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Importance of mapping of subsurface structures precisely in groundwater modeling

C.Krishnaiah
Central Water and Power Research Station, Khadakwasla, Pune - 411 024
E.mail : krishnaiahc@yahoo.com

ABSTRACT
Groundwater, an important source of water supply in many regions of India, has been incessantly contaminated from various man made and natural pollution sources. Thus, concern over the potential for migration of wastes in the subsurface has generated a great deal of interest in the study of mechanisms responsible for contaminant transport through groundwater.

Numerical models have frequently been proved to be inadequate in spite of considerable efforts made to represent the actual flow mechanism in the subsurface on which contaminant transport depends. However, when modifications representing the flow mechanisms related to some undetected heterogeneous subsurface features were made, improvements were obtained in the agreement between field and modeled flow results. This is because if the subsurface heterogeneities such as fractures, dykes, buried channels or lenses are not known precisely, there is a chance of missing the presence of higher or lower hydraulic conductivity zones, leading to erroneous predictions.

In view of the above, finite element numerical modeling technique is used to study the effect of the presence of various subsurface structures, which control the flow mechanism and in turn alter the transport phenomenon. A base case of a homogeneous subsurface is considered and changes in the subsurface flow pattern aroused by heterogeneities were compared and examined. The study indicated that the spread of pollution depends on hydrogeology at the source. It is noticed that the existence of dykes, fractures and buried channels and their orientation modeled in the area greatly influenced the spread of pollution. The spread of contamination also depends on presence of lenses like clay or sand. From these results it can be concluded that if the subsurface is not precisely mapped, the groundwater models may be proved inadequate in the prognosis of contamination transport.

INTRODUCTION

Understanding the heterogeneity in geological formations is critical for characterization of groundwater flow in the subsurface. Subsurface heterogeneities include variations in grain-size, porosity, lithologic texture, structure and diagenetic processes. All these factors cause variations in hydraulic conductivity, storage and porosity, and thus control flow and transport through the subsurface. Geological heterogeneity is recognized as a major control on aquifer yield, and constrains many other aspects of quantitative hydrogeology such as model calibration and recharge estimation. Geological heterogeneity though may be readily apparent in surface outcrops and well logs, these represent only small windows into subsurface aquifers and analogous outcrops may not even be present for many groundwater systems.

Quantitative hydrogeology originally did not emphasize geological heterogeneity because its theoretical foundation is based on flow through a homogeneous medium, which is a gross simplification when applied to the heterogeneous real world (Eaton 2006). He further states that, this is because in the beginning hydrogeologists primarily focused on problems of water supply in relatively uniform and highly conductive porous media.

In the beginning, Darcy (1856) conducted his experiments with the goal of evaluating the size of sand filters needed for municipal water supply, resulting in an empirical law. Theis (1935) developed an approach to calculate aquifer properties by mathematical analogy to heat flow in homogeneous materials. It was only with the advent of studies on groundwater contamination (Bredehoeft & Pinder 1973; Pinder 1973; Fried 1975) that the importance of geological heterogeneity began to be recognized. However, the limitations of computer simulation capability have long been a constraint on quantitative analysis of groundwater flow, resulting in assumption of relatively homogeneous media. In recent years, flow simulation has benefited from powerful computer processors and graphical user interfaces. So, the major obstacle to represent geological heterogeneity in groundwater flow models now has been overcome. However, incorporating truthful subsurface information about the heterogeneity is still imperfect.

In spite of considerable efforts made towards detailed studies of the ability of analytical and numerical models to represent field behaviour, the models have sometimes been proved to be inadequate as field data are either insufficient or unreliable. Questions have been raised about the ability of the model to represent actual flow mechanism on which contaminant transport depends. According to Rushton (1987), when modifications representing the important features of the flow mechanism were made, improvements were obtained in the agreement between field and modeled flow results. That is to say that if the flow mechanisms related to some undetected heterogeneous subsurface structures are ignored, the model will have adverse affects. Groundwater hydrology would be deterministic only if we knew all aquifer parameters at every point in an aquifer. Our ability to model subsurface flow and transport would be severely undermined by lack of information, a problem that cannot be resolved with mere computational resources. The purpose of this paper is to demonstrate the importance of knowing the heterogeneity of an aquifer adequately and its characterization in flow and transport models.

METHODOLOGY

Finite element numerical modeling technique was used to study the effect of the presence of various subsurface heterogeneities on transport phenomenon by comparing with a homogeneous subsurface model. Galerkin Finite Element Method (GFEM) was used to solve the governing equations of this model. To implement GFEM for solving the mathematical model, a software FEMTRANG was developed in FORTRAN 77 by Krishnaiah (2003) and verified with the standard analytical solution of a one-dimensional and two-dimensional numerical model of Sun & Yeh (1983) with good agreement. The study is described in the following paragraphs.

Homogeneous subsurface (a base case)

Initially a base case of a homogeneous subsurface was considered so that subsequent cases having different in-homogeneities can be compared and examined. A two-dimensional hypothetical problem of aquifer system with irregular geometry was considered and a finite element mesh as used by Sun and Yeh (1983) was adopted (Fig 1). The problem assumed in this case was discharging of effluents from an industry having concentration of (c′) 10 units into a small stream as shown in the Figure 1. The bottom of the stream was assumed to be sufficiently close to the groundwater

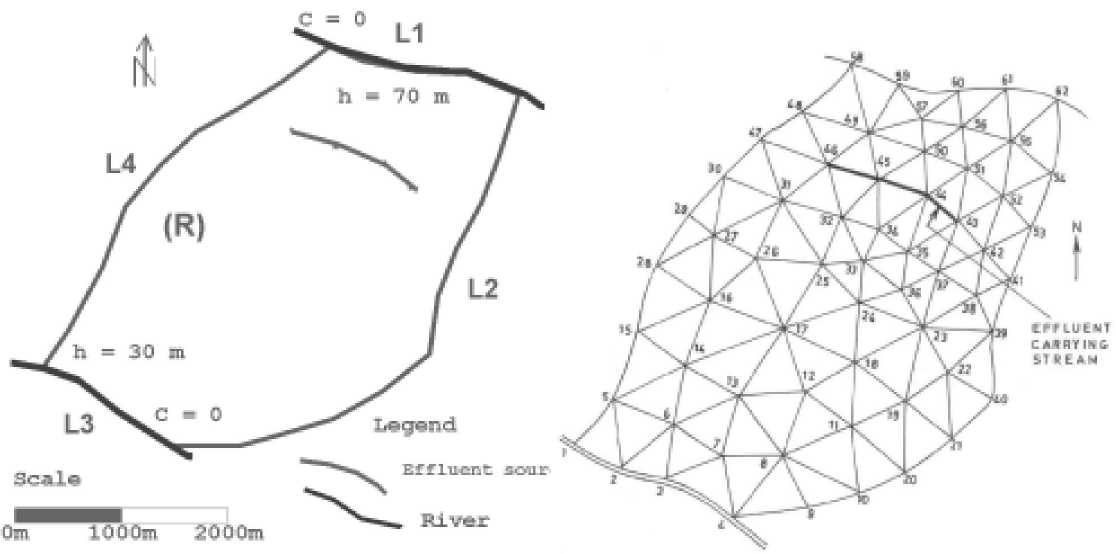


Figure 1. Aquifer system with irregular geometry between two rivers and triangular finite element discretization scheme (Sun & Yeh, 1983) for a base case.

table so that flow in the unsaturated region could be neglected. The aquifer was understood to be initially uncontaminated having background concentration value of 2 units.

The following conditions were assumed for the aquifer under study (Fig.1). West (L4) and east (L2) sides of the boundaries of aquifer of the region (R) were impervious, and rivers that maintain constant head, 70m and 30m respectively from an arbitrary reference level of zero bound its north (L1) and south (L3) boundaries. The region was divided into 97 elements with 62 nodes (Fig.1). It was also assumed that a steady state flow of groundwater was established and the scenario of groundwater table contours and effluent distribution are shown in Fig. 2.

The most common heterogeneities that may be present in the subsurface for the present study are given in Table 1 and the input parameters considered for the simulation of flow and concentration distribution of effluent are tabulated in Table 2. The model was run and the resultant water table distribution and the effluent concentration spread are shown in Figure 3 (a-h) for the heterogeneities considered.

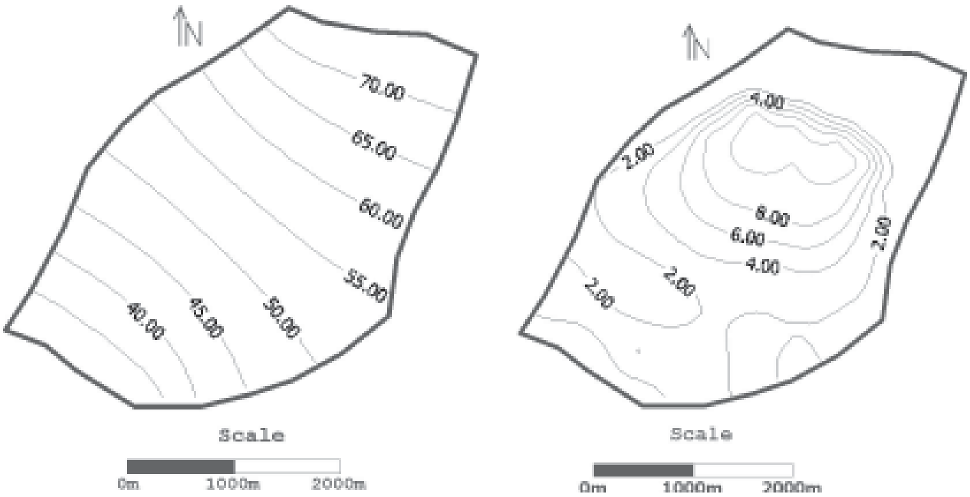


Figure 2. Contours of groundwater heads (m) and concentration for the base case at t = 20 years.

Table 1. Various subsurface heterogeneities considered in the modeled area.

1. Location of the source

Geological strata considered below the location of source:

1. A clay zone.
2. Sand/Alluvium zone.

2. Lineaments

Lineaments considered in the down gradient of source of pollution:

a. Impermeable dyke.

b. Permeable structure like fracture.

i. Extent of the lineament is restricted within the boundaries.

ii. Lineament is extending in L2 -L4 direction cutting boundaries.

c. Buried channel

3. Lenses

Lenses in the downstre am side of the source of pollution:

1. sand lens, and
2. clay lens

Table 2. Input values considered for different subsurface heterogeneities.

Model Parameters	Parameters Values							
	Base case	Source at clay zone	Source at alluvium	Dyke	Fracture	Buried channel	Sand lens	Clay lens
Hyd. con. K (m/Day)	3	0.1	15	0.1	15	15	15	0.1
Long. disp α_L (m)	50	20	100	10	80	100	100	20
Tran. disp α_T (m)	20	8	40	4	30	40	40	8
Porosity θ	0.18	0.3	0.3	0.1	0.25	0.2	0.3	0.3
Source concentration $c' = 10$ units Retardation factor $R_f = 1$ Time of simulation $t = 20$ years								

RESULTS AND DISCUSSION

Location of the source

Two possible geological strata viz., clay zone, sand/ alluvium were considered below the location of source (Fig.3a and b). In the case of clay, from the water table distribution and the effluent concentration spread it can be seen that the spread of the effluent is restricted to smaller area when compared to that of the base case (Figure 3a and b). This is due to the presence of zone having lower hydraulic conductivity at the source resulting reduced hydraulic gradient in the groundwater flow direction. In the case of Sand/ Alluvium, from the effluent distribution it can be observed that the effluent spread is much more than that was observed in the previous case. This is attributed to the existence of higher hydraulic gradient in the groundwater flow direction.

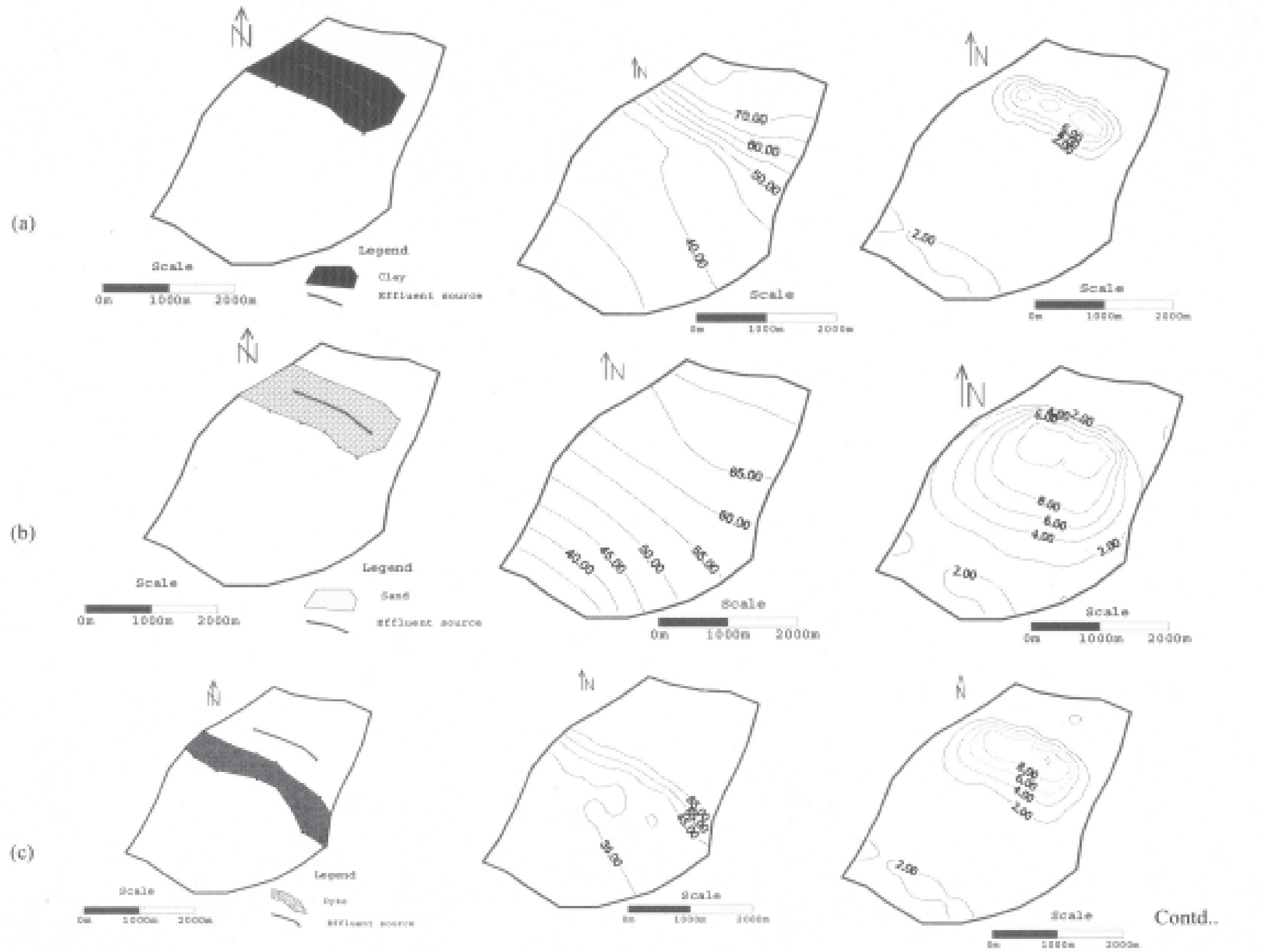
Lineaments

a. Dykes

Presence of concealed dykes in the subsurface control the movement of the groundwater because of their impermeable nature. It would act as a barrier to groundwater flow. From the Figure 3c , it is clear that the effluent which otherwise would have spread to longer distances (base case), is restricted to smaller distance because of the presence of the impermeable dyke.

b. Fractures

The extremely heterogeneous nature of fractured rock makes it difficult to apply conceptual approaches and field techniques that would have been used with more homogeneous unconsolidated aquifers. In fractured rock, historical and current regional and local stress fields control the occurrence of geologic structures and fractures are the predominant pathways for fluid movement. Joints, bedding-plane partings, and sometimes faults commonly are referred to as fractures and are not distributed uniformly through rock, thus making assumptions that commonly are applied to unconsolidated porous media, such as homogeneity and anisotropy, inappropriate (Sanford et al., 2006). Also, because individual fractures can have spatially varying characteristics and the connectivity of fractures can be highly complex, hydraulic properties of fractured rock do not vary smoothly in space. Because of the extreme heterogeneity in fractured rock, no single technique or interpretive approach can be used to explicitly and unambiguously map the spatial distribution of hydraulic properties that control fluid movement and chemical migration. Fractures go unnoticed unless a systematic investigation of the area is carried out. A few such situations are considered in the following cases.



i. Extent of the lineament is restricted within the boundaries

When compared to the case of dyke, in this case the effluent is spread to longer distances due to presence of higher hydraulic gradients in the down gradient of the source (Fig.3d).

ii. Lineament is extending in L2-L4 direction cutting the boundaries

In this case, the lineament (fracture) is considered at same location. However, it extends cutting across the L2 and L4 boundaries of the area. From the simulated results (Fig.3e) it is clear that water table contour having value 55 m is distorted when compared to the earlier case and the spread of the effluent is increased in the L2 and L4 directions. This is because the boundary is open at the location of the fracture.

c. Buried channel

Usually buried or palaeo-channels would not come into scientific notice unless the area under modeling is investigated properly. These higher permeable geological features play a crucial role in the groundwater movement that affects the subsurface pollution transport. One such case is considered to study its effect on pollution transport. A palaeo-channel, which cuts the pollution source and meets the boundaries L1 and L3, was assumed (Fig.3f). From the results of the simulation it is clear that in the presence of buried channel the plumes arrive faster than that in the base case. Had the palaeo-channel been unnoticed the pollutant would have arrived faster than predicted.

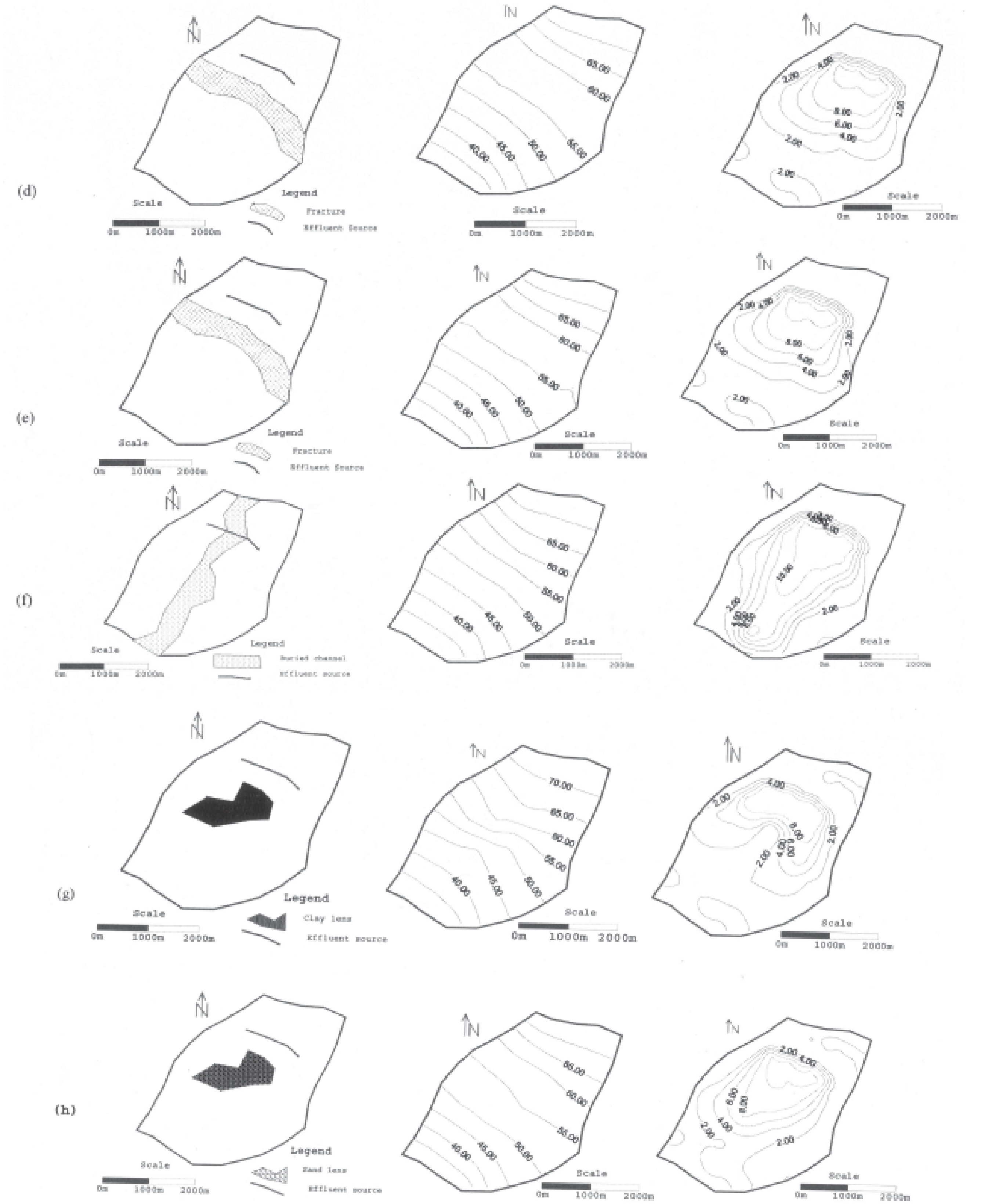


Figure 3(a-h). Location of subsurface heterogeneities and the resultant groundwater flow and pollution distribution. a. Clay Zone, b. Sand / Alluvium Zone, c. Dyke, d and e, Fracture, f. Buried Channel, g. Clay Lens and h. Sand lens

Lenses

The two types of lenses (Sand and Clay) that were considered in the down gradient of the pollution path (Fig. 3g and h) to study their effect on the groundwater table and the pollution transport show that the lenses having different flow and transport characteristics have different effects on water table and effluent transport distribution. In case of a clay lens that is embedded in material having more permeability, there is a greater dispersion than that in the base case. This is because the plume gets deflected around the clay lens. In case of sand lens the spread of the plume is more in longitudinal direction. This is because the pollutant moves more readily through the path of higher permeable zone. This phenomenon was also observed from laboratory experiments conducted by Skibitzke & Robinson (1963).

Conclusions

When a homogenous subsurface (a base case) is compared to that with a heterogeneous subsurface, the following inferences can be drawn:

- The presence of clay zone at the location of source restricts the spread of the plume where as the pollution spread is faster with the existence of sand/alluvium formation at the source.
- Being impermeable, a dyke near the source obstructs the spread of the contamination and the presence of fracture near the source allows the plume to spread faster in the space. The direction of spread depends on orientation and extension of the fracture.
- In the presence of palaeo-channel, the plume moves faster along channel in groundwater flow direction.
- In case of existence of either permeable or impermeable lenses in the area of modeling, the spread of pollution is more than that in the base case. In the case of clay lens, the spread is more in transverse direction i.e., around the clay lens, and in case of sand lens, the spread is more in longitudinal direction i.e., through the sand lens.

From this study it can be observed that, if representative flow mechanism resulting from subsurface structures were provided to the transport model, it would become a useful tool in the groundwater contamination analysis. Hence, it can be concluded that knowing the correct hydro-stratigraphic information of the flow domain is an essential pre-requisite for the construction of useful numerical model. Neglecting the in-homogeneities present in the subsurface would lead to significant errors in the prediction of contamination distribution. The suggested importance and limitations of the modeling, however needs to be tested in the case of a practical problem (case study). Such an exercise helps in knowing the percentage of errors involved in real cases.

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Dr C. Krishnaiah, obtained his M.Sc (Tech) in Applied Geophysics from Centre of Explore Geophysics (CEG), Osmania University, Hyderabad in 1986. He worked as Stipendiary Geophysicist in CEG for one year. He served as a Research Assistant in CSMRS, New Delhi for three and half years and after which he joined CWPRS as Research Officer. Now, he is working as a Senior Research Officer and received his Ph D in Geology from University of Pune 2003. Further he did his M. Sc in Geoinformatics from Sikkim Manipal University. His area of specialization is Engineering and Groundwater Geophysics. He offered solutions to about 30 real time problems under different geological settings. He has 21 research papers in national and international journals.