TRAINING COURSE

ON

# SOFTWARE FOR GROUNDWATER DATA MANAGEMENT

UNDER

## WORLD BANK FUNDED HYDROLOGY PROJECT

LECTURE NOTES
ON

# NETWORK DESIGN

BY

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# NETWORK DESIGN

## 1.0 INTRODUCTION

All groundwater flow and transport models are dependent on the inputs (forcing functions and boundary and initial conditions) and coefficients (hydraulic conductivity, porosity and dispersivity etc.). Model predictions are function of the model parameters which are numerical approximations of the continuous inputs and coefficients of the governing equations. Lack of knowledge about the model parameters can result from spatial variability of aquifer flow and transport properties ( e.g., hydraulic conductivity and hydraulic head) which may exhibit large fluctuations over relatively short distances. Commonly, there are few measurements of a property with which to develop a detailed estimate of the distribution of the property through out the area of the aquifer to be modeled. Considerable estimation error in the model parameters results from interpolating model inputs and coefficients at numerous points over a large area on the basis of measurement at only a few locations.

In the initial stages of investigations there is little or no information available to estimate aquifer properties or the boundary conditions needed to simulate flow and mass transport in the aquifer. At this stage, the uncertainty of the model predicted parameter in the aquifer is large. On the basis of this preliminary information a more detailed study of aquifer is usually made. Boreholes may be drilled to obtain core samples, pump tests performed to determine the transmissivity, and monitoring wells are installed to measure hydraulic head and concentration over time. As this information becomes available, more accurate and reliable estimates of the model inputs and parameters can be computed, resulting in a corresponding increase in the reliability of the model predictions. In the investigation of a real aquifer this iterative process of accumulating additional information is expensive and time consuming.

Also if the number of observation wells is very large in an area, the monitoring cost becomes high and this large amount of data may not improve the model predictions significantly.

Therefore there is a need to develop a optimal groundwater observation well network to minimise the uncertainty of ground water simulation model predictions and minimise the time and cost of monitoring.

## 2.0 GROUNDWATER REGIME MONITORING

Groundwater monitoring is a surveillance system of the storage and water quality status of the groundwater reservoirs, which are cyclically replenished every year from rainfall and other sources of recharge. In other words, monitoring of ground water regime is an effort to obtain information on ground water levels and chemical quality through representative sampling. The important attributes of ground water regime monitoring are (a) ground water level, (b) ground water quality, and (c) temperature.

## 2.1 NEED FOR GROUNDWATER REGIME MONITORING

The primary objective of establishing the groundwater monitoring network stations is to record the response of groundwater regime to the natural and artificial conditions of recharge and discharge with reference to geology climate, physiography, land use pattern and hydrologic characteristics. The natural conditions affecting the regime involve climatic parameters like rainfall, evapotranspiration etc. and the artificial conditions include pumpage from the aquifer, recharge due to irrigation system and other manmade causes like waste disposal etc. The data base generated can form the basis for groundwater development and management programme. The ground water level and quality monitoring assume particular importance in coastal as well as inland saline environment to assess the changes in salt water/fresh water interface, as also the gradual quality changes in the fresh ground water regime. The objectives of the groundwater monitoring may be broadly summarised as below:

I. Collection of basic data on groundwater conditions to

- a. study the inter-relationship between groundwater and climatic parameters such as rainfall, evaporation and evapotranspiration.
- b. study the influence of geology, topography and landuse on groundwater regime
- c. understanding the role of groundwater in the hydrologic cycle and the influence of the recharge on groundwater storage changes, chemistry and temperature.

II. Application of groundwater monitoring data for

- a. Reference purposes
- b. Prediction measures
- c. Environmental control
- d. Estimation of resources

## 2.1.1 TYPE OF MONITORING

Monitoring may come under two categories:

- i. Background monitoring to characterising the initial stage of a system,
- ii. 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

1. Conceptualise the groundwater system and recharge process.
2. Provide estimates of aquifer properties, recharge and discharge.
3. Provide historical data for detailed resource assessment and design of specific monitoring network.
4. Provide baseline information regarding spatial variations in water quality.
5. 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:

1. Hydraulic features like overall well field performance, individual well performance, induced recharge, over exploitation, water logging, saline water intrusion;
2. 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.

## 2.2 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.

### 2.2.1 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:

a) static or time-independent topographical features and also

b) 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 which is expressed as

Ground water inflow - Ground water outflow = Change in Ground water 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.

### 2.2.2 Groundwater Quality Monitoring

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.

### 2.2.3 Groundwater Temperature Monitoring

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.

### 2.2.4 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.

Because of the dampening effect of the reservoir storage variations in annual recharge do not get reflected immediately in the baseflow or in spring flow. However, the variations in the head affect the flow and the long term natural discharge averages the long term recharge where human intervention has not occurred Ground water abstraction is normally reflected in a reduction in baseflow/spring discharge. Recharge may be estimated by separation of recession part of runoff hydrograph and plotting of stream discharge versus time on a logarthemic scale to define recession phase.

### 2.2.5 Base Flow Monitoring

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.

## 2.3 LOCATION OF NETWORK STATIONS

The location of the network station should reflect ground water situation proposed to be monitored. This is a basic pre-requisite and an important aspect of the ground water monitoring strategy. While a network station, the various factors required to be considered are:

1. All the elements related to input and output components namely: rainfall, surface water irrigation system, well fields etc. must be studied and a network evolved on the regional or local scale.

2. Topographic inequalities may induce several systems and sub-systems of flow. While there may be one regional flow system because of the local variations there can be many local flow systems. Similarly in an area because of variations in the hydraulic conductivity in the aquifers, head variations can occur with depth resulting in vertical flow. It is thus essential to consider these factors viz: topographic setting, variation in transmissivity, both laterally and vertically, even in the same litho units, while establishing stations. The network design aims at three dimensional monitoring: regional, intermediate and local flow systems.

3. Considering the fact that the change in water level essentially reflects change in storage condition, variation in storage properties of the aquifer viz., specific yield or storage coefficient, must be considered while locating the stations.

4. Hydrogeological units must be defined on a regional or local level depending on the scale of study and considering the following factors: (i) Lithology and its influence on the conduit and storage properties, (ii) rainfall distribution, (iii) surface water bodies and water logging situation, (iv) irrigation structures, (v) relief characteristics, (vi) forests, (vii) stage of groundwater development, and (viii) quality of ground water.

## 2.4 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:

1. It should be representative of the hydrogeological situation in the area.
2. It should be in good condition, without being silted up. The parapet at curbing provided must be stable and must not collapse.
3. The aquifer tapped should be identifiable.
4. 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.
5. It should have sufficient water column so that it does not dry up in summer.
6. It should be accessible in all seasons.
7. 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.

## 3.0 GROUNDWATER REGIME MONITORING IN INDIA

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 to 15336 in 1991 filling up the data gaps in the process. The statewise distribution of hydrograph network stations is given in Table. However some of the wells have gone defunct. At present there are 14995 network stations (March, 1995). The network stations have been located based on prevailing hydrogeological and other related conditions.

The majority of these hydrograph network stations are the open dugwells owned by private individuals or other organisations. Some piezometers have however been constructed to monitor phreatic as well as confined aquifers. Of the 14995 network stations monitored, there are 13581 open dugwells and 1414 piezometers (Table I).

## 4.0 GROUNDWATER MONITORING NETWORK DESIGN

Everett (1980) has defined monitoring network as "...a scientifically designed surveillanve system of continuing measurements and observations, including evaluation procedures".

TABLE

STATUS OF NATIONAL HYDROGRAPH NETWORK STATIONS

| Sl No | State | No. of Network Stations Central Ground Water Board ( As on 01.04.1995) DW | PZ | TOTAL | State Govt. organisations |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 |
| 1. | Andaman Nicobar | 29 | 0 | 29 | |
| 2. | Andhra Pradesh | 947 | 95 | 1042 | 3118 |
| 3. | Arunachal Pradesh | 17 | 0 | 17 | |
| 4. | Assam | 324 | 47 | 371 | 170 |
| 5. | Bihar | 599 | 0 | 599 | 586 |
| 6. | Chandigarh | 1 | 13 | 14 | - |
| 7. | Dadra & Nagar | 7 | 0 | 7 | - |
| 8. | Daman & Diu | 3 | 3 | 6 | - |
| 9. | Delhi | 49 | 12 | 61 | - |
| 10. | Goa | 43 | 10 | 53 | - |
| 11. | Gujarat | 822 | 152 | 974 | 2480 |
| 12. | Haryana | 394 | 127 | 521 | 2282 |
| 13. | Himachal Pradesh | 78 | 0 | 78 | 750 |
| 14. | Jammu & Kashmir | 162 | 0 | 162 | 0 |
| 15. | Karnataka | 1320 | 29 | 1349 | 1539 |
| 16. | Kerala | 625 | 26 | 651 | 206 |
| 17. | Lakshadweep | 30 | 0 | 30 | - |
| 18. | Eastern M.P.<br>Western M.P. | 630<br>720 | 0<br>0 | 630<br>720 | 4450<br>- |
| 19. | Maharashtra | 1347 | 62 | 1409 | 3217 |
| 20. | Manipur | 14 | 11 | 25 | - |
| 21. | Meghalaya | 33 | 4 | 37 | - |
| 22. | Mizoram | 0 | 0 | 0 | - |
| 23. | Nagaland | 6 | 2 | 8 | - |
| 24. | Orissa | 1071 | 51 | 1122 | 105 |
| 25. | Pondichery | 7 | 8 | 15 | |
| 26. | Punjab | 424 | 73 | 497 | 361 |
| 27. | Rajasthan | 1198 | 216 | 1414 | 6248 |
| 28. | Sikkim | 0 | 0 | 0 | - |
| 29. | Tamilnadu | 688 | 78 | 766 | 2500 |
| 30. | Tripura | 34 | 3 | 37 | NA |
| 31. | Uttar Pradesh | 1465 | 49 | 1514 | 3600 |
| 32. | U.T. of Mahe | 1 | 0 | 1 | - |
| 33. | West Bengal | 493 | 343 | 836 | 1214 |
| | Toral | 13581 | 1414 | 14995 | 328226 |

A groundwater observation network consists of a group of observation wells more or less randomly located over an area that may provide a sufficiently accurate data for various parameters over a period of time.

## 4.1 TO CHECK THE ADEQUACY OF THE MONITORING NETWORK

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

(i) Calculate mean water table in the area:

$$WT_m = \frac{\sum_{i=1}^{n} WT_i}{n} \qquad \text{.......(1)}$$

where,

$WT_i$ = water level at ith location

$WT_m$ = mean water level in the area

n = number of observation points

(ii) Calculate Variance (square of standard deviation)

$$S^2 = \frac{\sum_{i=1}^{n} (WT_i)^2 - \frac{(\sum_{i=1}^{n} WT_i)^2}{n}}{n-1} \qquad \text{.......(2)}$$

(iii) Calculate the Coefficient of variation ($C_v$)

$$C_v = \frac{100\sqrt{S^2}}{(\sum_{i=1}^{n} \frac{WT_i}{n})} \qquad \text{.......(3)}$$

(iv) Optimum number of observation wells (N) required to estimate the average water table within percentage error (Err) is

$$N = (\frac{C_v}{p})^2 \qquad \text{.......}(4)$$

(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 (eq. 4). The modified equation is

$$N = (\frac{C_v}{E})^2 \qquad \text{.......}(5)$$

where, E is called Error and is defined as

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

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

## 4.2 OPTIMAL NETWORK DESIGN

As emphasised earlier, that the groundwater monitoring network is required to collect the information about various groundwater attributes. These attributes can neither be monitored at very small distances or very large distances, because the former involves huge recurring expenditure and the later introduce uncertainties in the data. Therefore, an optimal network of monitoring network stations is required to satisfy the needs of the user without spending too much of money.

Recent practice of optimal network design is based on the theory of regionalisation and is discussed here.

### 4.2.1 Concept of Regionalised Variable and Kriging

For making predictions in groundwater hydrology, numerical modelling of the aquifer system is done by solving the flow and/or solute transport equations. In such models various spatial parameters (such as head, storage coefficient, transmissivity etc.) are required at large number of locations depending upon the model and/or discretisation scale. Collection of data at large number of points is very expansive and time consuming. Therefore, some tool is necessary to link the two situations, and to supply the parameter values for all discretised volumes from the available observed data.

### Regionalized Variables

Various parameters important in hydrogeology (e.g. hydraulic head, transmissivity, permeability, thickness of aquifer, storage coefficient, rainfall, recharge etc.) are all function of space and are often variable. The spatial variability of these parameters is, in general, not purely random i.e. there is some kind of correlation in the spatial distribution of these magnitudes. Matheron (1963) described these types of quantities as "Regionalised Variables". Therefore, all the parameters used in groundwater hydrology can be called regionalised variables.

Regionalised variables are of two type (i) stationary - the variable has a definite trend in space, e.g. piezometric head, (ii) Non-stationary - the variable has no systematic trend in space, e.g., transmissivity.

### Kriging Technique

Kriging technique is based on concept of regionalised variable. The important variables such as ground water level, transmissivity, storage coefficient etc. are all functions of space. If measurements are made at two different locations the closer the measurement points are to each other, the closer the measured values. In other words there is some kind of correlation in the spatial distribution of these magnitudes.

The general theory of Kriging was developed by Matheron (1971) but the technique is named after D.R. Krige who first applied the underlying theory to gold mining in South Africa. Kriging is a geostatistical interpolation technique for auto correlated regionalised variable. The technique is based on unbiased and minimum variance conditions for estimation and involves linear system of equation to calculate the weights of the data.

Kriging is considered for optimisation of hydrograph network stations for the following reasons:

a) It has the ability to estimate the reliability of the data at unmeasured points.

b) It is an exact interpolator at measured data points.

c) It uses the information from data points closely surrounding the point to be estimated by incorporating auto correlation structure of the data.

The first step of application of kriging is derivation of a semi variogram which is a graph of variability of the difference of the regionalized data versus the distance between the data points.

The equation of the semi variogram is

$\gamma(h) = 1/2 \text{ Var } [Z(x+h)-Z(x)]$

where, $\gamma(h)$ = Semi variogram

Var h = Variance of data points

$Z(x)$ = regionalised variable at point x

h = distance between the data points

$Z(x+h)$ = another regionalised variable at a distance (h) from $Z(x)$

The semi variogram is approximated initially from the given set of measured values of the regional variable. The semi variogram is fit as closely as possible with one of the theoretical semi variograms viz. Linear, Spherical, Exponential or Gaussian (Fig. 1). The final equation of the semi variogram is selected using the validation process. In this process, the known data points are suppressed and then estimated using the remaining points. The equation of semi variogram is adjusted until the weighted average error is approximately zero, the mean square error is made as small as practical, and the average ratio of theoretical and calculated variance is near unity.

## Estimation of regionalised variable

If Z(x) represents any random function with values measured at 'n' location points in space $Z(x_i)$ i = 1,2,3....n and if the value of the function Z has to be estimated at the point $X_o$ which has been measured the kriging estimate is defined as

$$Z^*(X_o) = \sum_{i=1}^{n} \lambda_i Z(X_i)$$

where $Z^*(X_o)$ is the estimation of the function Z(x) at a point xo and $\lambda_i$ are weighing factors

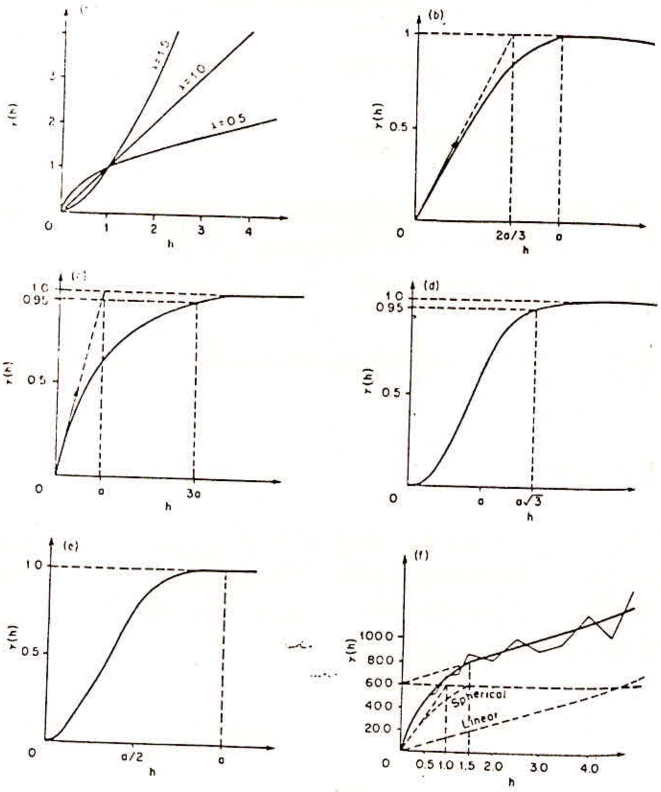
## Variance of the Estimation Error

Variance of the Estimation Error is estimated by

$$\sigma k^2 = C(O) - \sum_{i=1}^{n} \lambda_i C(X_i,X_o) + \mu$$

where,

$\sigma k^2$ = variance of the estimation error



| | | |
|---|---|---|
| (a) model in $h^\lambda$ | $\omega h^\lambda$ | $\lambda < 2$ |
| (b) spherical model | $\omega\left[\frac{3}{2}\left(\frac{h}{a}\right) - \frac{1}{2}\left(\frac{h}{a}\right)^3\right]$ | $h < a$ |
| | $\omega$ | $h > a$ |
| (c) exponential model | $\omega[1 - \exp(-h/a)]$ | |
| (d) Gaussian model | $\omega\{1 - \exp[-(h/a)^2]\}$ | |
| (e) cubic model | $\omega\left[7\left(\frac{h}{a}\right) - 8.75\left(\frac{h}{a}\right)^3 + 3.5\left(\frac{h}{a}\right)^5 - 0.75\left(\frac{h}{a}\right)^7\right]$ | $h < a$ |
| | $\omega$ | $h < a$ |

(f) fitting on a "linear plus spherical" model (example)

| | |
|---|---|
| $13.3\,h + 60\left[\frac{3}{2}\left(\frac{h}{1.5}\right) - \frac{1}{2}\left(\frac{h}{1.5}\right)^3\right]$ | $h < 1.5$ |
| $13.3\,h + 60$ | $h > 1.5$ |

Fig.1 : Common variogram models (from Delhomme, 1976). Here, *h* denotes the length of the vector h. The expressions are given for $\gamma$(h).

$X_i$ = weighting factors

$C(O)$ = General covariance

$C(X_i,X_o)$ = covariance between the points $X_i$ and $X_o$.

$\mu$ = Lagrange multiplier

Note that the variance of the estimation error $\sigma k^2$ of random variable. It is instead a measure of the uncertainity in the estimation of Z at the unmeasured location. By defination the $\sigma x^2$ at measured location is zero.

The square root of variance of estimation error $\sigma x^2$ gives the standard deviation of estimation error $\sigma k$.

**Confidence Interval**

Knowing the variance of error is in principle, not enought determine the confidence interval of estimation. However, since it is assumed that the distribution of error is normal, in that case that 95% confience interval is + $2\sigma k$ and 67% confidence interal is + $\sigma k$ where $\sigma k$ is standard deviation of error.

$$\sigma k = \sqrt{Var}\ (Z^*-Z_o)$$

Then estimate of $Z_o$ with 95% chance is

$$Z^* \pm 2\sigma k$$

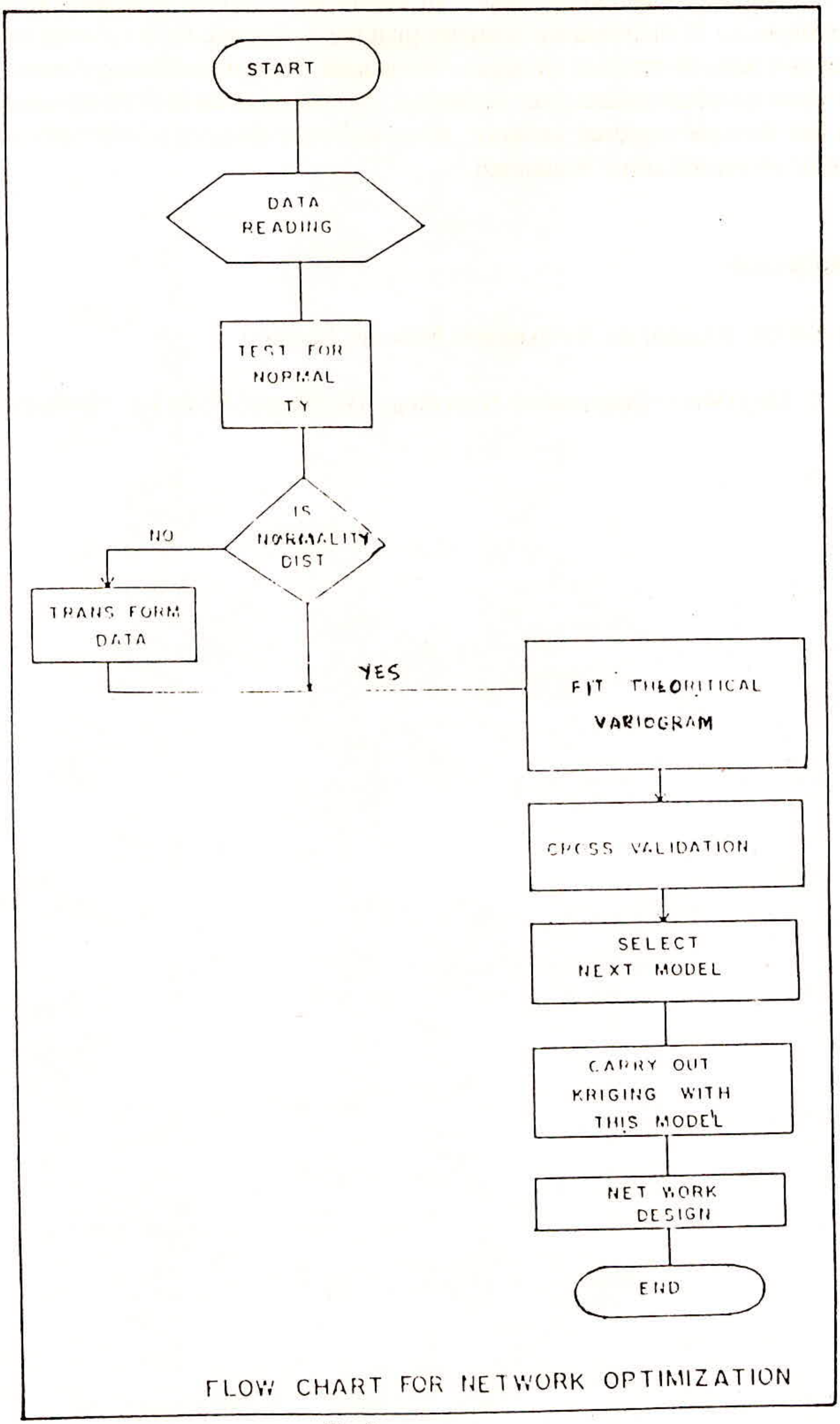
## 4.3 NETWORK DESIGN AND OPTIMISATION

The various stages involved in the design of network stations using kriging is shown in the form of a flow chart (Fig. 2).

The kriging variance of estimation error is a very powerful tool for optimizing a network because of the formula

$$\sigma k^2 = Var\ [Z^*(X_o)-Z(X_o)]$$
$$= C(0) - \sum_{i=1}^{n} \lambda_i\ C(Xi,Xo) + \mu$$

The Kriging variance depends only on the semi variogram and the configuration of the observation points in relation to the points estimated. It does not depend on the observation value. Therefore, if semi variogram is already known, the variance or standard deviation of estimation error for any particular water level observation can be estimated.



FLOW CHART FOR NETWORK OPTIMIZATION

Fig 2

The variance/standard deviation of estimation error is calculated by selecting new observation wells. If the variance is higher than the acceptable limit in some part of the study area then few new observation wells are introduced. This procedure continues till the desired level of variance of estimated error is reached. On the other hand if the variance of estimated error is low then the required variance, some wells are dropped till the satisfactory value of variance of estimated error is attained.

## REFERENCES

CGWB (1995), Manual on Hydrograph Network Station.

Marsily G De (1986), Quantitative Hydrology (Academic Press Inc. Santiago)