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Subsurface Hydrology at Waste Disposal Sites

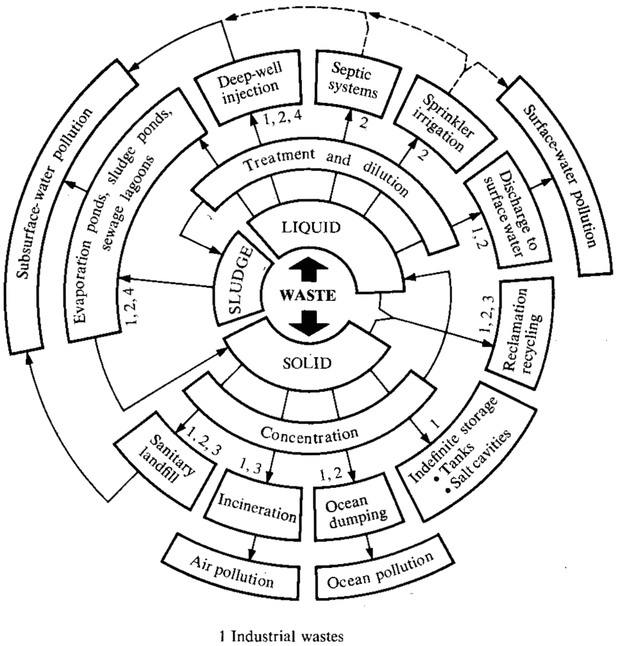
Abstract: One result of the growing concern over surface-water pollution has been an increase in the popularity of ground-based waste disposal practices that save the streams but have a high potential for subsurface pollution. One of these, sanitary landfill, appears quite promising in its ability to handle large waste loads with a minimum of contamination; but two others, waste lagoons and deep-well injection of liquid wastes into geologic formations, lead to irreversible subsurface pollution. In all cases, the mechanism of pollution is an interaction between the pollutant source and the existing soil-moisture and groundwater flow systems. A mathematical model of the subsurface flow can be used to predict this interaction and to assess the impact on the environment of a proposed disposal site. The model applied in this paper can predict transient and steady state subsurface flow systems in two or three dimensions and includes consideration of both the saturated and the unsaturated zones. It can be applied at the reconnaissance stage on a regional basis to analyze a large number of alternative sites and at the chosen site to test the efficiency of various design alternatives and to provide guidance in the design of a monitoring system. The model predicts only convective transport and does not consider dispersion or hydrochemical reactions.

Introduction

• *Waste disposal and the subsurface environment*

The disposal of waste is usually a case of choosing the least objectionable from a set of alternatives (Fig. 1). There are no currently feasible waste disposal methods that do not have the potential for serious pollution of our natural environment. While there has been a growing concern over air and surface-water pollution, the current activism has not yet encompassed the subsurface environment. In fact, the pressures to reduce surface pollution are in part responsible for the fact that those in the waste management field are beginning to covet the subsurface as a waste disposal site. The two disposal techniques now viewed most optimistically for the future are deep-well injection for liquid wastes and sanitary landfill for solid wastes. Both these techniques can lead to subsurface pollution. In addition, subsurface pollution can be caused by leakage from ponds and lagoons, which are widely used as components of larger waste disposal systems.

Proposals to allocate portions of the subsurface to waste disposal clearly fall in the realm of social choice. It is important that the environmental ramifications of such a choice be fully understood. Groundwater accounts for over 95 percent of the world's freshwater storage. It



1 Industrial wastes (including radioactive)
2 Sewage and Agricultural wastes
3 Municipal refuse
4 Oilfield brine

Figure 1 Waste disposal alternatives.

provides one-fifth of all water used in the United States and in some areas is the major source of supply. Further, the subsurface flow systems are inextricably linked to the surface-water systems by the interactions of the hydrologic cycle and there is always a high probability that pollution of the subsurface will ultimately contribute to surface-water pollution. One can also argue that the storage capacity of subsurface geologic formations is a valuable but limited natural resource. Proper management of this resource requires that waste disposal be considered in competition with other possible uses of the subsurface, such as underground gas storage and artificial ground recharge. Subsurface waste disposal should not be considered a practical alternative unless priorities have been established and protection can be provided for the total hydrologic environment.

The mechanism of subsurface pollution is an interaction between the pollutant source and the existing soil-moisture and groundwater flow systems. Polluted water enters a regional system in which the flowlines are controlled by the hydrogeologic setting. Flow arises in regional recharge areas and discharges at the surface in streams, lakes, and swamps. If representative values of the soil and formation properties are available, it is possible to analyze these systems. One of the most powerful methods of analysis involves the use of mathematical prediction models based on the equation of subsurface flow and solved numerically with the aid of a digital computer. With such models one can calculate the length of the flow path and the time of travel from a pollutant source to a surface discharge point or from a pollutant source to a freshwater aquifer. The models can be applied on a regional scale to assess the relative suitability of many alternative sites and on a local scale at the site to predict the consequences of various proposed designs. Models can also provide guidance in the design of monitoring systems. They may even have application in the preparation of improved legislation and regulatory codes.

• *Hydrodynamics and hydrochemistry*

Pollutants move through a subsurface flow system by a complex interaction of four processes: convection, dispersion, molecular diffusion, and hydrogeochemical retardation. Under convective transfer, pollutants travel at the same rate of flow and in the same direction as the carrier fluid. This is the primary mechanism. The other three processes are secondary mechanisms that lead to some divergence from this idealized transport process.

Dispersion involves the longitudinal and lateral spreading of the pollutant under the influence of the random interaction of fluid flow paths and soil grains when viewed at the microscopic level. Dispersion tends to spread a pollutant front, with some pollutants arriving ahead of the convective front and some lagging behind. While convective transfers are quantitatively more important than the superimposed dispersive components, dispersion is nevertheless an important diluting influence.

Many authors have included molecular diffusion in their mathematical analyses, but all have concluded that its diluting influence is unimportant in comparison with dispersion.

Hydrogeochemical interaction between fluid and soil is probably the most important retarding influence on pollutant transport. There is a tendency toward the natural purification of a pollutant, particularly as it flows through fine grained sediments, due to ion exchange of chemical constituents, filtering action on bacterial agents, and the possible functioning of clay layers as semipermeable membranes. The degree and type of hydrogeochemical interaction are highly dependent on the chemical nature of the pollutant. For some pollutants, such as radioactive waste, we have a large body of research results on which to base predictions; for other pollutants, including most industrial wastes, hydrogeochemical data are scarce.

A full analysis of subsurface pollution should include all four processes. The model applied in this paper simulates only the primary process. It predicts the convective movement of pollutants through subsurface flow systems but does not take into account the effects of dispersion, molecular diffusion, and hydrogeochemical interaction. The *flow path lengths* determined from the solutions presented in this paper are independent of the pollutant type. The *times of travel*, on the other hand, are dependent on the dispersive and hydrogeochemical properties of the pollutant. The convective time calculations presented later predict the average travel time with respect to dispersion and provide a conservative estimate with respect to hydrogeochemical retardation. When the hydrogeochemical mechanisms are quantitatively understood, it would be reasonable to use retardation coefficients to obtain more accurate estimates of pollution buildup rates.

In succeeding sections of this paper, I briefly review the hydrogeologic state of the art for the three waste disposal methods that have potential for subsurface pollution and then describe how the hydrodynamic aspects of this art can be brought closer to science through the use of mathematical models.

Methods of subsurface waste disposal

• *Sanitary landfill*

The sanitary landfill is rapidly becoming the most commonly used method of solid waste disposal, especially for municipal refuse. Landfilling is carried out either as a trench-and-fill operation or as an area fill. The essential feature of either approach is a daily covering of the refuse with a layer of compacted earth material.

High-moisture-content regions are common within a fill. They may develop in three ways: by natural conditions in humid climates, where annual precipitation is in excess of evapotranspiration[1]; by saturation of the refuse from below under the influence of rising water tables[2]; and by water introduced to the fill by the user to obtain higher compacted refuse density[3]. The presence of continuous moisture movement and partial saturation in a fill produces a leachate with a high concentration of dissolved solids and bacterial pollutants. The leachate will move out of a fill and into the regional hydrogeologic system under the influence of the local soil-moisture and groundwater flow systems present at the site.

Increased use of sanitary landfill as a waste disposal technique has led to a number of recent research studies both in the laboratory[4] and in the field[2,5]. As a result, some criteria for sanitary landfill development are slowly evolving[6–8]. Geologically favorable sites involve a thick layer of low permeability material at the surface. These formations retard leachate movement, furnish separation from groundwater supply, and provide hydrochemical protection. Hydrologically favorable sites require flow patterns that do not lead to premature surface discharge nor to direct or rapid recharge of freshwater aquifers. There is a preference for sites well above the water table. At the present time, criteria and design features are based on rather arbitrary standards[7]. There is a need for flexible criteria that take into account the hydrogeologic setting and for site-oriented designs based on predicted performance. Several design modifications have been suggested, including highly compacted land covers to reduce infiltration, collection of leachate by tiles or pumping systems[2], and use of gravel drainage layers beneath the fill[9].

The general conclusion of past research studies is that the sanitary landfill appears to be a rather reliable waste disposal method that leads to little widespread water quality deterioration. Monitoring at favorable sites has shown only local pollution. There are, however, two serious reservations attached to this conclusion. First, sanitary landfilling is a relatively recent technique and only a few years of measurements are available. Steiner et al.[7] note that leachate appearance may be offset from the initial time of emplacement by as much as 20 years and that short-term studies may hence be inadequate to establish the magnitude of the problem. Second, there is little documentation of disposal at totally unfavorable sites, yet it is clear that such sites are often chosen due to social and political pressures.

Hydrogeologic concepts are often used qualitatively during siting. Monitoring is rare, although the two field-research studies[2,5] included onsite instrumentation to analyze the receiving groundwater flow systems. I could not locate any examples of the use of mathematical models.

• *Ponds and lagoons*

Waste-disposal texts are quick to point out that ponds and lagoons are an unsavory method of waste disposal. Yet they are in widespread use in waste disposal systems. They serve as sewage lagoons and evaporation ponds and are used for the drying of sludge (which is an unavoidable output of many types of waste-treatment facility). If properly sealed at the bottom, ponds do not present a source of groundwater pollution, but more usually ponds are built on the natural ground surface.

The interaction of the site with the groundwater flow system is similar to that for sanitary landfills, but contamination is much more likely to take place. Ponding creates saturation at the surface and downward propagation of a wetting front, which will eventually cause water-table mounding and a total integration of the pond with the subsurface flow system. In addition, the leachate is ready-made and in the case of industrial wastes is often more toxic and nondegradable than that which arises from sanitary landfill. The use of seepage pits, trenches, and ponds is the most common method of disposal of low-level radioactive wastes.

Two more positive types of ground disposal deserve mention. These involve the disposal of partially treated sewage wastewater by artificial recharge from spreading basins[10] and by sprinkler irrigation[11]. There are technical problems, and the capacity of porous media to assimilate pollutants under the self-purification process is not yet fully understood, but research continues. Mathematical models should have a role to play in furthering this understanding.

• *Deep-well injection*

In the last ten years there has been a mushrooming literature proposing injection of liquid industrial wastes into deep geologic formations. The articles range from those that seem to express little concern for environmental safeguards to the cautious approval expressed by Warner[12] in the most comprehensive review of this subject. Recently, however, the environmental alarm has been sounded[13–15]. Piper[14] had these comments:

"In its predilection for grossly oversimplifying a problem, and seeking to resolve all variants by a single massive attack, the United States appears to verge on accepting deep injection of wastes as a certain cure for all the ills of water pollution."

"Injection is no more than storage—for all time in the case of the most intractable wastes—in underground space of which little is attainable in some areas and which is exhaustible in most areas."

"Admittedly, injecting liquid wastes deep beneath the land surface is a potential means for alleviating pollution of rivers and lakes. But, by no stretch of the imagination is injection a panacea that can encompass all wastes and resolve all pollution, even if economic limitations should be wained. Limitations on the potentials for practical injection are stringent indeed—physical, chemical, geologic, hydrologic, economic and institutional."

As yet, the number of injection wells in the U.S. is not great (124 in 1970[12,14]), but pressures to clean up surface-water pollution will undoubtedly lead to an increase of several orders of magnitude in the next few years. The wells are often used for the most toxic and nondegradable wastes: sulfuric and hydrochloric acids, steel mill pickling liquors, cyanide wastes, spent caustics, and phenols[12–14]. Deep-well injection is also being considered for radioactive wastes[8,16,17].

Most states have regulatory processes for deep-well injection, but many of these are based on statutes designed for the return of oilfield brine to the subsurface. There are important differences between the reinjection of brine into the formation from which it came and the injection of waste[14]. The criteria built into the various regulatory processes are often weak and qualitative. It is generally recognized that suitable geologic formations must be thick sedimentary formations of large area and high porosity and permeability and that such formations must be confined by low permeability strata. It is usually required that they contain saline water and be well below freshwater formations. However, the criteria often neglect the fact that injected waste will enter and alter an existing flow system. Movement and mixing will take place under the natural and imposed hydraulic gradients and because of dispersion. Criteria are needed that favor low original gradients, small increases in gradient under injection, a limited degree of lateral invasion, and low rates of dispersion.

Broadly speaking, there are two types of failure of waste-injection wells. A *technical* failure arises when constructional or operational problems lead to abandonment because design injection rates cannot be delivered to the subsurface at design pressures. This type of failure is primarily of interest to the industry concerned. An *environmental* failure occurs when the waste-injection process leads to unexpected contamination of fresh-water resources or to mechanical damage to the geologic environment. The most documented account of deep-well failure of the latter kind concerns the injection well at the Rocky Mountain Arsenal near Denver, Colorado. At that site, a direct and conclusive correlation was made between injection volumes and pressures and seismic activity. Injection initiated 710 small earthquakes (up to 4.3 on the Richter scale) in four years[18]. Recently, the failure of the Baldwin Hills Reservoir in Los Angeles has also been ascribed to fault movement caused by increased pressure due to subsurface injection[19].

It is imperative that proposed waste-injection projects undergo the most rigorous kind of predictive analysis. This will require far greater amounts of field testing than have heretofore been carried out, together with the routine use of numerical mathematical models for predictive and design purposes.

Mathematical model of subsurface flow

The mathematical model that is applied in this paper is one developed by the author for three-dimensional, transient, saturated-unsaturated flow in a groundwater basin[20]. The programmed solution is versatile in that it can collapse from a transient analysis to steady state, from three dimensions to two, and from saturated-unsaturated systems to systems involving only one condition or the other. It allows consideration of nonhomogeneous and anisotropic geologic formations and admits any configuration of all pertinent boundary conditions. Naturally, the model owes much to earlier developments, particularly to the steady state and transient treatments of regional groundwater flow[21–23] and to Rubin's soil physics models[24].

Mathematical models of subsurface flow have been used only rarely in the siting of waste disposal projects and the few that have been used have been limited to saturated flow. Such models are satisfactory for deep-well injection analyses, but they are not suitable for the analysis of ground-based waste disposal methods such as sanitary landfill, where much of the flow may occur in the unsaturated zone. There is abundant evidence in soil physics literature that attempts to dismiss the near-surface unsaturated conditions from consideration can lead to serious error.

Equation of flow

The potential for the three-dimensional field governing fluid flow through porous media is

$$\Phi = gz + \int_{p_0}^{p} dp/\rho, \tag{1}$$

where Φ is the hydraulic potential at a given point, g is the acceleration due to gravity, z is the elevation of the given point above datum, p is the fluid pressure at the point, p_0 is atmospheric pressure, and ρ is the density of water.

Defining $\phi = \Phi/g$, setting $p_0 = 0$ (gauge pressure), and replacing p by $p = \rho g \psi$, we reformulate Eq. (1) as

$$\phi = z + \psi. \tag{2}$$

In this equation ϕ is the hydraulic head, z is the elevation head, and ψ is the pressure head. All are measured in cm of water above datum. The values of ϕ and ψ vary with time and space, whereas z is constant in time and equal to the elevation at any given point.

If we invoke Darcy's law, which relates the velocity of flow to the hydraulic gradient,

$$\mathbf{V} = K\nabla\phi, \tag{3}$$

and the equations of continuity for water and soil (both of which are considered to be compressible), we can develop a general equation of subsurface flow[20]:

$$\nabla \cdot [\rho K(\nabla\psi + \nabla z)] = \rho[S(\alpha + n\beta) + C]d\psi/dt. \tag{4}$$

This equation is developed in terms of the pressure head ψ, where $\psi > 0$ infers saturated conditions (as in the groundwater zone below the water table), and $\psi < 0$ infers unsaturated conditions (as in the soil moisture zone above the water table). The $\psi = 0$ isobar delineates the position of the water table. In Eq. (4) K is the hydraulic conductivity of the soil or geologic formation, n is the porosity of the soil (pore volume/total volume; moisture content by volume at saturation), S is the fractional saturation (moisture content by volume/porosity), α is the vertical compressibility of the soil, β is the compressibility of water, and C is the specific moisture capacity of the soil [defined in Eq. (5d) below].

It should be noted that

$$\rho = \rho(\psi); \tag{5a}$$

$$K = K(F,\psi) = K_{ii} = \text{principal components of the second-order tensor } [K_{ij}]; \tag{5b}$$

$$\theta = \theta(F,\psi) = nS; \text{ and} \tag{5c}$$

$$C = C(F,\psi) = ndS/d\psi = d\theta/d\psi, \tag{5d}$$

where θ is the volumetric moisture content and F refers to soil type or geologic formation. In saturated regions the hydraulic conductivity is a function of position due to the inhomogeneity of the geologic formations; i.e., $F = F(x,y,z)$. In unsaturated regions K is a function of position and time, even in homogeneous soils, because of the variation of K with ψ. The tensor notation for K emphasizes the common occurrence of anisotropic soils. Usually $K_{yy} = K_{xx} > K_{zz}$, where x and y are the horizontal coordinate axes. For any given soil, Eqs. (5b) and (5c) are the functional relations that describe the unsaturated hydrologic properties of the soil. Equation (5d) states that C is simply the slope of the $\theta(\psi)$ curve. At saturation, $K = K_0$ and $\theta = n$, where K_0 is a constant, equal to $(K_{xx}K_{zz})^{1/2}$, and n is nearly constant, varying only in deep compressible formations under large pressure changes. Figure 2 shows a set of characteristic curves of $\theta(\psi)$ and $K(\psi)$ for a hypothetical soil type. The unsaturated relationships are hysteretic with a dependence on whether the soil is wetting or drying.

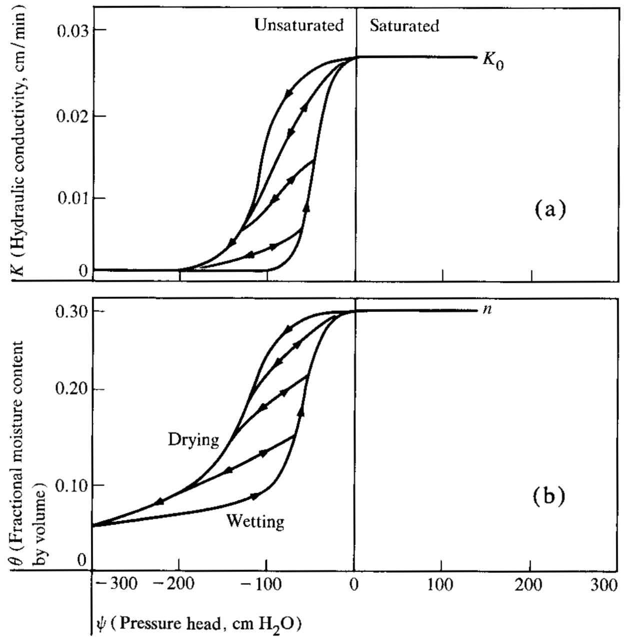


Figure 2 Functional relationships between pressure head and (a) hydraulic conductivity and (b) moisture content for a hypothetical unsaturated soil.

Referring to the right-hand side of Eq. (4), one should note that in saturated zones $S = 1$ and $C = 0$, and in unsaturated zones $\alpha = 0$ and the solution becomes so insensitive to the value of β that β is often set to zero. For steady state flow, the entire right-hand side of Eq. (4) is zero.

Numerical solution

Equation (4) is a nonlinear parabolic partial differential equation. In this study solutions were obtained with the line-successive over-relaxation (LSOR) method, oriented in the z direction, using a block-centered nodal grid with variable mesh spacings. This technique is an iterative numerical scheme that uses implicit finite-difference formulations. Details are included in Ref. 20.

Programming of the solution was carried out in FORTRAN IV. The program is written in such a way that the region can be of any general shape as long as it does not lead to a discontinuity in any vertical nodal column.

At any boundary node, boundary conditions can be imposed that specify the flux, the head, or no-flow conditions. One can write the boundary conditions in terms of either the total hydraulic head ϕ or the pressure head ψ. For example, along an x-y boundary, we can impose any of the following conditions:

$$\phi = \phi_c \text{ or } \psi = \phi_c - z; \tag{6a}$$

$$\partial\phi/\partial z = 0 \text{ or } 1 + \partial\psi/\partial z = 0; \tag{6b}$$

$$K_{zz}\partial\phi/\partial z = I \text{ or } K_{zz}(1 + \partial\psi/\partial z) = I, \quad (6c)$$

where ϕ_c is a constant head and I is a constant flux. The flux I could be a rainfall rate or a water-spreading rate or, if negative, an evaporation rate.

It is also possible to simulate an internal source representing a recharge well. The node containing the well itself is considered to be outside the model, and the six surrounding nodal blocks are treated with the appropriate form of the flux boundary (6c), with the I values set to simulate the desired total recharge rate Q. It is also possible to represent an internal source by a constant head node using condition (6a).

The specified head or flux conditions at a node may vary from time step to time step, so that $\phi_c = \phi_c(t)$, $I = I(t)$, or $Q = Q(t)$. The conditions may also change from one boundary type to another during the course of solution. An application of this latter option occurs when a high rainfall rate creates ponding at the surface and (6c) reverts to (6a) across the upper boundary.

For steady state solutions only boundary conditions (6a) and (6b) are appropriate. For transient solutions a set of initial conditions must also be supplied. The program allows specification of constant hydraulic head ϕ throughout the system, constant pressure head ψ throughout the system, or any initial configuration of steady state flow conditions.

The fact that the unsaturated flow parameters K and θ are nonlinear functions of the dependent variable ψ adds some complexity to the method of solution. The functional relationships (Fig. 2) are built into the program in the form of a table of values representing the coordinate points in a line-segment representation of the curves. During the iterative solution, linear predictor equations are used at the beginning of each time step and the parameter values are corrected implicitly at each iteration. This technique introduces some stability restrictions which are outlined in Ref. 20.

The necessary input data for a simulation are

1. specification parameters: two- or three-dimensional; steady state or transient; all saturated, all unsaturated, or saturated-unsaturated;
2. region shape and size, and mesh design;
3. values of ρ, β, and g;
4. values of over-relaxation factor and other parameters that control numerical solution and plotting scales;
5. boundary condition configuration and boundary values of ϕ_c and I;
6. initial conditions;
7. configuration of soil types and geologic formations; and
8. hydrologic properties for each soil type: functional relations $\theta(\psi)$ and $K(\psi)$ with the saturated-soil values n and K_0, and the compressibility α.

Output from the program is in the form of plots of pressure-head (ψ), hydraulic-head (ϕ), and moisture-content (θ) fields for any desired cross section at any time step. From the pressure-head diagram one can locate the position of the water table; from the hydraulic-head diagram, one can determine the flow velocity at any point, the times of travel along various flow paths, the rate of infiltration at the waste source, and the rate of discharge to the surface at the exit points.

At the present time there are computer limitations (on both time and storage capacity) to the use of numerical simulations for three-dimensional transient systems on a regional scale. Small-scale, three-dimensional transient systems, three-dimensional steady state systems, and regional, two-dimensional transient systems can be handled. In this paper, I have limited myself to two-dimensional cross sections. The simulations were carried out on an IBM System/360 Model 91 at the Thomas J. Watson Research Center; rapid plotting was facilitated by a Stromberg-Datagraphix Model 4020 photographic plotter. Computer times were in the range of one to eight minutes for steady state problems and ten to 30 minutes for 100-time-step solutions to transient problems. A three-dimensional transient system solution is included in Ref. 20.

Applications

• *Regional reconnaissance*

A reasonable starting point in the siting of a waste disposal project is a steady state analysis of the natural regional flow system. Such an approach provides a prediction of the long-term-average flow conditions without considering the transient influences of the time-dependent climatic conditions and occasional artificial perturbations at the surface. Field experience has shown the steady state approach to have merit in regional reconnaissance studies [22].

Figure 3 outlines a two-dimensional vertical cross section through a hypothetical basin. The dimensions of the section are 3000 m long by 110 m deep. The mathematical model for this section consists of a 96 × 38 nodal grid with uniform nodal spacings of 30 m in the horizontal direction and 3 m in the vertical direction. The subsurface boundary ABCDEF is considered to be a no-flow boundary. Along the surface AHGF the average annual pressure heads ψ are specified and range from −1500 cm ($\theta = 0.02$) at the topographic high at H to 0 ($\theta = 0.30$, saturation value) at A and G, where streams are assumed to flow in a direction perpendicular to the diagram. Were this a real basin, the surface heads would be based on the average annual soil moisture conditions as determined from the available field data, but with the added constraint that steady state solutions using these heads must pre-

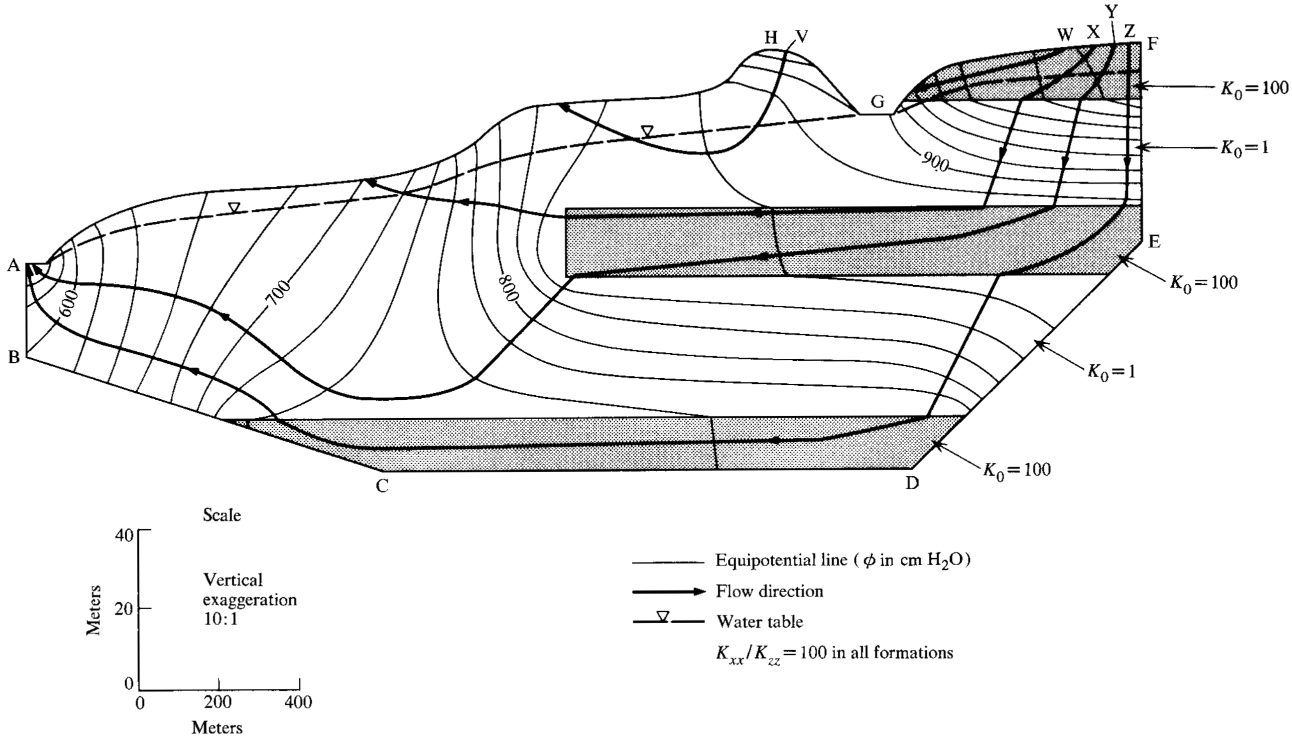


Figure 3 Steady state regional flow in a vertical cross section through a groundwater basin.

serve a water-table configuration corresponding to the average annual recorded depths.

Several geologic layers have been built into the model, with the unsaturated hydrologic properties of each represented by the individual wetting curves of Fig. 2. All the layers have the same porosity value n, but they have different values of the saturated hydraulic conductivity K_0. The relative K_0 values are noted on the diagram. For all layers an anisotropy $K_{xx}/K_{zz} = 100$ was chosen. If the flow net is plotted at a 10:1 vertical exaggeration, the orthogonality relationship between equipotential lines and flow lines is preserved[22].

The steady state hydraulic-head field determined from the mathematical model is shown in Fig. 3. Flow is essentially from right to left with the flow quantities concentrated in high permeability layers. The dashed line represents the water-table position and the heavy arrows outline the flow paths originating from several points on the surface. The diagram emphasizes that radically different flow paths may emanate from closely neighboring surface points. If these points represent the locations of proposed waste disposal facilities such as sanitary landfills and waste lagoons, it is possible to analyze the natural flow pattern in terms of the desirability of the proposed sites.

Table 1 lists the hydrogeologic data that can be garnered from the simulations shown in Fig. 3. The absolute value of the saturated hydraulic conductivity K_0 [$= (K_{xx}K_{zz})^{1/2}$] has been arbitrarily set equal to 5 cm/day for the least permeable layer. The depth to the water table can be read directly from the diagram. The other calculations are complicated by the vertical exaggeration of the plot, the anisotropic K values, the $K(\psi)$ variation in the unsaturated zone, and the fact that the velocity, calculated from Darcy's Law (3), is variable along any given flow path. To determine the values listed in Table 1, the flowlines were drawn orthogonal to the equipotential lines on the 10:1 vertical exaggeration of Fig. 3, and then redrawn at true scale to calculate the length of the flow path. Values of the horizontal hydraulic conductivity were used throughout the calculations, and the flow paths were divided into short linear segments over zones of travel.

The wide range of values listed in Table 1 may be surprising, but the values are consistent if one realizes that they result from an interaction of the permeability values, the gradients, and the distances traveled, and that all of these values range over two orders of magnitude. One of the shortest flow paths, that emanating from point V, has one of the longest times of travel. (This time would be halved, however, by the introduction of a waste pond at V that causes a water-table mound under H and discharges into the trough at G.) Despite a slightly longer flow path, site Z has a time of travel less than half that of

Table 1 Hydrogeologic data for comparison of the waste-disposal sites indicated in Fig. 3.

	Site				
	V	*W*	*X*	*Y*	*Z*
Saturated hydraulic conductivity at surface (cm/day):					
Horizontal	50	5000	5000	5000	5000
Vertical	0.5	50	50	50	50
Depth to water table (m)	20	12	12	12	12
Length of flow path (m)	540	360	1900	2800	2900
Time of travel (yr)	330	1.02	123	660	226
Entry rate at site (cm/day)	0.06	58	30	10	2.0
Discharge rate at exit point (cm/day)	0.75	78	1.5	3.5	5.0

site Y. This is because so much of its flow route traverses high permeability layers and avoids the low gradient, low permeability path just above point C in Fig. 3.

The flow pattern is strongly dependent on the geologic configuration[22]. Where uncertainties exist as to the extent or thickness of subsurface formations or their permeability values, several versions of the model should be analyzed. The values in Table 1 would then be best presented as ranges of possible values. It should also be noted that the configuration of the flow pattern depends only on the absolute values of K_0. The times of travel listed in Table 1 are inversely proportional to K_0. If all the permeabilities in the system were one order of magnitude larger, the times of travel would be reduced to the range of 0.1 to 66 years.

Ponds and lagoons

The use of detailed simulation at a specific site is best introduced for the relatively simple case of a waste pond. The construction of such a pond at the surface will produce a transient head buildup that will ultimately lead to a new steady state flow pattern with a groundwater mound connecting the natural system with the imposed pond. Design criteria should be based on the final expected steady state configuration.

Figure 4 shows how radically different this steady state system can be for two cases. In both, a 30-cm deep pond is located at AF ($\psi = 30$ cm, $\phi_c = 775$ cm). Along the remainder of the surface FED, natural rainfall and evaporation are ignored (although they could be taken into account) and an impermeable boundary is assumed. In Fig. 4(a) an impermeable geologic boundary exists along the base BC, and DC is an equipotential boundary with $\phi_c = 415$ cm. The result is a horizontal flow system with a fairly even water table slope. Although the hydraulic gradient is nearly constant along DC, the bulk of the outflow takes place below the water table. This is due to the effect of the significant permeability reductions (Fig. 2) over the range of unsaturated pressure heads that exist above the water table.

Figure 4(b) shows the inverse situation with DC being an impermeable boundary and BC an equipotential surface. The base of this model is presumably the upper boundary of an underlying high permeability aquifer. Here all the action is confined to the vicinity of the pond. Downward gradients are steep and the groundwater mound is pronounced. Almost all of the outflow crosses the lower boundary directly beneath the pond.

The hydraulic head difference between the pond and the equipotential boundary is the same in Fig. 4(b) as it is in Fig. 4(a) and the same isotropic, homogeneous soil is considered in each case. Yet the total outflow rate (and hence the total inflow rate) is 36 times greater in 4(b) than it is in 4(a).

Although the predicted steady state flow configuration is of direct design importance, it may also be of interest to know the nature and rate of the transient buildup. Figure 5 shows such an analysis for the case shown in Fig. 4(a). The initial condition is that of constant hydraulic head throughout the system with the water table at mid-depth. The boundary condition imposed at the pond in this case is a constant inflow rate $I = 0.05K_0$. With an inflow rate less than the saturated hydraulic conductivity K_0, ponding will not occur until the rising groundwater mound reaches the surface. Ultimate ponding is guaranteed by making the inflow rate greater than the predicted steady state throughflow I_{max}, calculated from Fig. 4(a) (here $I = 3I_{max}$). If I is less than I_{max}, a steady state flow system will arise in which the groundwater mound does not reach the surface. The calculation of this critical inflow rate is of direct interest in cases where ponding is undesirable, such as in the case of radioactive waste dis-

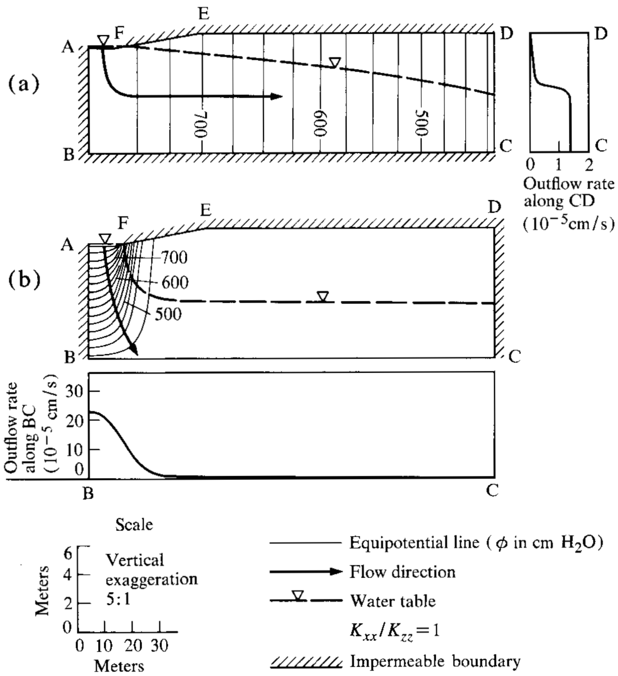


Figure 4 Steady state flow from a waste lagoon for two sets of boundary conditions: (a) impermeable base, equipotential side; (b) equipotential base.

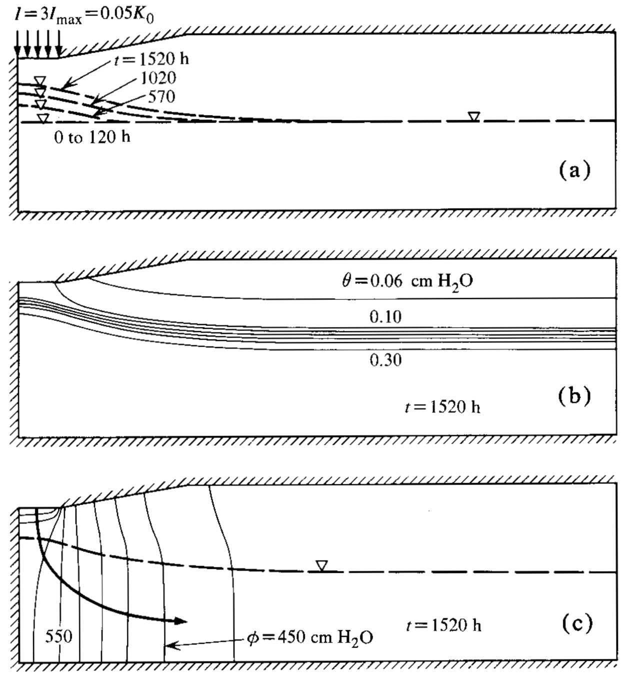


Figure 5 Transient buildup of a groundwater mound beneath a waste lagoon: (a) position of the water table; (b) soil-moisture-content field; and (c) hydraulic-head field.

posal. In fact, it may be generally desirable to keep the upper foot of soil unsaturated since this zone has a high potential for the removal of some pollutants under aerobic conditions[11].

Rather than imposing an inflow rate at AF, one could impose a constant-head boundary condition for the transient analysis. Then a saturated zone would propagate downward as well as upward and the water table mound would be created when the two fronts meet in the middle.

The simulation results shown in Fig. 5 were computed on a 24×25 nodal grid with variable spacing. A 300-time-step solution, taking 20 min computer time, carried the real time to 1520 h, or about two months. The groundwater mound did not reach the surface during this period and it would clearly be several more months before the final steady state configuration would be achieved. Figures 5(b) and 5(c) show the moisture-content field and the hydraulic-head field at 1520 h.

• *Sanitary landfill*

The hypothetical landfill site shown in Fig. 6 is similar to some reported in Illinois[2]. The discharge of leachates from the fill may occur at any or all of the three possible discharge points noted in Fig. 6(a) as 1) seepage from the base of the fill; 2) discharge to the stream at the right-hand side of the section; and 3) outflow to the underlying high permeability aquifer. The main purpose of the design considerations at a site such as this would be to determine the percentage of leachate outflow to each of the three discharge possibilities and to choose a design that maximizes the most desired flow condition and minimizes the least desired.

The boundary conditions in all the steady state cases analyzed in Fig. 6 show impermeable vertical boundaries on both sides and specified heads along the base and on the fill surface. The basal heads in Figs. 6(a) and 6(b) show a left-to-right gradient in the underlying aquifer. These two diagrams also have specified heads over the non-fill portion of the surface whereas the other parts of Fig. 6 specify a no-flow boundary there.

If the absolute permeability value of the homogeneous layer shown in Figs. 6(a) and 6(b) is low enough, and if hydrogeochemical retardation of the pollutant is known to occur, a single-layer site may offer sufficient geologic protection in the form of low flow rates and long travel times. In most cases the site should not be considered without the presence of a restricting layer between the surface formation and the underlying aquifer, as shown in Figs. 6(c) through 6(f). In all cases, a soil anisotropy ratio of 100:1 was used and the flow nets were plotted at a 10:1 vertical exaggeration. Since few data are available, the hydraulic characteristics of the landfill material

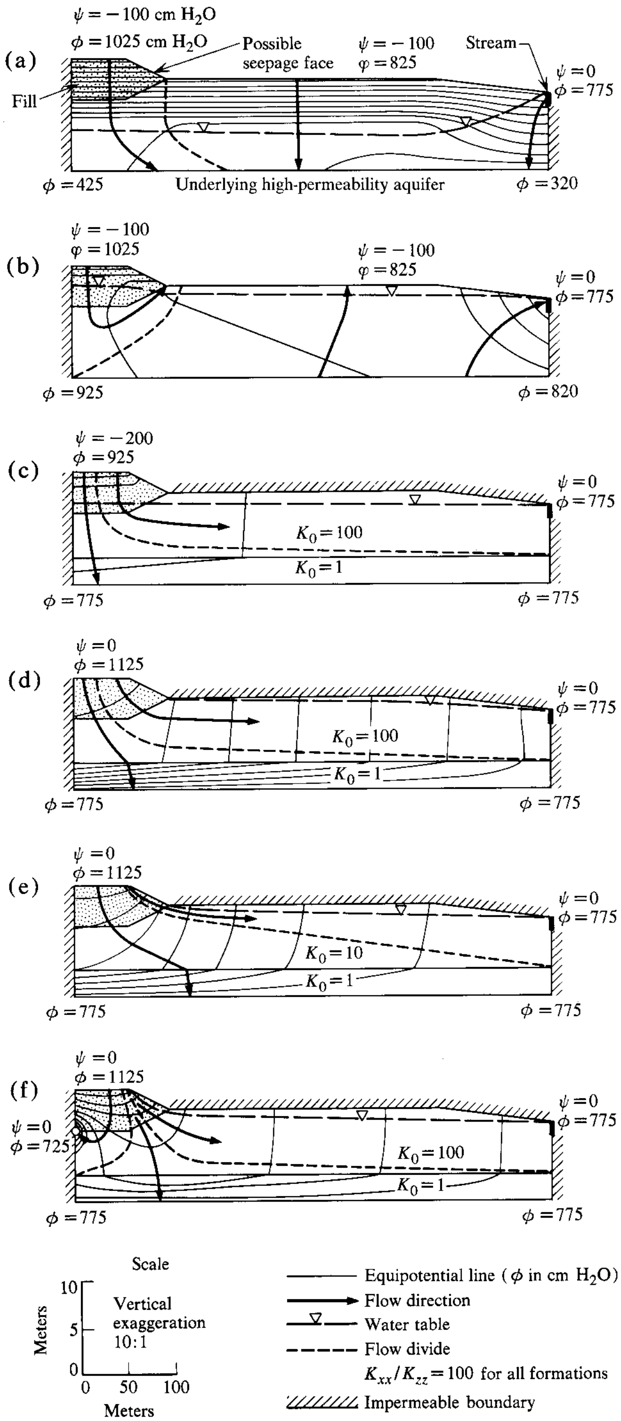


Figure 6 Steady state flow in the vicinity of a sanitary landfill for six sets of hydrogeologic conditions.

were assumed to be the same as the original surficial material. In actuality, the landfill material would probably show greater porosity and greater saturated permeability.

The diagrams of Fig. 6 are designed to show the dependence of the steady state flow patterns on several input parameters:

Table 2 Percentage discharge of leachates from the sanitary landfill shown in Fig. 6 to possible discharge points.

Discharge	*Landfill figure*					
	a	*b*	*c*	*d*	*e*	*f*
Underlying aquifer	100	0	40	40	90	8
Stream	0	0	60	60	10	12
Seepage from base of fill	0	100	0	0	0	0
Drain	0	0	0	0	0	80

1. the relative values of the hydraulic head in the underlying aquifer compared to those at the fill and the stream [compare 6(a) and 6(b)];
2. the average annual pressure head (moisture content) at the surface [compare 6(c) and 6(d)]; and
3. the permeability ratio between the restricting layer and the surface layer [compare 6(d) and 6(e)].

Table 2 lists the percentage discharges to the possible discharge points under the various hydrogeologic settings. The percentages for 6(c) and 6(d) are the same but the flow rates are quite different. The right-hand column of the table and Fig. 6(f) show the potential effect of a drain to divert flow from the natural discharge points to a leachate collection system.

There are some cases for which a steady state analysis, either at the site or on a regional scale, may be misleading. This is especially true when wide seasonal climatic variations induce gross seasonal divergences from the average annual conditions. This point is illustrated in Fig. 7. The flow system, but not the interpretation in Fig. 7(e), is taken from my earlier presentation [20] of the model. The figure shows the transient development of a flow system (including the development of a perched water table) from an initial steady state flow pattern with a very flat water table under the influence of a protracted rainy season or an annual period of melting snow. Figure 7(e) shows the location of the flow lines extending from two proposed disposal sites to their stream discharge points at $t = 0$, as determined from Fig. 7(b), and at $t = 460$ h, as determined from Fig. 7(d). Clearly, the flow lines have undergone a transient shift in location, thus introducing pollutants to a larger volume of the subsurface than might have been anticipated from a steady state analysis. In many cases the lengths of flow paths and times of travel may vary significantly through short transient periods and from season to season throughout the year.

The calculation of time of travel during the transient development of a flow system is complicated because the flow velocities are changing not only with space but also with time. If the transient buildup times are long, the first discharge of pollutants may be significantly later than that calculated from a steady state analysis of the final conditions.

• *Deep-well injection*

A complete mathematical model of the hydrodynamics at a deep-well injection site should consist of a three-dimensional transient analysis. Such an analysis would be an extension of the two-dimensional (horizontal) radial developments that are the basis of the pump-test technology so highly developed and widely used in the fields of groundwater hydrology and petroleum reservoir engineering. This technology has not been used to its full potential in the deep-well injection field, although reviews in the injection context are provided in Refs. 25 and 26, and recent developments in extending the analyses to the important, more permeable caprocks are described in Ref. 27. On the basis of pump-test theory, it is possible to calculate the waste volumes that can be injected at various design injection pressures.

Unfortunately, the pump-test analyses are seldom interpreted in the light of the regional flow system. In Fig. 8 I have tried to show with a steady state analysis the type of interaction that must be considered. This diagram shows the steady state equipotential pattern that would result from injecting fluid at point X into a system that is otherwise identical to that shown in Fig. 3. The design injection head is 88.5 m. (In that the analysis is two-dimensional, the injection point is actually a line-source rather than a point well, but the principles are the same.) The shaded area shows the steady state zone of flow lines introduced by the addition of the flow from the injection well. Once steady state conditions have been attained, it is this zone that would undergo permanent pollution. During the transient buildup there would be a shift in the flow-line location and a resulting transient zone of pollution. It would take a transient analysis to show the nature of this shift. It is possible that part of the shift would take place before the arrival of the contamination front and that the transient pollution zone would then be smaller.

Analyses similar to that shown in Fig. 8 were carried out for higher injection pressures. The results showed larger invasion zones that sometimes included part or all of the overlying central aquifer.

The purpose of this two-dimensional steady state analysis is illustrative only. A three-dimensional transient model integrating a well and a regional system is the proper modeling requirement at a proposed injection site. I have included such an analysis in Ref. 20 for a producing well.

Output from a transient analysis would include the time-dependent values of the hydraulic head and the pressure head at each node in the system (like the ϕ-t relationship shown in the inset of Fig. 8 for point Y). An

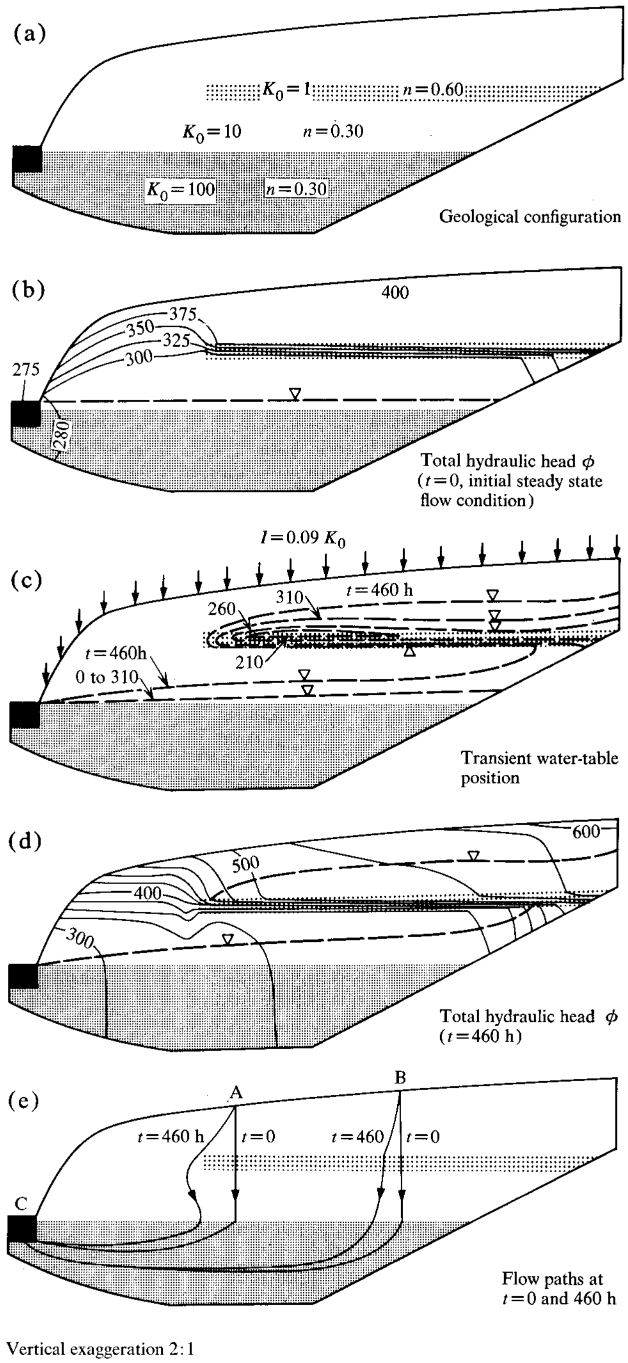


Figure 7 Transient development of a perched regional flow system showing the time-dependent shift in the location of specific flow lines.

obvious application of such data is as input to stress calculations on faults or fractures where the possibility of injection-induced seismic activity is being assessed.

A conservative but not unreasonable approach to waste injection at the current state of knowledge would allow this method to be used only in cases where the complete steady state pollution zone can be written off (a social

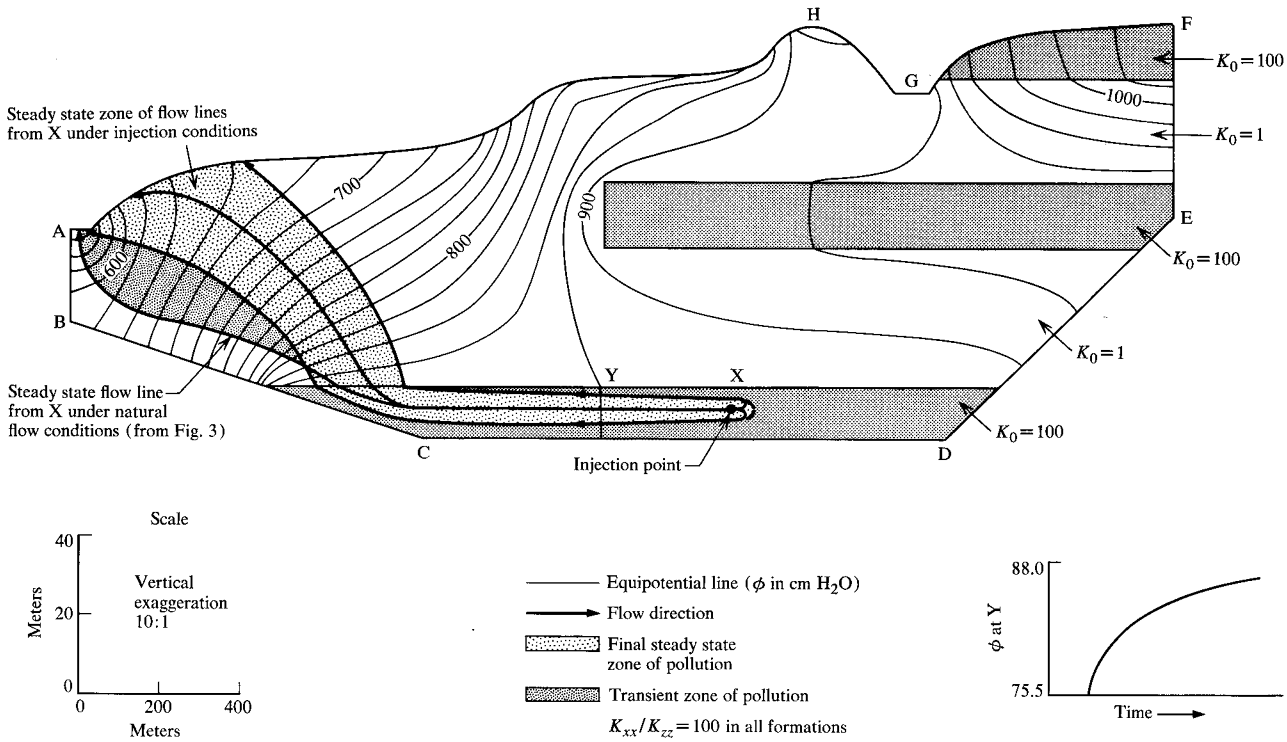


Figure 8 Influence of a waste-injection well on a steady state regional flow system.

choice), or where it can be proven that hydrochemical retardation will produce a smaller stable invasion zone. It is likely that such sites are few indeed.

Summary

A mathematical model of subsurface flow can be used to assess the impact on the environment of three methods of waste disposal that have a potential for subsurface pollution: sanitary landfills, waste lagoons, and waste-injection wells. The model can predict both transient and steady state subsurface flow patterns in two or three dimensions and includes consideration of both saturated and unsaturated zones. Quantitative interpretation of the output provides predictive values of rate of entry of pollutants into the flow system, lengths of flow paths, travel times of pollutants, discharge rates to surface water, water-table movements, and pressure-field development. The model does not consider dispersion or hydrochemical interactions between pollutants and soils.

The mathematical model can be applied at the reconnaissance stage on a regional basis, in steady state form, to analyze a large number of alternative sites. It can then be used at the selected site during the design stage to study the transient buildup to steady state conditions. It can also be used to assess the efficiency of various design alternatives such as leachate collection systems or impervious linings and to investigate the influence of variations in uncertain field data. Finally, simulations can provide guidance in the design of a monitoring system, and the model can be used dynamically, as monitoring proceeds, to investigate the effects of flaws in the original analysis.

Groundwater hydrology is but one component in a highly complex decision making process that is invoked when waste disposal alternatives are assessed. Nevertheless, it seems reasonable to bring the most sophisticated technical developments in subsurface flow analysis to bear on these problems. Growing concern over surface-water pollution, weak subsurface regulatory practices, and the ever increasing generation of waste are elements of a situation that may well be creating a worse pollution problem than the one we are trying to cure.

More study is needed before final conclusions can be drawn regarding the general applicability of either sanitary landfill or deep-well injection, but one must be careful not to tar both techniques with the same brush. Early indications are that sanitary landfill can provide a safe and reliable method of disposing of solid wastes. The injection of liquid wastes into deep geologic formations, on the other hand, leads to irreversible subsurface pollution. The environmental limitations on the potential for practical injection are extremely stringent.

At the present time, the development of hydrodynamic models far surpasses those of hydrochemical models. In fact, hydrochemical interactions between fluid and soil have not as yet been built into mathematical flow models. Combined convection-dispersion models have been limited to transient dispersion in a steady state convective field[28]. One solution involving transient dispersion in a transient flow field has been given by Pinder and Cooper[29] for a saltwater intrusion problem. One of the prime research needs in this field is for the development of a mathematical model that combines transient hydrodynamics, transient dispersion, and hydrochemical interaction on a regional hydrogeologic scale.

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