245 stations in 27 States and 6 Union Territories spread over the country. The monitoring is done on monthly or quarterly basis in surface waters and on half yearly basis in case of ground water. The monitoring network covers 250 Rivers, 78 Lakes, 6 Tanks, 26 Ponds, 8 Creeks, 19 Canals, 19 Drains and 382 Wells. Among the 1245 stations, 695 are on rivers, 86 on lakes, 19 on drains, 19 on canals, 6 on tank, 12 on creeks/seawater, 26 on pond and 382 are groundwater stations. Presently the inland water quality-monitoring network is operated under a three-tier programme i.e. GEMS, Monitoring of Indian National Aquatic Resources System and Yamuna Action Plan. Water samples are being analyzed for 28 parameters consisting of physico-chemical and bacteriological parameters for ambient water samples apart from the field observations. Besides this, 9 trace metals and 28 pesticides are analyzed in selected samples. Bio-monitoring is also carried out on specific locations. In view of limited resources, limited numbers of organic pollution related parameters are chosen for frequent monitoring i.e. monthly or quarterly and major cations, anions, other inorganic ions and micro pollutants (Toxic Metals & POP's) are analyzed once in a year to keep a track of water quality over large period of time. The water quality data are reported in Water Quality Status Year Books.

GROUNDWATER NETWORK DESIGN TECHNIQUES

The monitoring network should provide data which fulfils the technical objectives and the defined information needs which have been derived from the groundwater management objectives. From the point of view of the groundwater manager, the objective of the monitoring network is preferably defined in terms of target parameters. The distribution of the observation points of the network should enable the determination of the target parameter anywhere in the system by interpolation of the measurements at the observation points with sufficient accuracy.

Consequently, the derived value for the target parameter is referred to as the estimated value. The selection of density and frequency should be made in such a way that the estimated value of the target parameter is sufficiently accurate. The difference between the estimated and the real value is called the estimation error. Quite similar to the design of the monitoring network in space, the monitoring in time, in other words, the sampling frequency should be based on the quantification of the relationship between the desired accuracy and the frequency. Loaiciga et al. (1992) identify the main approaches to groundwater monitoring network design as (1) the hydrogeological and (2) the statistical approaches.

Hydrogeological Approach

The hydrogeological approach is the basis of the procedure most commonly used in practice. In the hydrogeological approach, no explicit quantification of the uncertainty is given. Instead, the network design follows from a deterministic, hydrogeological, area description based on expert judgment. Loaiciga et al. (1992) define this approach as the case where the network is designed based on the calculations and judgment of the hydrologist without the use of advanced geo-statistical methods. The hydrogeological approach is better suited for site-specific studies where there is, for example, a well-delimited source of contamination. The number and locations of sampling sites are strictly determined by the hydrogeological conditions (i.e. scale of hydrogeological variability) near the source of contamination, such as a waste impoundment. The approach relies heavily on descriptive information about the aquifers of interest, and often does not fully utilise the available quantitative hydrogeological information. Hence, in areas where relevant hydrological data are limited or even absent – in so-called scarce data areas – this approach may be the only possible technique.

Just as the hydrogeological approach can provide information on the spatial layout of the network design, it can also help determine the sampling frequency in time. This is typically done by taking into account the seasonal changes for some objectives and some human activities e.g. farming and by application of Darcy's law to describe groundwater velocity. For example, by estimating hydraulic conductivity and porosity (or by determining the type of sediment) in the near surroundings of a groundwater abstraction well, the flow velocity can be calculated and related to, say, the groundwater quality sampling interval. In general, more frequent sampling will be needed in shallow, high velocity aquifers with a more vulnerable, while less frequent sampling is needed in deeper and in confined aquifers.

Statistical Approaches

Commonly, groundwater monitoring networks are established with one of two principal objectives in mind. These objectives are to, (l) statistically describe areal groundwater quantity or quality characteristics and (2) detect existence of a contamination plume or define local areas of contamination. Concerning the first objective, groundwater monitoring networks need to provide data that can answer the questions, "What is the typical water level or quality in a particular area" and "Is water quantity or quality in the area suitable for the intended uses?" With respect to the second objective, the network needs to provide information to answer the question, "Where is groundwater quality unsuitable for any use?". These two objectives can be accomplished by application of two approaches. These approaches to network design are based on either (i) standard statistical techniques or (ii) geostatistical techniques.

Standard statistical techniques

Statistically a certain number of observation wells are necessary to find the average water table or average water quality with a certain percentage of error. The steps involved in the estimation of the optimum number of observation wells are given below:

(i) Calculate mean water table in the area:

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

where, x_i = water level at ith location, $\overline{x}$ = mean water level in the area, n = number of observation points

(ii) Calculate standard deviation.

$$s = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2}{n-1}} \tag{2}$$

(iii) Calculate the Coefficient of variation (C_v)

$$C_V = \frac{s}{\overline{x}} \times 100 \tag{3}$$

(iv) Optimum number of observation wells (N) required to estimate the average

$$N = \left(\frac{C_V}{E_p}\right)^2 \tag{4}$$

Where, E_p is the allowable percentage of error in the estimation of mean water table.

(v) Additional observation wells required = N – n

This method is based only on the percentage error and covariance of the variation in water level. Therefore, this formula has been modified and range of variation of water levels has been introduced in the formula. The modified equation is

$$N = \left(\frac{C_V}{E}\right)^2 \tag{5}$$

where, E is called Error and is defined as

$$E = \frac{\text{Percent Error } (E_p) \text{ x Range of variation of water table } (R)}{\text{Mean water table } (WT_m)}$$

in which, R = Maximum water level - Minimum water level.

Geostatistics

Geostatistics is a collection of statistical methods for the analysis and estimation of spatial data for use primarily in the earth sciences. According to Matheron (1963) "Geostatistics is the application of the formalism of random functions to the reconnaissance and estimation of natural phenomena". It can be described as a systematic approach for making inferences about quantities that vary in space. Geostatistical techniques incorporate the spatial characteristics of actual data into statistical estimation processes. Geostatistics has perhaps been most clearly described by ASCE (1990), as follows:

Geostatistics...provides the statistical tools for (1) Calculating the most accurate (according to well-defined criteria) predictions, based on measurements and other relevant information; (2) quantifying the accuracy of these predictions; and (3) selecting the parameters to be measured, and where and when to measure them, if there is an opportunity to collect more data.

Geostatistics is based on the Theory of Regionalized Variables. When a variable is distributed in space, it is said to be "regionalized" (Journel and Huijbregts, 1978). A Regionalized Variable (ReV) is defined by Matheron (1963) as the variable that spreads in space and exhibits certain spatial structure. Such variables show a complex behaviour. Their variations in space are erratic and often unpredictable from one point to another; however, these are not completely random as these exhibit some spatial correlation. All the parameters generally used in groundwater hydrology, such as transmissivity, hydraulic conductivity, piezometric heads, vertical recharge etc. can be called regionalized variables.

The main features of linear geostatistics, which is the most popular branch of geostatistics, are: (1) It uses the spatial-correlation structure of spatial functions; (2) its estimates are calculated by weighting the measurements with coefficients that are determined from the minimization of the mean square error, subject to un-biasedness conditions; and (3) it can process measurements averaged over different volumes and sizes.

Semivariogram

Kriging uses the semivariogram to measure the spatial correlated components, a component that is also called spatial dependence or spatial autocorrelation. The semivariogram is half of the arithmetic mean of the squared difference between two experimental measures, ($Z(x_i)$ and $Z(x_i+h)$), at any two points separated by the vector h. Before values of any parameter can be estimated with kriging, it is necessary to identify the spatial correlation structure from the semivariogram, which shows the relationship between semivariance and the distance between sample pairs.

$$\gamma^*(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \tag{6}$$

where $\gamma^*(h)$ = estimated value of the semivariance for lag h; N(h) is the number of experimental pairs separated by vector h; $z(x_i)$ and $z(x_i+h)$ = values of variable z at x_i and x_i+h, respectively; x_i and x_i+h = position in two dimensions. A plot of $\gamma^*(h)$ versus the corresponding value of h, also called the semivariogram, is thus a function of the vector h, and may depend on both the magnitude and the direction of h. A sample plot of semivariogram is shown in Fig. 1.

The distance at which the variogram becomes constant is called the range, *a*. It is considered that any data value Z(x) will be correlated with any other value falling within a radius, *a* and thus range corresponds to the zone of influence of the RV. The value of the semivariogram at a distance equal to the range is called the sill. Semivariograms may also increase continuously without showing a definite range and sill. The value of the semivariogram at extremely small separation distance is called the nugget effect. . Ideally, the experimental semivariogram should pass through the origin when the sample distance is zero. But, many regionalised variables show nugget effect. It could be caused by sampling errors or short scale variability of the property which cannot be detected at the scale of sampling.

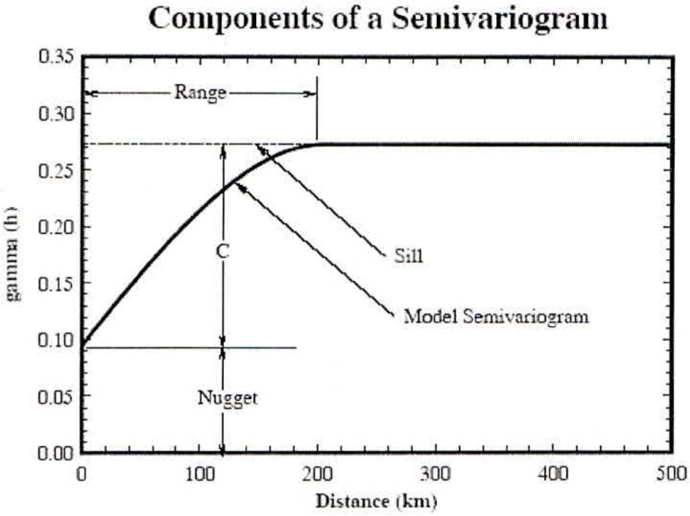


Fig. 1 Sample Plot of Semivariogram

The semivariogram, given in Eq. 6 is also termed the true semivariogram of the ReV. As only one realization of the RF is available, the true semivariogram can only be estimated and this estimate is known as the experimental semivariogram. If the sampling is done on a regular grid, the $\gamma^*(h)$ may be estimated for values of h, known as lag distance or lag increment which are multiples of the grid spacing. This situation is rare in practice, particularly in the context of groundwater and the chance of finding pairs at exactly same specified distance h is very small. To overcome this, a tolerance, δh is placed on the distance. Every pair of observations that are separated by a lag $h \pm \delta h/2$ are then used to estimate $\gamma^*(h)$.

The above procedure, is used for calculating the isotropic experimental semivariogram, also known as omni-directional semivariogram. In this case, it is assumed that the variation is the same in every direction. To find the anisotropies, the semivariograms are calculated in different directions. To do this, a tolerance, $\delta\theta$, is placed on the directional angle. The tolerance in direction and distance are represented in Fig. 2.

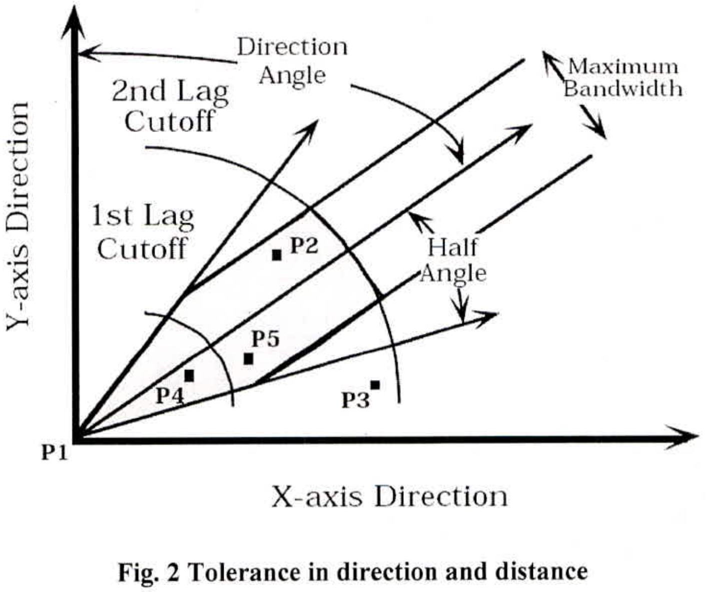


Fig. 2 Tolerance in direction and distance

Structural Analysis

The observed data is used to calculate the experimental semivariogram. A mathematical function used to approximately represent this semivariogram is known as the theoretical semivariogram. Some of the theoretical semivariogram models are (Fig. 3).

Spherical model: -

$$\gamma(h) = \begin{cases} C_0[1-\delta(h)] + C\left[\dfrac{3}{2}\dfrac{h}{a} - \dfrac{1}{2}\dfrac{h^3}{a^3}\right] & h \le a \\ C_0 + C & h > a \end{cases} \tag{7}$$

Exponential model: -

$$\gamma(h) = C_0[1-\delta(h)] + C\left[1 - \exp\left(-\frac{h}{a}\right)\right] \tag{8}$$

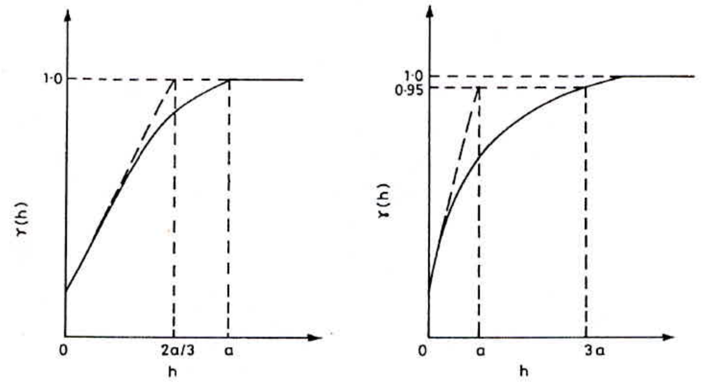
Gaussian model: -

$$\gamma(h) = C_0[1-\delta(h)] + C\left[1 - \exp\left(-\frac{h^2}{a^2}\right)\right] \tag{9}$$

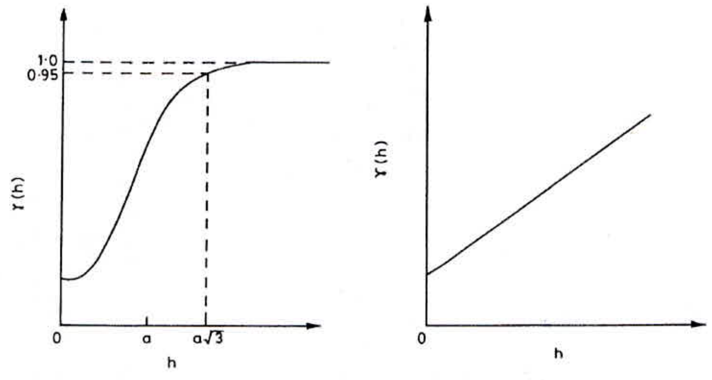
Linear model: -

$$\gamma(h) = C_0[1-\delta(h)] + bh \tag{10}$$

where, δ(h) is the Kronecker delta = $\begin{cases} 1 & h = 0 \\ 0 & h \neq 0 \end{cases}$, C_0 is the Nugget effect, C_0+C is the Sill, *a* is the Range and *b* is the slope.



(a) SPHERICAL (b) EXPONENTIAL



(c) GAUSSIAN (d) LINEAR

Fig. 3 Theoretical models of semivariogram

Kriging

Kriging is a geostatistical method for spatial interpolation. It is a technique of making optimal, unbiased estimates of regionalized variables at unsampled locations using the structural properties of the semivariogram and the initial set of data values. Consider a situation in which a property is measured at a number of points, x_i , within a region to give values of $z(x_i)$, i=1,2,3,...,N. (x_i is the coordinate of the observation point in 1, 2 or 3-dimensional space). From these observations, the value of the property at any place x_0 can be estimated as

$$z^*(x_0) = \sum_{i=1}^{N} \lambda_i z(x_i) \qquad i=1,2,3,\ldots\ldots,N \tag{11}$$

where,

$z^*(x_0)$ = estimated value at x_0

λ_i = weights chosen so as to satisfy suitable statistical conditions

$z(x_i)$ = observed values at points x_i, i= 1,2,3,.......,N

N = sample size

In kriging, the weights λ_i are calculated so that $Z^*(x_0)$ is unbiased and optimal i.e.

$$E\{Z^*(x_0) - Z(x_0)\} = 0 \tag{12}$$

$$\mathrm{Var}\{Z^*(x_0) - Z(x_0)\} = \text{minimum} \tag{13}$$

The best linear unbiased estimate of $Z(x_o)$ is obtained by using Lagrangian techniques to minimise Eq. (13) and then optimising the solution of the resulting system of equations when constrained by the nonbiased condition of Eq. (12). The following system of equations, known as kriging system, results from the optimization:

$$\begin{cases} \sum_{j=1}^{N} \lambda_j \gamma(x_i, x_j) + \mu = \gamma(x_i, x_0) & i = 1,2,3,\ldots\ldots, N \\ \sum_{j=1}^{N} \lambda_j = 1 \end{cases} \tag{14}$$

where, μ = Lagrange multiplier, $\gamma(x_i, x_j)$ = semivariogram between two points x_i and x_j.

Solution of the above set provides the values of λ_i, which can be used with Eq. 11 for estimation. The minimum estimation variance, or kriging variance, is written as:

$$\sigma_k^2(x_0) = \sum_{i=1}^{N} \lambda_i \gamma(x_i, x_0) + \mu \tag{15}$$

Network Optimization

The network optimization method uses the results of interpolation systems which provide in addition to the interpolated values an estimate of the error. Its reduction is the most used criterion for the optimization of observation network.

The kriging variance is a powerfull tool for optimizing a network because in the expression

$$\sigma_k^2(x_0) = \sum_{i=1}^{N} \lambda_i \gamma(x_i, x_0) + \mu \tag{16}$$

the kriging variance depends only on the semi-variogram and the configuration of observation points in relation to the point to be estimated. It does not depend on the observation value. Therefore if the semi-variogram is already known, the kriging variance for any particular water level observation scheme can be determined before putting that scheme into effect. The kriging variance is therefore an indicator of precision to determine the location of any additional measuring point or to decide whether or not to strengthen the observation network. The kriging variance involves only the variogram model, the number of stations and their geographical positions. It is independent of the observed values and therefore the network can be planned. It is this characteristic that determines the optimal network.

To determine the accuracy of existing network, watertable contour map can be prepared by kriging at pre-determined grid interval. This map is based on all available information (water levels). The estimation error contour map thus produced shows the uncertainty already present in the existing observation well network. The reduction in number of observation wells without increasing the existing uncertainty is achieved by superimposing a square grid pattern over the area and selecting one well per square grid. The data of these wells is then kriged to prepare the water table contour map and estimation standard deviation contour map. This is repeated by varying the size of square grid. The size of square grid whose data set provide the contour maps for kriged water table and estimation standard deviation closed to the existing network is selected. This gives the minimum number of observation wells required in estimating the water levels.

In selecting the optimum number of observation wells required to reduce already existing average uncertainty, the location of addition wells can be suggested by observing the contour map of estimation standard deviation of reduced network. New fictitious measurement points are added in the area where the standard deviation is high. In this way, theoretical network of observational wells is constructed using the wells already existing in the area.