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# SALT WATER INTRUSION IN COASTAL AQUIFERS

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# PREFACE

Coastal regions deserve special attention due to their unique nature of hydrological processes and also because of their economic significance. Since coastal areas are characterised by the interaction of land, sea and atmosphere, management of such zones requires good understanding of all the interactive components. Among various hydrological problems encountered in the coastal regions, floods and salinisation cause concern. Several management practices are in operation towards improving the situation. However, activities intended towards amelioration and development of coastal zones may induce hydrological/ environmental repercussions, which may not be desirable always. Therefore, management of coastal areas should be environmentally sound and sustainable. Since groundwater is a major source for fresh water in the coastal region, protection of coastal aquifers from contamination through salt water ingress is of paramount import. Over-exploitation of groundwater, tidal effects, reduction in recharge of the aquifer, aquaculture activities, possible rise in sea level etc. can induce salt water intrusion in coastal areas. It is required to assess the spatial and temporal extent and intensity of intrusion in order to initiate preventive/ precautionary measures. Application of solute transport models can be of great use in performing this assessment. The study summarised in this report is about simulation of salt water intrusion using the USGS solute transport model, SUTRA in a hypothetical multi-layered coastal aquifer system. Brief background on the topic and description of application of the SUTRA model to obtain saltwater intrusion profiles are featured in the report. Further, the effect due to changes in the permeabilities of aquifers and aquitards, changes in flux at the boundaries, and changes in dispersivities in the medium on the intrusion profiles are investigated. The report is expected to provide guidance in conducting saltwater intrusion studies in multi-layerd coastal aquifer systems.

The study has been carried out by Mr. Mathew K. Jose with the guidance of Dr. G.C. Mishra as part of the work programme of the Ground Water Modelling and Conjunctive Use Division of the Institute during 1998-99.

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# CONTENTS

# ABSTRACT

Eco-friendly and sustainable management of water resources is indispensable in coastal and deltaic regions due to their unique nature of hydrological processes and economic significance. Since coastal areas are characterised by the interaction of land, sea and atmosphere, management of such zones requires management of all the interactive components in a rational and comprehensive manner. Thus, environmental management of coastal areas presupposes management of coastal waters, coastal lands and coastal ecosystems. Among various hydrological problems needed to be addressed in the coastal regions, salinisation and associated issues draw special attention. Quantitative understanding of the pattern of movement and mixing between fresh and salinewater, and of the factors that influence these processes, is required to manage and protect the freshwater resources in the coastal regions. A sustainable groundwater development and management programme in coastal aquifers should therefore aim at maintaining an acceptable spatial and temporal equilibrium of saltwater ingress in the aquifer system at a regional scale while ensuring quality standards in the pumped water. Such objectives necessitate analysis of the saltwater intrusion problem at regional scale as well as at local scale. Remedial measures are devised/ evaluated after performing a prognostic analysis of the problem using field data and hydrogeological information of the aquifer system. Mathematical modelling of flow and solute transport in coastal aquifer systems can assist greatly to achieve this end. In the present study, saltwater intrusion processes in a (hypothetical) homogeneous and multi-layered coastal aquifer system are simulated using the USGS finite element model for "saturated-unsaturated fluid density-dependant groundwater flow with energy transport or chemically reactive single species solute transport" (SUTRA) for different boundary conditions and aquifer parameters. The saltwater intrusion profiles for steady-state/ transient conditions are obtained and analysed. The effects of changes in the permeabilities of aquifers and aquitards, changes in the influx at the bounday, and changes in dispersivities in the medium on the saltwater intrusion process are investigated. The effect of material-independent/ material-dependent dispersivities are also subjected to analysis. It is inferred from analyses that permeability of the medium, dispersivity in the medium and influx at the boundaries affect the extend and intensity of saltwater intrusion in a coastal aquifer system. However, material-dependent dispersivity in a multilayered aquifer system did not make discernible changes in the intrusion profile compared to that with material-independent dispersivitiy for the present set-up. Elaborate discussion of results and analyses are presented in the report with the aid of tables/ plots.

# LIST OF FIGURES

# LIST OF TABLES

# 1.0 INTRODUCTION

The coast is where land, water and air interact. Generally, coastal areas comprise of low lands with small gradients bordering estuaries/sea and/or lower reaches of rivers, coastal marshes and lagoons. The economic significance of coastal regions requires no elaboration as many of the largest cities of the world are near to sea and about one third of the human habitat is within a 100 km strip along the coast line (*Volker, 1991*). Further, coastal deltas are major areas of grain production too. Issues pertain to coastal zones are, in general, storm surge preparedness, flood control, protection from coastal erosion and reclamation of land, proper policy response to future sea level rise and coastal inundation, depletion of forest resources, increased salinity intrusion in coastal land and aquifers, marine and industrial pollution, effects due to change in agricultural practices and land use pattern and impact of aquaculture and fisheries.

Since coastal areas are characterised by the interaction of land, sea and atmosphere, management of such zones requires management of all the interactive components in a rational and comprehensive manner. Therefore, environmental management of coastal areas presupposes management of coastal waters, coastal lands and coastal ecosystems (*Carter, 1988*). Being the only reliable source, coastal communities rely on groundwater for their water supply. However, the hydrogeological equilibrium/ balance of the coastal aquifer, that might have been established over long periods, is highly vulnerable. Lowering water table as a result of pumping may contaminate the coastal aquifer with salt water. Removal or lowering of coastal dunes also has a similar effect. Draining of coastal wet lands and dredging of navigation channels may deteriorate the condition. Further, such activities may lead to land subsidence also.

## 1.1 HYDROLOGICAL ISSUES OF COASTAL REGIONS

Hydrology of coastal areas is distinct. In a delta the water levels and flows are influenced by the water levels of the sea or estuary. Usually upstream discharge and tidal flow predominate local discharge generated by runoff. Impact assessment of developmental activities on the coastal eco-system is normally complicated due to the involvement of so many factors and their interactions (*Tuin, 1991*). As a result, it is not feasible to draw guidelines to address the various interactive processes. It would be realistic to confine to impacts that may be expressed in terms of changes in the quantity and quality of water for subsequent use as inputs for the evaluation of impacts on the other sectors.

Among the various problems needed to be addressed, floods and salinisation and associated issues draw special attention in the hydrology of the coastal region. Various management practices, structural as well as non-structural, have been in operation towards alleviating the adverse effects of such problems. However, beyond the immediate goals, the long-term adverse impacts of those measures are normally ignored. Thus, need for exhaustive understanding of the processes in the coastal areas and interactions within the eco-system becomes a priority in water resources management.

## 1.2 SALINISATION PROBLEM

The migration of saltwater into freshwater aquifers under the influence of groundwater development is termed as *saltwater intrusion (Freeze and Cherry, 1979)*. There is a likelihood of intrusion of salt, both, into surface water bodies and fresh water aquifer in low lying coastal areas. Saline water originates mainly from sea into open estuaries. Penetration of sea water into rivers is induced by the density difference between fresh and saline water and also due to head differences during low-river-flow. Normally, the denser saline water forms a deep wedge that is separated from freshwater by a transition zone. Under un-perturbed conditions, the saline water body remains stationary, its position being defined by the freshwater potential and hydraulic gradient. But when the aquifer is disturbed by activities like pumping of freshwater or changing recharge conditions, the salinewater body may gradually advance until a new equilibrium state is reached. Problem arises when saline water from the deeper saline wedge enters the wells thereby affecting the water quality. Fresh water aquifers under coastal areas may become saline due to overdraft of fresh water pockets, reclamation of low-lying areas, tidal effects, sea level changes, as well as aquaculture and fisheries activities.

Saltwater intrusion is driven mainly by transport of saltwater due to advection and dispersion. The process by which solutes are transported by the bulk motion of the flowing groundwater is termed as *advection*. However, there is a tendency for the solute to spread out from the path and this spreading process is called *hydrodynamic dispersion (Freeze and Cherry,* *1979)*. Dispersion is due to the combined action of both a purely mechanical phenomenon and a physico-chemical phenomenon. The *mechanical dispersion* is produced by non-uniform velocity distribution of fluid flow, due to boundary effects acting in three different ways: (i) the velocity is zero on the solid surface, which creates a velocity gradient in the fluid phase; (ii) the variation of pore spaces cause discrepancies between the maximum velocities along the pore axes; and (iii) the streamlines fluctuate with respect to the mean direction of flow. The physico-chemical dispersion is the *molecular dispersion* resulting from the chemical potential gradient, which is correlated to the concentration *(Fried and Combarnous, 1971)*. Mathematical models which simulate saltwater intrusion through advection only are known as sharp interface models whereas models that take into account both the processes of advection and hydrodynamic dispersion are called dispersed-interface transport models. In the former it is assumed that the saltwater and freshwater are immiscible fluids separated by a sharp interface, while in the latter a transition zone of mixed salt and fresh water is considered to be present at the interface (*Ashtiani et al., 1999*). Obviously, the latter only can simulate real-life field conditions effectively.

## 1.3 METHODS OF CONTROL

Various control/ remedial methods were proposed to maintain sustainable development of coastal freshwater aquifers (*Todd, 1959; Custodio, 1987*). However, it is required to assess the spatial and temporal extent of intrusion phenomenon and also the transient nature of the coastal aquifer system in order to initiate preventive measures efficiently. Monitoring wells can be installed to get information on saltwater-freshwater interface and the rate at which salinity levels change. Prognostic analyses of the problem are carried out based on the field observation data and hydrogeological information of the aquifer system and remedial measures are evaluated. Mathematical modelling of flow and solute transport in coastal aquifer system can assist greatly to achieve this end. As an aid to effective management of coastal aquifers, numerous models were developed and used over the years. Those range from simple analytical solutions to complex numerical models. Among the various solute transport models available, SUTRA (Voss, 1984), HST3D(Kipp, 1987), and SALTFLOW(Molson and Frind, 1994) are popular.

Following are a few methods (*Todd, 1959*) considered for controlling saltwater intrusion: (i) reduction or rearrangement of the pattern of groundwater pumping, (ii) artificial recharge of the intruded aquifer from spreading basins or recharge wells, (iii) development of a pumping trough adjacent to the coast by means of a line of pumping wells parallel to the coastline, (vi) development of fresh water ridge adjacent to the coast by means of a line of recharge wells parallel to the coastline, and (v) construction of an artificial sub-surface barrier. Of these alternatives, the first is proved to be effective and economic *(Freeze and Cherry, 1979)*.

## 1.4 OBJECTIVES OF THE STUDY

It is intended to simulate a (hypothetical) multi-layered coastal aquifer system using the USGS finite element model for "saturated-unsaturated fluid density-dependant groundwater flow with energy transport or chemically reactive single species solute transport" (SUTRA) for different boundary conditions and aquifer parameters. The saltwater intrusion profiles for steady-state/ transient conditions shall be obtained to study the behaviour of the process for different cases. The set-up of the multi-layered coastal aquifer system and boundary conditions are described in a subsequent section of the report.

# 2.0 SCOPE OF THE PROBLEM AND REVIEW

Seawater intrusion in coastal areas may be viewed as a natural process that occurs by virtue of the density contrast between freshwater and salinewater. The denser salinewater is separated from freshwater by a transition zone and poses no hazard to water quality until the equilibrium is disturbed. Thus, a quantitative understanding of the pattern of movement and mixing between fresh and salinewater, and of the factors that influence these processes, is required to manage and protect the freshwater resources in the coastal regions. A sustainable groundwater development and management programme in coastal aquifers should therefore aim at (i) maintaining an acceptable spatial and temporal equilibrium of saltwater ingress in the aquifer system at a regional scale and (ii) ensuring quality standards in the pumped water. These objectives necessitate analysis of the saltwater intrusion problem at regional scale as well as at point/ local scale.

## 2.1 LITERATURE REVIEW

Review of various methods/ models, which includes analytical as well as numerical solutions, for studying saltwater intrusion problems in coastal aquifer systems are available in literature *(Reilly and Goodman, 1985; Sharma, 1996)*. However, a brief sketch of the evolution of methodologies and significant advances made there on is presented.

Towards understanding the nature of the saltwater-freshwater interface in coastal aquifers, some analyses were carried out independently by Ghyben and Herzberg around the turn of the century *(Freeze and Cherry, 1979)*. Their findings known as the *Ghyben-Herzberg relation* expresses the depth to the saltwater interface at a point as a function of groundwater head (position of the water table) at that point in a homogeneous, unconfined aquifer. However, in most real situations, this relation underestimates the depth to the saltwater interface since the inherent hydrostatic assumptions are not satisfied. Henry (*1960*) presented a mathematical solution for the steady state case that includes dispersion. Cooper et al. (*1964*) provides a summary of various analytical solutions.

A survey of the literature reveals that studies/ investigations pertaining to saltwater-freshwater relationships in coastal aquifer systems gained much momentum by late sixties. The advances made since then can be categorised under five topics *(Reilly and Goodman, 1985)*: (1) applications using two dimensional cross-section analyses, (2) applications using two dimensional areal analyses, (3) applications using three dimensional analyses, (4) upconing applications using cylindrical coordinate systems, and (5) comments on advances in numerical methods and field studies.

Finite element method was used by Lee and Cheng (*1974*) to study the steady state seawater encroachment in coastal aquifers in the vertical plane. A constant dispersion coefficient was used in the homogeneous, isotropic aquifer. Huyakorn and Taylor (*1976*) presented different finite element formulations for the coupled flow and transport equations, for steady state conditions. Earlier applications of finite-element numerical models in simulating transient positions of saltwater front in confined as well as unconfined aquifer systems are described in Pinder and Gray *(1977)*.

A computationally efficient finite-element simulation model was propose by Frind (*1982a*) for simulating long term transient response in density dependant transport problems. He had introduced equivalent freshwater heads in order to eliminate static quantities in the fluid continuity equation. The model was used to study field problems like leachate transport in an unconfined aquifer and seawater intrusion in a continuous coastal aquifer-aquitard system (*Frind, 1982b*).

An important landmark in saltwater intrusion modelling endeavours was the development of a finite element simulation model for saturated-unsaturated fluid density-dependant groundwater flow with energy transport or chemically reactive single species solute transport at the U.S.Geological Survey *(Voss, 1984)*. The model had been revised twice, in 1990 and 1997, since its inception. Subsequently, SUTRA model has been widely used for numerous saltwater intrusion investigations (*Voss and Souza, 1987; Oberdorfer et al., 1990; Price and Woo, 1990; Reilly, 1990; Griggs and Peterson, 1993; Narayan and Armstrong, 1995; Ghassemi et al., 1996; Kumar, 1998; Ashtiani et al., 1999*).

Inouchi et al. (*1985*) reported a finite element model to describe unsteady motion of interface and groundwater level in a confined coastal aquifer system that is assumed to be homogeneous and isotropic with horizontal flow only. Huyakorn et al *(1987)* formulated a three dimensional finite element model, with hydraulic head and concentration as the dependant variables in the governing equations, to simulate saltwater intrusion in single/ multilayered coastal aquifer systems. The finite element model SUTRA was used at the U.S.Geological Survey to simulate variable density flow and solute transport in the layered regional aquifer of southern Oahu, Hawaii containing a narrow freshwater-saltwater transition zone (*Voss and Souza, 1987*).

Reilly *(1990)* employed the SUTRA model to examine groundwater flow in layered coastal aquifers. The U.S. Geological Survey has provided a quasi-three dimensional model (SHARP) for simulating transient interface in layered coastal aquifer systems (*Essaid, 1990*). The problem of seawater intrusion in confined coastal aquifers under the influence of tides was investigated by Inouchi et al. *(1990)* using analytical and numerical models. Senger and Fogg *(1990a)* presented a method for direct simulation of steady state flow of variable density groundwater using stream functions. Further, the concept of discharge potentials were utilised in framing the governing equations and formulated a three dimensional variable density shallow groundwater flow with the Dupuit-Forchheimer assumption *(Strack, 1995)*. The effect of uniform recharge on seawater intrusion into coastal aquifers has been investigated using a one dimensional finite element model by Mahesha and Nagaraja (*1996*). With the simple model it is reported to have observed that intrusion affected aquifers might be reclaimed to a reasonable extent, over a period of a few years, in areas receiving good rainfall. Ashtiani et al. *(1999)* modified SUTRA code to solve the mixed form of the variably saturated flow equation in order to analyse the effects of tidal fluctuations on seawater intrusion in an unconfined aquifer.

In the formulation of mathematical models for saltwater intrusion studies, various numerical techniques such as Method of Characteristics (MOC), Finite Difference Method (FDM), Finite Element Method (FEM), Boundary Integral Equation Method (BIEM) and Boundary Element Method (BEM), were employed by investigators. Apparently, among the various models available, the FEM based models excel in number and popularity. Detailed classification of the reported studies using different modelling approaches by various investigators may be found elsewhere (*Sharma, 1996* ).

# 3.0 CONCEPTUALISATION OF THE PROBLEM

SUTRA model is primarily intended for two-dimensional simulation (steady-state/ transient) of flow, and solute and energy transport in saturated and variable density systems. Simulation can be done in either areal plane or in a cross-sectional plane. As the model will provide accurate answers only to well-defined and well discretised problems, it is necessary to formulate a suitable simulation set-up.

Seawater intrusion may occur through an areal plane (land surface) by means of recharge of saline water during sea level changes (tides etc.) and also through a vertical plane at the aquifer-sea boundary. In the present study, it is intended to investigate the intrusion process across a vertical plane bordering the layered aquifer and the sea. The hypothetical layered coastal aquifer system visualised for the simulations is 100 m long and 50 m thick.

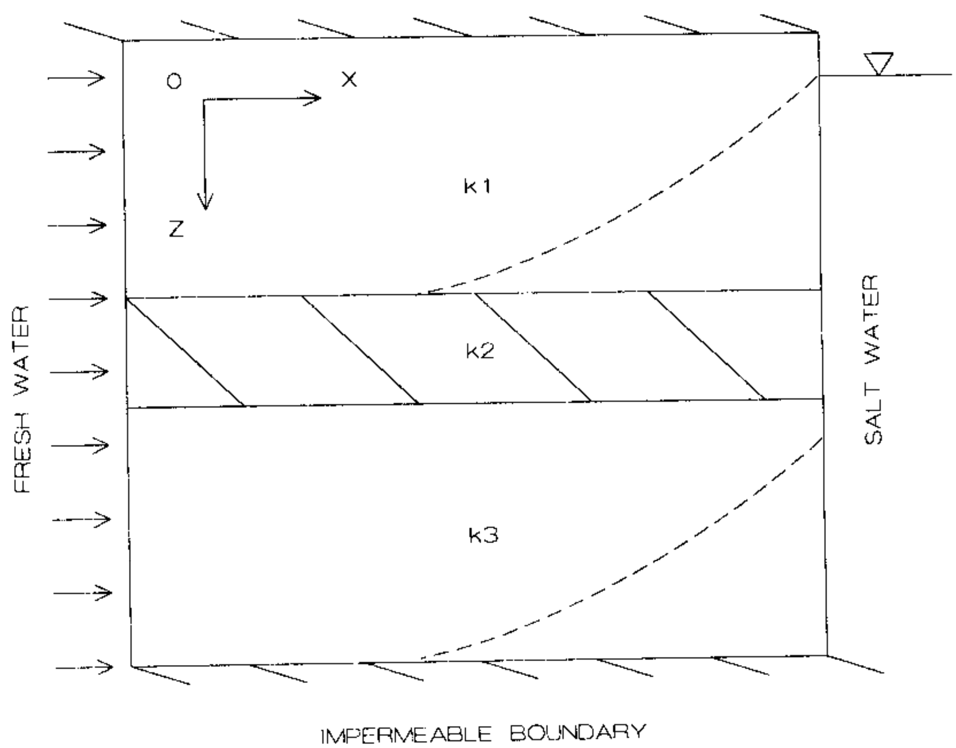



**Fig. 3.1** Cross-sectional sketch of the hypothetical coastal aquifer-aquitard system

The boundary conditions and internal geometry of the two aquifer layers and intervening confining units are shown in Fig-3.1. The left-hand (land-ward side) inflow boundary has an evenly distributed mass flux, $Q_{IN}$ with concentration, $C_{IN}$. The top boundary is a no-flow boundary making the set-up a confined aquifer system. The bottom of the aquifer system is an impermeable boundary. The right-hand boundary (sea-ward side) is at hydrostatic pressure of seawater through use of specified pressure nodes. Water which enters the section through these nodes has concentration, $C_{BC} = C_s$ of seawater.

### 3.1 DISCRETISATION

The finite-element representation of the system is comprised of 1326 nodes and 1250 elements. The rectangular elements are all of the same dimensions, with sides 2 m x 2 m. A cross-sectional width (thickness in the third dimension) of 1 m is assumed. The coastal aquifer system is partitioned into a top and a bottom aquifer by the presence of an aquitard of thickness 10 m. Thicknesses of the top aquifer and bottom aquifer are 20 m each. Different lengths of time steps, varying from 60 sec. to 1000 sec., are used with number of time steps equals 1000 for simulations under transient conditions. The pressure, concentration and velocities are solved for every time step.

The seawater intrusion into the confined aquifer-aquitard system is a non-linear process and is solved by approaching the steady state situation gradually with a series of time steps. Initially, the aquifer system is saturated with freshwater and there is no saltwater present in the system. At time t=0, saltwater begins to intrude the freshwater system by moving under the freshwater from the sea boundary; the intrusion being caused by the greater density of the salt water.

Density is represented as a linear function of concentration *(Voss and Souza, 1987)*:

$$\rho = \rho_0 + \frac{\partial \rho}{\partial C} ( C - C_0 ) \tag{3.1}$$

where $\rho_0$ is the fluid density at $C = C_0$; $C_0$ is a base concentration; and $\partial\rho/\partial C$ is constant coefficient of density variability with respect to concentration. For the present investigations:

$\rho_0$ = 1000. [kg/m$^3$] which is freshwater density;

$C_0$ = 0. [kg (dissolved solids) / kg (seawater)]; and

$\partial\rho/\partial C$ = 700. [kg (seawater)$^2$ / kg dissolved solids · m$^3$] at about 20° C temperature

# 4.0 METHODOLOGY

The numerical algorithm and the associated computer code that is used for this study is referred to as SUTRA (*Voss, 1984*). This model uses a two-dimensional bi-linear Galerkin finite-element approximation in space and an implicit finite difference approximation in time to solve the governing equations. One of the unique aspects of the SUTRA methodology is that in addition to representing the dispersion tensor in the standard flow-direction-independent form, an 'ad-hoc model' for flow-direction-dependent longitudinal dispersion is available. A brief description of the model formulation, discretisation and application is followed:

## 4.1 DESCRIPTION OF THE MODEL

SUTRA is a finite element simulation model for saturated-unsaturated fluid-density-development ground water flow with energy transport or chemically reactive single-species solute transport. SUTRA may be employed for area and cross-sectional modelling of unsaturated zone flow. Solute transport simulation using SUTRA may be employed to model natural or man-induced chemical species transport including processes of solute sorption, production and decay and may be applied to analyse ground water contaminant transport problems and aquifer restoration designs. In addition, solute transport simulation with SUTRA may be used for modelling of variable density leachate movement and for cross-sectional modelling of salt water intrusion in aquifers in near-well or regional scales with either dispersed or relative sharp transition zones between fresh water and salt water. SUTRA energy transport simulation may be employed to model thermal regimes in aquifers, subsurface heat conduction, aquifer thermal energy storage systems, geothermal reservoirs, thermal pollution of aquifers and natural hydrogeologic convection systems.

Three versions of SUTRA were released so far: (i) Version V1284213 - Orignal version released in 1984; (ii) Version V06902D - First revision in 1990. Minor modifications in old data files are necessary; (iii) Version V09972D - Second revision in 1997. Addition of option to use FORTRAN 90 dynamic array dimensioning. Addition of two output files containing simulation results in simple column format.

SUTRA is written in FORTRAN 77 including optional FORTRAN 90 statements allowing dynamic array allocation. SUTRA requires that files needed for the simulation be defined prior to execution. A Name File (SUTRA.FIL) is used for this purpose. For each file (up to six), the unit number is specified on one record followed by a record specifying the file name. Generally, the program is easily installed on most computer systems. The code has been used on a wide variety of computers, ranging from UNIX based computers to DOS-based 386 computers with as little as 640K of RAM.

## 4.2 PURPOSE AND SCOPE

SUTRA is a computer program which simulates fluid movement and transport of either energy or dissolved substances in a subsurface environment. The model employs a two-dimensional hybrid finite element and integrated finite difference method to approximate the governing equations that describe the two interdependent processes that are simulated: (i) fluid density-dependent saturated or unsaturated ground water flow, and (ii) either transport of a solute in the ground water in which the solute may be subject to equilibrium adsorption on the porous matrix and both first-order and zero-order production or decay, or transport of thermal energy in the ground water and solid matrix of the aquifer. Capabilities of model SUTRA as an aid tool are to:

- Assess well performance and pumping test data,
- Analyse density-dependent flow or constant-density flow in both the saturated and unsaturated zones,
- Analyse chemical species transport, including processes of solute absorption, production and decay,
- Predict hazardous waste migration from land disposal sites,
- Analyse aquifer restoration, waste confinement, hydraulic barriers, liners and water quality protection system,
- Analyse aquifer thermal regimes, subsurface heat conduction, aquifer thermal energy storage systems, geothermal reservoirs, thermal pollution of aquifers and natural hydrogeologic convection systems,
- Model variable density leachate movement, and
- Model cross-sectional salt water intrusion in aquifers at near-well or regional scales

with either dispersed or relatively sharp transition zones between fresh water and salt water.

## 4.3 SUTRA- PROCESSES

Simulation using SUTRA is in two dimensions, although a three-dimensional quality is provided in that the thickness of the two-dimensional region in the third direction may vary from point to point. Simulation may be done in either the areal plane or in a cross-sectional view. The spatial coordinate system may be either Cartesian (x,y) or radial-cylindrical (r,z). Areal simulation is usually physically unrealistic for variable-density fluid problems.

Ground water flow is simulated through numerical solution of a fluid mass balance equation. The ground water system may be either saturated, or partly or completely unsaturated. Fluid density may be constant or vary as a function of solute concentration or fluid temperature.

SUTRA tracks the transport of either solute mass or energy in the flowing ground water through a unified equation which represents the transport of either solute or energy. Solute transport is simulated through numerical solution of a solute mass balance equation where solute concentration may affect fluid density. The single solute species may be transported conservatively or it may undergo equilibrium sorption. In addition, the solute may be produced or decay through first-order or zero-order processes. Energy transport is simulated through numerical solution of an energy balance equation. The solid grains of the aquifer matrix and fluid are locally assumed to have equal temperature, and fluid density and viscosity may be affected by the temperature.

Almost all aquifer material, flow and transport parameters may vary in value throughout the simulated regional. Sources and boundary conditions of fluid, solute and energy may be specified to vary with time or may be constant. SUTRA dispersion processes include diffusion and two types of fluid velocity-dependent dispersion. The standard dispersion model for isotropic media assumes direction-independent values of longitudinal and transverse dispersivity. A velocity-dependent dispersion process for anisotropic media is also provided. This process assumes that longitudinal dispersivity varies depending on the angle between the flow direction and the principal axis of aquifer permeability which permeability is anisotropic.

## 4.4 GOVERNING EQUATIONS

The Simulation of sea water intrusion requires the solution of partial differential equations that describe "conservation of mass of fluid" and "conservation of mass of solute". These are summarised below *(Voss, 1984)*.

### 4.4.1 Conservation of Mass of Fluid

The fluid mass balance in a saturated porous medium can be expressed as :

$$\frac{\partial(\epsilon\rho)}{\partial t} = -\nabla\cdot(\epsilon\rho V) + Q_p \qquad (4.4.1)$$

where (x,y,z) is porosity (dimensionless); $\rho$ (x,y,z,t) is fluid density [M/L$^3$]; $Q_p$(x,y,z,t) is fluid mass source [M/L$^3$T)]' V (x,y,z,t) is fluid velocity [L/T]; x,y,z are Cartesian coordinate variables [L]; t is time [T]; and $\nabla$ is $[(\partial/\partial x)i+(\partial/\partial y)j+(\partial/\partial z)k]$. The term on the left hand side of equation (4.4.1) expressed the change in fluid mass contained in the void space of the local volume with time. The first term on the right hand side of this equation represents the contribution to local fluid mass change due to excess of fluid inflows over outflows and the second term ($Q_p$) accounts for external additions of fluid.

The fluid mass balance (equation 4.4.1) can also be represented by :

$$(\rho S_{op})\frac{\partial p}{\partial t} + \left[\epsilon\frac{\partial p}{\partial C}\right]\frac{\partial C}{\partial t} - \nabla\cdot\left[\left(\frac{\epsilon\rho k}{\mu}\right)\cdot(\nabla p-\rho g)\right] = Q_p \qquad (4.4.2)$$

Where $S_{op}$ =$[(1-\epsilon)\alpha + \epsilon\beta]$ is specific pressure storativity [LT$^2$/M]; $\alpha$ is porous matrix compressibility [LT$^2$/M]; $\beta$ is fluid compressibility [LT$^2$/M]; C is solute mass fraction; k(x,y,z) is solid matrix permeability tensor [L$^2$]; $\mu$(x,y,z,t) is fluid viscosity [M/LT], p(x,y,z,t) is fluid pressure [M/LT$^2$], and g is the gravity vector [L/T$^2$].

### 4.4.2 Conservation of Mass of Solute

The solute mass balance for a single species stored in solution is expressed as:

$$\frac{\partial(\epsilon \rho C)}{\partial t} = -\nabla \cdot (\epsilon \rho V C) + \nabla \cdot [\epsilon \rho (D_m I + D) \cdot \nabla C] + Q_p C^* \qquad (4.4.3)$$

where $D_m$ is apparent molecular diffusivity of solutes in the solution in a porous medium [$LT^2/M$]; I is the identity tensor [dimensionless]; D is the dispersion tensor [$LT^2$]; and $C^*$ is the solute mass fraction of fluid sources ($M_s/M$). The term on the left hand side of equation (4.4.3) expresses the change in solute mass with time in a volume due to mechanisms represented by terms on the right hand side. the first term on the right hand side of equation (4.4.3), involving fluid velocity (V), represents advection of solute mass into or out of the local volume. The second term, involving molecular diffusivity of solute ($D_m$) and dispersivity (D), expresses the contribution of solute diffusion and dispersion to the local changes in solute mass. The diffusion contribution is based on a physical process driven by concentration gradients, and is often negligible at the field scale. The last term accounts for dissolved-species added by a fluid source with concentration $C^*$.

The mechanical dispersion tensor D is related to the velocity of ground water flow. For an isotropic porous medium in two spatial dimensions, it is expressed as follows:

$$D = \begin{bmatrix} D_{xx} & D_{xy} \\ D_{yx} & D_{yy} \end{bmatrix} \qquad (4.4.4)$$

The tensor D is symmetric and its elements are:

$$\begin{aligned} D_{xx} &= \frac{1}{V^2} [ d_L V_x^2 + d_T V_y^2 ] \\ D_{yy} &= \frac{1}{V^2} [ d_T V_x^2 + d_L V_y^2 ] \\ D_{xy} = D_{yx} &= \frac{1}{V^2} [ d_L - d_T ] [ V_x V_y ] \end{aligned} \qquad (4.4.5)$$

where $V(x,y,t) = (V^2_x+V_y^2)^{1/2}$ is the magnitude of fluid velocity [L/T]; $V_x(x,y,t)$ and $V_y(x,y,t)$ are the components of velocity in the x and y directions [L/T]; and $d_L(x,y,t)$ and $d_T(x,y,t)$ are, respectively, the longitudinal and transverse dispersion coefficients [$L^2/T$]. The longitudinal and transverse dispersion coefficients describe dispersive fluxes along the direction of fluid flow and perpendicular to it. The coefficients $d_L$ and $d_T$ are velocity dependent, namely

$$\begin{aligned} d_L &= \alpha_L V \\ d_T &= \alpha_T V \end{aligned} \qquad (4.4.6)$$

and $\alpha_L(x,y)$ and $\alpha_T$ (x,y) are the longitudinal and transverse dispersivity, respectively, of the solid matrix [L]. Studies have shown that field observed dispersion coefficients are orders of magnitude larger than those observed in small scale laboratory tests. Similarly, field observations show that the dispersion coefficient increases with displacement distance at a given side.

## 4.5 SUTRA- NUMERICAL METHODS

SUTRA may be employed in one-dimensional or two-dimensional analyses. Flow and transport simulation may be either steady state or transient. SUTRA simulation is based on a hybridisation of finite-element and integrated finite-difference methods employed in the framework of a method of weighted residuals. The method is robust and accurate when employed with proper spatial and temporal discretsation. Standard finite-element approximations are employed only for terms in the balance equations which describe fluxes of fluid mass, solute mass and energy. All other non-flux terms are approximated with a finite element mesh version of the integrated finite-difference methods. The hybrid method is the simplest and most economical approach which preserves the mathematical elegance and geometric flexibility of finite-element simulation while taking advantage of finite-difference efficiency.

The model will provide clear and accurate results to well-posed well-defined and well-discretised problems. Spatial discretisation requires a fine mesh in areas where either accurate results are needed or where parameters vary greatly over short distances.

Nevertheless, spatial discretisations should be consistent with dispersivity parameters. Voss (1984) recommended a grid spacing of less than four times the dispersivity in ech direction, whereas Molson and Frind (1994) suggested a more stringent criteria in which the grid Peclet Number (ratio of the spatial discretisation and the dispersion length) and the Courant Number (ratio of the advective distance during one time step to the spatial discretisation) should match the following constraints:

$$P_x = \frac{\Delta x}{\alpha_L} \le 2; \quad P_y = \frac{\Delta y}{\alpha_T} \le 2; \quad P_z = \frac{\Delta z}{\alpha_T} \le 2 \qquad (4.4.7)$$

$$C_x = \frac{V_x \Delta t}{\Delta x} \le 1; \quad C_y = \frac{V_y \Delta t}{\Delta y} \le 1; \quad C_z = \frac{V_z \Delta t}{\Delta z} \le 1 \qquad (4.4.8)$$

where $P_x$, $P_y$ and $P_z$ are the Peclet numbers; $C_x$, $C_y$ and $C_z$ are the Courant Numbers; $\Delta x$, $\Delta y$ and $\Delta z$ are the grid spacings, $\alpha_L$ and $\alpha_T$ are the longitudinal and transverse dispersivity, respectively; and $\Delta t$ is the time step.

SUTRA employs a new method for calculation of fluid velocities. Fluid velocities, when calculated with standard finite-element methods for systems with variable fluid density, may display spurious numerically generated components within each element. These errors are due to fundamental numerical inconsistencies in spatial and temporal approximations for a pressure gradient and density, gravity terms which are involved in velocity calculation. Spurious velocities can significantly add to the dispersion of solute or energy. This false dispersion make accurate simulation of all but systems with very low vertical concentration or temperature gradients impossible, even with fine vertical spatial discretisation. Velocities as calculated in SUTRA, however, are based on a new, consistent, spatial and temporal discretisation. The consistency evaluated velocities allow stable and accurate transport simulation (even at steady state) for systems with large vertical gradients of concentration or temperature. An example of such a system, that SUTRA successfully simulates, is a cross-sectional regional model of a coastal aquifer wherein the transition zone between horizontally flowing fresh water and deep stagnant salt water is relatively narrow.

The time discretisation used in SUTRA is based on a backward finite-difference approximation for the time derivatives in the balance equations. Some non-linear coefficients are evaluated at the new time level of solution by projection while others are evaluated at the previous time level for non-iterative solutions. All coefficients are evaluated at the new time level for iterative solutions. The finite-element method allows the simulation of irregular regions with irregular internal discretisation. This is made possible through use of quadrilateral elements with four corner nodes. Coefficients and properties of the system may vary in value throughout the mesh.

SUTRA includes an optional numerical method based on asymmetric finite-element weighting functions which results in "upstream weighting" of advective transport and unsaturated fluid flux terms. Although upstream weighting has typically been employed to achieve stable, non-oscillatory solutions to transport problems and unsaturated flow problems, the method is not recommended for general use, as it merely changes the physical system being simulated by increasing the magnitude of the dispersion process. A practical use of the method is, however, to provide a simulation of the sharpest concentration of temperature variations possible with a given mesh. This is obtained by specifying a simulation with absolutely no physical diffusion or dispersion and with 50% upstream weighting. The result may be interpreted as the solution with the minimum amount of dispersion possible for a stable result in the particular mesh in use.

In general simulation analyses of transport, upstream weighting is discouraged. the non-upstream methods are also provided by SUTRA and are based on symmetric weighting functions. These methods are robust and accurate when the finite-element mesh is properly designed for a particular simulation and should be used for most transport simulations.

## 4.6 DATA REQUIREMENTS

The most essential types of data required are salinity records with depths in a number of observation wells, hydro-dispersive parameters (or at least detailed description of lithology, by which estimates of hydraulic conductivity can be made from similar type of areas), and tidal lags and heights at various points in the region of interest. It is also necessary to have recharge information. This involves not only the knowledge of rainfall but also how much of it enters the ground water system and how much is drawn off by vegetation. Other useful information would include an accurate topographic map, a land use map, water supply data including extraction data, local knowledge and experience, and estimates of expected changes in regional rainfll patterns.

Two SUTRA data files are required: (i) SUTRA input data and (ii) initial conditions of pressure and concentration or temperature for the simulation. Re-programming of subroutines BCTIME and UNSAT is required to implement time-dependent boundary conditions and unsaturated flow functions, respectively. A graphical post-processor, SUTRA-PLOT developed by Souza (1987) is available along with SUTRA, which aids translation of simulation results into meaningful inferences.

# 5.0 SIMULATIONS AND ANALYSIS

The numerical experiments carried out using the finite-element model SUTRA are either for a homogeneous coastal aquifer system (by keeping the permeabilities of all the layers same) or for a multilayered coastal aquifer system. The transient nature of simulations and effect of permeability of the medium, boundary conditions and dispersivity on saltwater intrusion profiles are investigated. Further, the influence of flow barriers of different permeabilities on the intrusion phenomenon in a layered aquifer system is also studied. Finally, the usage of material or position-dependent dispersivities in modelling layered coastal aquifer systems is also examined.

Simulations were performed with sufficient number of time steps to attain steady-state condition. The transient/ steady-state concentrations obtained from the simulation results are normalised by the saltwater Concentration, $C_s$= 0.0357 kg(dissolved solids) / kg(seawater), and plotted in the corresponding vertical plane to get the isochlors (contour lines of equal values of normalised concentrations). Isochlors vary from 0.0 (freshwater) to 1.0 (saltwater). The isochlor values chosen to represent in the plots are 0.02, 0.10, 0.25, 0.50, 0.75, and 0.90 for the homogeneous as well as the layered aquifer system.

## 5.1 PHYSICAL SET-UP

Simulations are carried out for saltwater intrusion into a confined coastal aquifer system in a vertical cross-section to attain steady-state. Recharge of freshwater flows over saltwater in the section and discharges at the vertical aquifer-sea boundary. Profiles of saltwater intrusion which is a non-linear process is obtained by gradually approaching steady state with series of time steps. Initially the aquifer is saturated with freshwater and at time, t=0 saltwater begins to intrude the freshwater system by moving under the freshwater from the aquifer-sea boundary.

The finite-element representation of the system is comprised of 1326 nodes and 1250 elements with sides 2 m x 2 m. The coastal aquifer extends to 100 meters landwards with a depth of 50 m. The aquifer system is partitioned into a top and a bottom aquifer with a thickness of 20 m each by the presence of an aquitard of thickness 10 m.

### 5.2 SIMULATION SET-UP

A total simulation period of $10^6$ seconds (divided into 1000 time steps) were found to be sufficient for the process to reach steady-state situation. The left-hand inflow boundary has an evenly distributed mass flux, $Q_{IN}$ (varying from 1kg/s to 8kg/s) with concentration, $C_{IN}$=0.0. The top boundary is a no-flow boundary which makes the set-up a confined system. The bottom of the aquifer system is an impermeable boundary. The right-hand boundary is at hydrostatic pressure of seawater through use of specified pressure nodes. Water which enters the section through these nodes has concentration, $C_s$=0.0357 kg(dissolved solids) per kg(seawater). The values/ range of values assigned for various parameters used in the simulations are given below:

| | |
|---|---|
| Soil Porosity, $\epsilon$ | = 0.35 and 0.49 |
| Soil Permeability, k | = $1.020408\times10^{-8}$ $m^2$ to $1.020408\times10^{-16}$ $m^2$ |
| Saltwater Concentration, $C_s$ | = 0.0357 kg(dissolved solids) / kg(seawater). |
| Saltwater Density, $\rho_s$ | = 1025 kg/ $m^2$ |
| Freshwater Density, $\rho_0$ | = 1000 kg/ $m^2$ |
| Density variation, $\partial\rho/\partial C$ | = 700. [kg (seawater)$^2$ / kg dissolved solids. $m^3$] |
| Freshwater concentration, $C_0$ | = 0. [kg (dissolved solids) / kg (seawater)]; and |
| Freshwater input rate, $Q_{IN}$ | = 1 kg/s to 8 kg/s |
| Molecular diffusivity, D | = $6.6\times10^{-6}$ $m^2$/s |
| Acceleration due to gravity, g | = 9.8 m/$s^2$ |
| Thickness of the cross-section, B | = 1 m |
| Dispersivities, $\alpha_L = \alpha_T$ | = 1m to 10m |
| Simulation time, t | = $10^6$ sec. |

### 5.3 SIMULATIONS- HOMOGENEOUS COASTAL AQUIFER

Three cases are studied using a hypothetical homogeneous coastal aquifer (by making permeabilities of all the layers equal), particulars of which are tabulated in Table 5.1.

The transient nature of the saltwater intrusion process is illustrated by Case-A1. Fig.5.1(A&B) compares the intrusion profiles in the cross-section after a time period of 0.3 hours and 70 hours respectively. Initially the profiles are vertical as the freshwater influx is yet to reach the seaward side of the cross-section. Later, (after 70 hours) freshwater discharge is established in the aquifer, mostly through the top portion of the aquifer system due to the boundary hydrostatic pressure, and is clear from the inclined profiles. Traces of saltwater concentration may be detected in the aquifer even half-way through section. Similarly, Fig.5.2(C&D) compares the intrusion profiles in the medium after 210 hours and 280 hours (i.e., 1000 time steps) respectively. The profiles are apparently similar in all respects indicating that the intrusion process has reached a steady state within the system with the present set-up of boundary conditions and parametric values.

| A- HOMOGENEOUS AQUIFER | | | |
|---|---|---|---|
| CASES | PLOTS | DESCRIPTION OF INVESTIGATION | PARAMETER VALUES FOR SETS OF CASES |
| CASE- A.1 | Fig. 5.1<br>Fig. 5.2 | Comparison of transient nature of saltwater intrusion profiles | $t_1$ = 0.30 Hrs.<br>$t_2$ = 230 x $t_1$<br>$t_3$ = 690 x $t_1$<br>$t_4$ = 920 x $t_1$ |
| CASE- A.2 | Fig. 5.3 | Effect of change in permeability of the medium | $k_1 = 1.02 \times 10^{-9}$ $m^2$<br>$k_2$ = 0.5 x $k_1$ |
| CASE- A.3 | Fig. 5.4 | Effect of change in freshwater input rate at the boundary | $Q_1$ = 8 kg/s<br>$Q_2$ = 0.5 x $Q_1$ |

**TABLE: 5.1** List of cases analysed using SUTRA for Homogeneous aquifer

Effect of permeability of the medium is examined in Case- A2 wherein two simulations are performed with different permeabilities while all other aspects of the set-up remain unaltered. Saltwater intrusion Profiles in Fig.5.3(A) is obtained with a permeability of $k = 1.02 \times 10^{-9}$ $m^2$ whereas profiles in Fig.5.3(B) is due to a permeability half-the-value of the previous plot. It is quite evident from the plots that reduction in the permeability caused a proportionate reduction in the areal extent of the intrusion zone in the vertical cross-section. As a result, the freshwater discharge through the aquifer-sea boundary is more pronounced in the latter case.

It is noticed that there is a reversing effect on the saltwater intrusion when the freshwater injection rates at the boundary are changed. Case- A3 consists of two simulation results with different freshwater injection rates. Saltwater intrusion Profiles in Fig.5.4(A) is for an injection rate, $Q_{IN}$ = 8kg/s while profiles in Fig.5.4(B) is for an injection rate, $Q_{IN}$ = 4kg/s (i.e., half of the former simulation). The plots of isochlors show that reduction in the recharge rate of the aquifer hastened the intrusion process and advanced the areal extent of the intrusion zone. Further, inter-comparison of Case- A2 and Case- A3 reveals that the effect of reduction in permeability of the medium is tantamount to an increment in freshwater input rate at the boundary on the saltwater intrusion profile of the otherwise unaltered set-up. Thus, intrusion profiles of Fig.5.3(B) and Fig.5.4(A) compare very well.

## 5.4 SIMULATIONS- LAYERED COASTAL AQUIFER SYSTEM

Five cases for the layered coastal aquifer system are investigated using SUTRA simulations. The various cases with description of investigations and particulars of parameter values assigned during simulations are tabulated in Table 5.2. The middle layer may act as a flow-barrier depending up on the permeability value assigned to it in the simulations.

The effect on saltwater intrusion profiles due to changes in permeabilities and freshwater influx have been already examined cases from homogeneous coastal aquifer. The same parameters are again subjected to examination for the case of layered aquifer system for the reason that, unlike the single aquifer case, the behaviour of intrusion pattern with changes in the layer permeabiiities is not similar, possibly, due to asymmetry of material properties in the vertical section. In Case- B1 and Case- B2, soil porosity values used in the simulations for the aquifer portions and aquitard are $\epsilon$ = 0.35 and $\epsilon$ = 0.49 respectively.

Case- B1 explores the influence of permeability on the saltwater intrusion profiles in the layered aquifer system. Freshwater input through the boundary is kept at the rate of 1 kg/s. The permeabilities of the layers (from top to bottom) are $k_{T1}$=1.02x$10^{-10}$ $m^2$, $k_{M1}$=1.02x$10^{-12}$ $m^2$, $k_{B1}$=1.02x$10^{-9}$ $m^2$ and $k_{T2}$=0.1x $k_{T1}$, $k_{M2}$=0.1x $k_{M1}$, $k_{B2}$=$k_{B1}$ corresponding to the profiles shown in Fig.5.5(A) and Fig.5.5(B) respectively. In Fig.5.5(A) there is a saltwater intrusion zone in the top aquifer, though the concentrations are small. Also, the intrusion zone in the bottom aquifer spreads beyond half-way in the cross-section.

Profiles of Fig.5.5(B) are generated with permeabilities smaller by one order of magnitude for the top and middle layers while keeping the permeability of the bottom layer as the same. It is seen that the intrusion zone in the top aquifer has vanished and full discharge of fresh

| B- LAYERED AQUIFER | | | |
|---|---|---|---|
| CASES | PLOTS | DESCRIPTION OF INVESTIGATION | PARAMETER VALUES FOR SETS OF CASES |
| CASE- B.1 | Fig. 5.5 | Effect of change in permeabilities of the layers on saltwater intrusion profiles | $k_{T1}$=1.02x10$^{-11}$ m$^2$<br>$k_{M1}$=1.02x10$^{-13}$ m$^2$<br>$k_{B1}$=1.02x10$^{-9}$ m$^2$<br>$k_{T2}$=10 x $k_{T1}$<br>$k_{M2}$=10 x $k_{M1}$<br>$k_{B2}$=1 x $k_{B1}$ |
| CASE- B.2 | Fig. 5.6 | Effect of change in freshwater input rate at the boundary | $Q_1$ = 8 kg/s<br>$Q_2$ = 0.25 x $Q_1$ |
| CASE- B.3 | Fig. 5.7 | Influence of dispersivities | $\alpha_{L1}=\alpha_{T1}$=2m<br>$\alpha_{L2}=\alpha_{T2}$=4m<br>$\alpha_{L3}=\alpha_{T3}$=10m |
| CASE- B.4 | Fig. 5.8.1<br>Fig. 5.8.2<br>Fig. 5.8.3 | Influence of aquitard permeabilities | $k_{M1}$=1.02x10$^{-9}$ m$^2$<br>$k_{M2}$=1.02x10$^{-10}$ m$^2$<br>$k_{M3}$=1.02x10$^{-11}$ m$^2$<br>$k_{M4}$=1.02x10$^{-12}$ m$^2$<br>$k_{M5}$=1.02x10$^{-13}$ m$^2$<br>$k_{M6}$=1.02x10$^{-16}$ m$^2$ |
| CASE- B.5 | Fig. 5.8.9 | Effect of material-independent/ material-dependent dispersivities | $\alpha_{L1}=\alpha_{T1}$=10m<br>(all layers)<br>$\alpha_{L2}=\alpha_{T2}$=10m<br>(top and bottom layers)<br>$\alpha_{L2}=\alpha_{T2}$=1m<br>(aquitard) |

**TABLE: 5.2** List of cases analysed using SUTRA for Layered aquifer water is established at the aquifer-sea boundary. There is, practically, little intrusion into the middle layer owing to the small permeability. Further, though the permeability of the bottom layer was not altered, the isochlors in the bottom aquifer have now retreated backwards. This is because of a decline in the solute movement from the upper layers to the bottom layer due to reduced connectivity and also due to lack of saltwater intrusion in the upper layers. It is, therefore, obvious that the saltwater intrusion profile in a deeper aquifer in a multi-layered system can be influenced not only by its own permeability but also by the permeabilities of layers above.

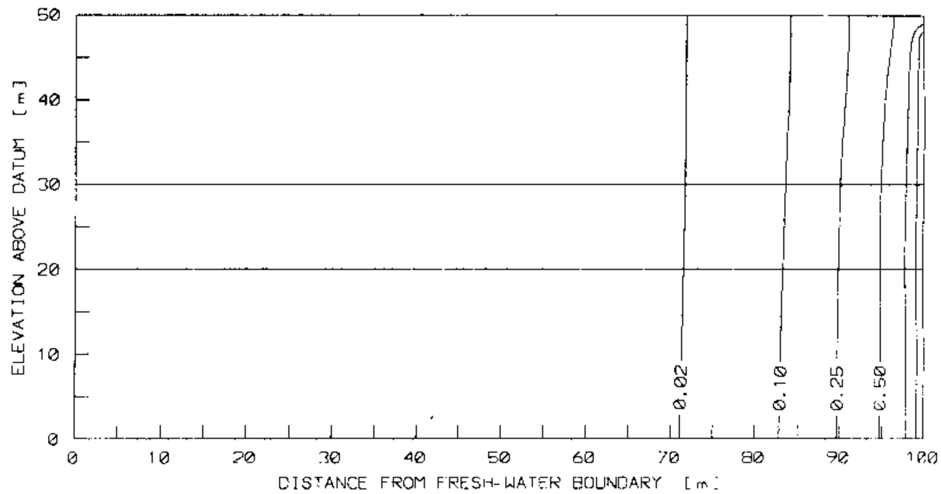
Case- B2 examines the effect of change in fresh water influx on the saltwater intrusion profiles in a layered aquifer system. The permeabilities of the layers are: $k_T$=1.02x$10^{-9}$ $m^2$, $k_M$=1.02x$10^{-13}$ $m^2$, $k_B$=1.02x$10^{-9}$ $m^2$. The profiles shown in Fig.5.6(A) and Fig.5.6(B) are obtained with freshwater injection rates of 8 kg/s and 2 kg/s respectively, through the left-hand boundary. When the rate of recharge in the aquifer system is high the saltwater intrusion zones in the top and bottom aquifers are confined to a small region as shown in Fig.5.6(A). Having the same permeability values, the pattern of intrusion profiles in both the aquifers is similar. Profiles of Fig.5.6(B) are obtained with a reduced freshwater influx. A four-time reduction in the freshwater injection rate caused the intrusion zone to progress further into the medium. However, there is a staggered transition-zone due to the presence of the flow barrier (aquitard).

From discussions in Section 4.4, it is obvious that dispersivity in the medium influences the movement of solute. The behaviour of intrusion profiles with different dispersivities is compared in Case- B3. The permeabilities of the layers are: $k_T$= $k_B$= 1.02x$10^{-9}$ $m^2$ and $k_M$=1.02x$10^{-12}$ $m^2$. Freshwater injection rate is 4 kg/s through the boundary. Since the layers are homogeneous and isotropic, the longitudinal and transverse transmissivities are taken to be equal for the simulations. Three dispersivity values viz., 2 m, 4 m, and 10 m have been used to get the saltwater profiles depicted in Fig.5.7(A), Fig.5.7(B), and Fig.5.7(C) respectively. The spreading-out of the isochlors with increasing dispersivity values is quite visible in the plots. With a dispersivity, $\alpha_{L1}$= $\alpha_{T1}$= 2m the isochlors are concentrated in a zone near to the aquifer-sea boundary. Whereas when the dispersivity, $\alpha_{L3}$= $\alpha_{T3}$= 10m the isochlors are dispersed into the aquifer. It may be noticed that the increased dispersivity in the aquitard triggered larger mixing of the fluids and thereby more connectivity between the layers. Careful consideration of the grid dimensions and the range of aquifer parameter values used, a dispersivity value of 2 m has been selected for all other simulations made under different cases.

The transfiguration of saltwater intrusion profiles with the introduction of flow barriers of varying permeabilities is illustrated by means of a number of plots in Case- B4. Freshwater influx applied is 4 kg/s and dispersivity assumed in the medium is 2 m for all the simulations. The permeability values used in the simulations for the flow barrier (aquitard) range from $k_M$=1.02x$10^{-9}$ $m^2$ to $k_M$=1.02x$10^{-16}$ $m^2$. In the case of Fig.5.8-1(A), ($k_M$=1.02x$10^{-9}$ $m^2$), the connectivity between the layers is complete indicated by the distortion-free isochlors. In subsequent simulations the permeability of the aquitard has been reduced by an order of magnitude in each case. The change in pattern of intrusion profiles with reduced aquitard permeabilities may be visualised from plots in Fig.5.8-1 and Fig.5.8.-2. Apparently, there is a gradual withdrawal of the intrusion zone in the medium ( particularly in the bottom aquifer) with a reduction in the aquitard permeability. The extent of retreat of isochlors is more in the bottom aquifer as a result of reduced connectivity with the top aquifer, wnich in turn limits the solute movement from the top layer to the bottom layer. Comparison of Fig5.8-3(E), for which $k_M$=1.02x$10^{-13}$ $m^2$, and Fig5.8-3(F), for which $k_M$=1.02x$10^{-16}$ $m^2$, reveals that further reduction, beyond $k_M$=1.02x$10^{-13}$ $m^2$, in the permeability of the flow barrier yields little change in the intrusion profile.

In layered coastal systems, the scale of horizontal movement is usually very different from the scale of movement through confining units. This requires that dispersivities used to describe the system under investigation reflect the difference in scale. For adequate simulation of saltwater intrusion in a coastal aquifer a material-dependent dispersivity may be used. To investigate the effect of using a material-dependent dispersivity in modelling saltwater intrusion process two simulations have been carried out (Case- B5). Layer permeabilities used are $k_T$= $k_B$= 1.02x$10^{-9}$ $m^2$ (for top and bottom layers) and $k_M$= 1.02x$10^{-16}$ $m^2$ (for aquitard). Freshwater injection rate applied is 4 kg/s at the boundary. Profile in Fig.5.9(A) is obtained with a material-independent dispersivity of 10 m throughout the system; whereas use of material-dependent dispersivities ($\alpha_L$= $\alpha_T$= 10 m, for top and bottom layers and $\alpha_L$= $\alpha_T$= 1 m, for aquitard) yielded Fig.5.9(B). As evident from the plots, the cases investigated neither showed any staggered zones (*Reilly, 1990* ) in the profile nor there is any noticeable difference between the profiles obtained by use of material-independent dispersivity and material-dependent dispersivity for the layered aquifer system. The reason, presumably, could be the small lateral extent of the present simulation set-up wherein the values of dispersivity can not vary largely in the aquifer and aquitard portions of the system. Hence, the advantage of using material-dependent dispersivities may be felt only in the case of regional simulation of large multilayered coastal aquifer systems.

[A]




[B]

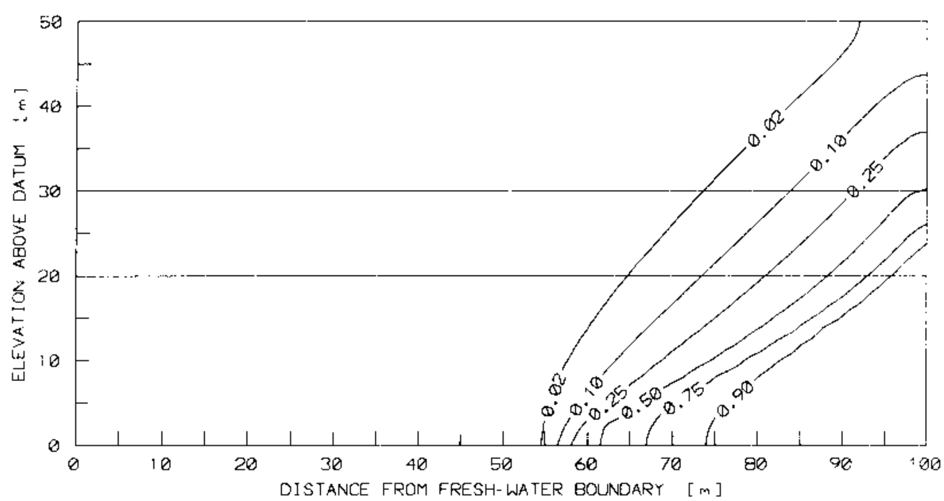
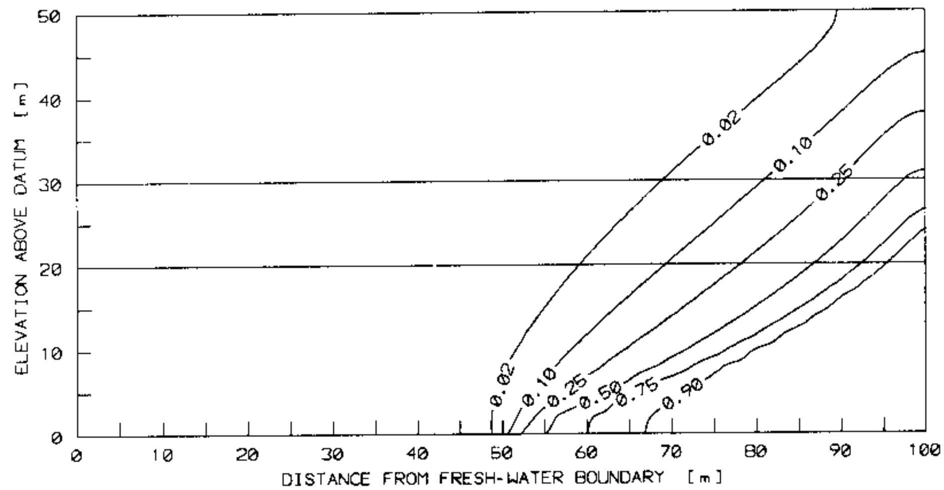



**Fig. 5.1** Transient profiles of saltwater intrusion for the hypothetical cross-section with a uniform permeability ($k=1.02x10^{-9}$ $m^2$) for all the layers; (A) profile after a simulation period of 0.30 hours, (B) profile after a simulation period of 70 hours

[C]




[D]

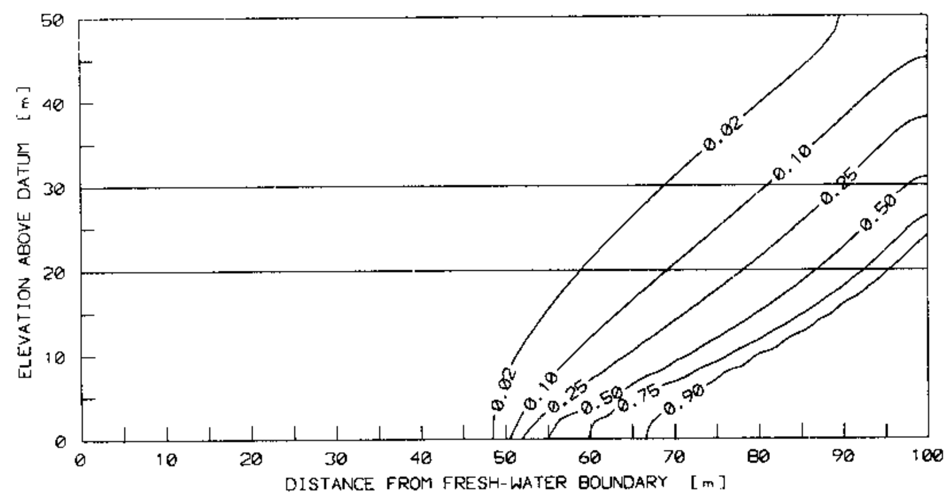
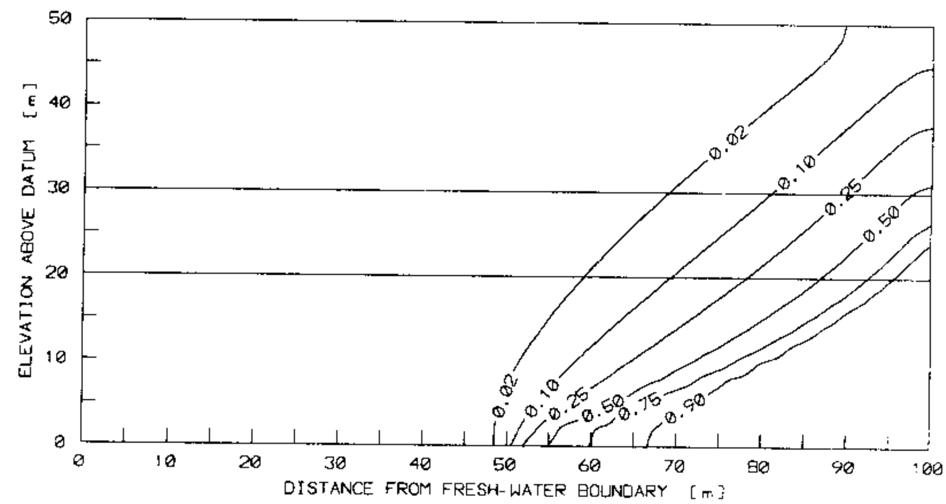



**Fig. 5.2** Steady-state profiles from transient simulation of saltwater intrusion in the hypothetical cross-section of a homogeneous aquifer with permeability, $k=1.02x10^{-8}$ $m^2$; (C) profile after a simulation period of 210 hours, (D) profile after a simulation period of 280 hours

[A]




[B]

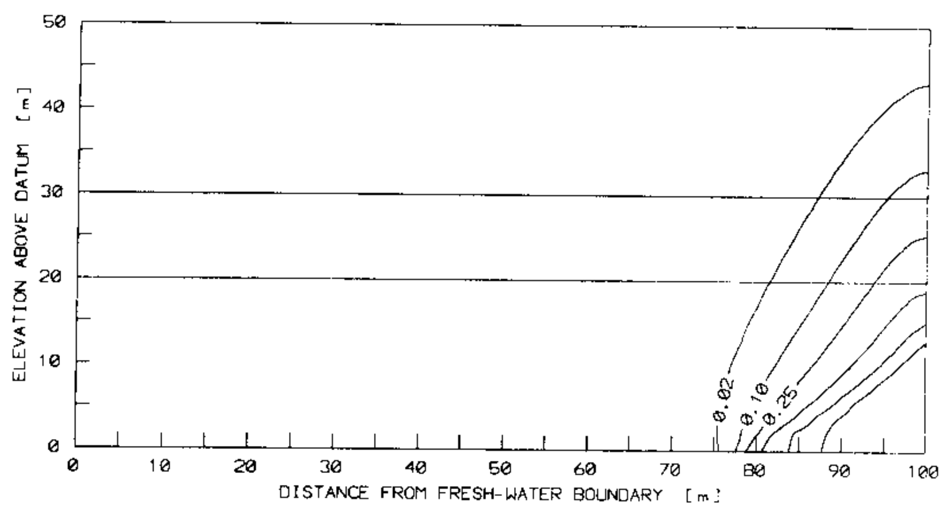
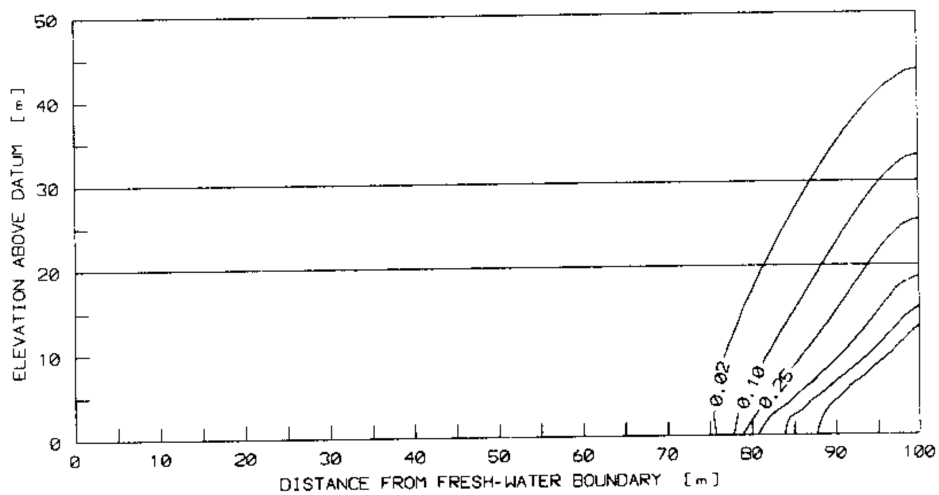



**Fig. 5.3** Comparison of effect of permeability on saltwater intrusion in a homogeneous aquifer; (A) Isochlors for the cross-section when permeability, $k=1.02\times10^{-9}$ $m^2$, and (B) Isochlors for the cross-section when permeability, $k=5.10\times10^{-10}$ $m^2$ (half the value of case A).

[A]




[B]

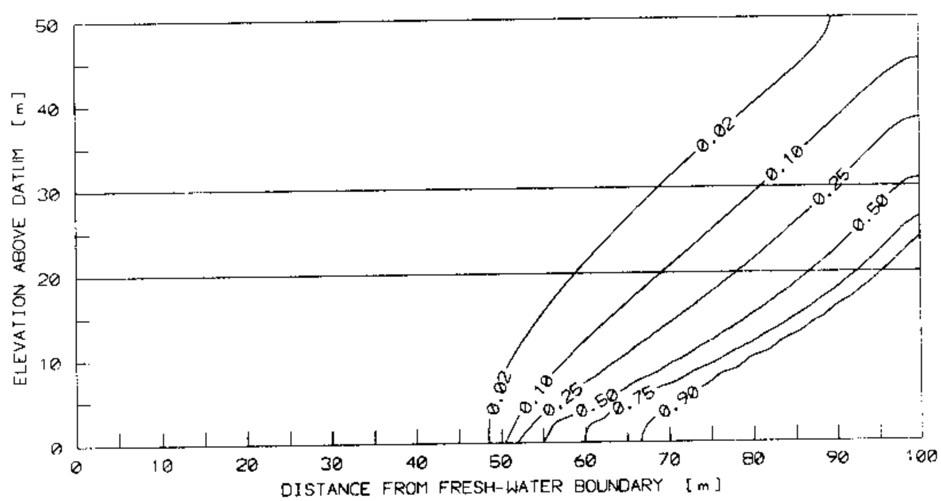
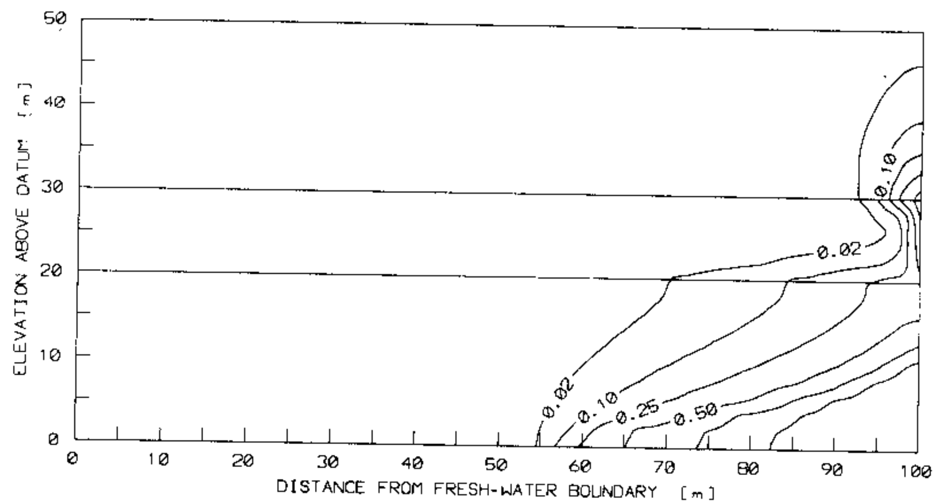



**Fig. 5.4** Comparison of effect of influx at the fresh-water boundary on saltwater intrusion in a homogeneous aquifer; (A) Isochlors for the cross-section when fresh-water injection rate, $Q_{IN}$=8 kg/s, and (B) Isochlors for the cross-section when fresh-water injection rate, $Q_{IN}$=4 kg/s (half the value of case A).

[A]




[B]

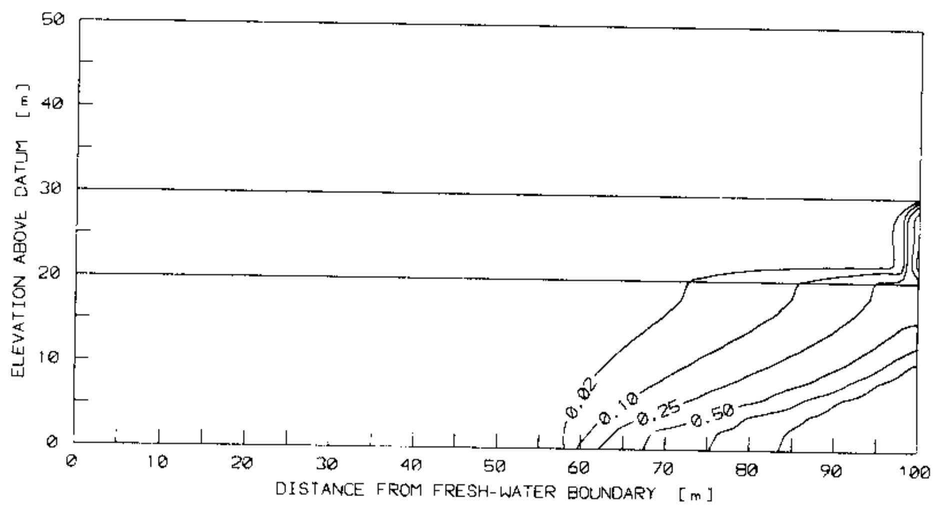
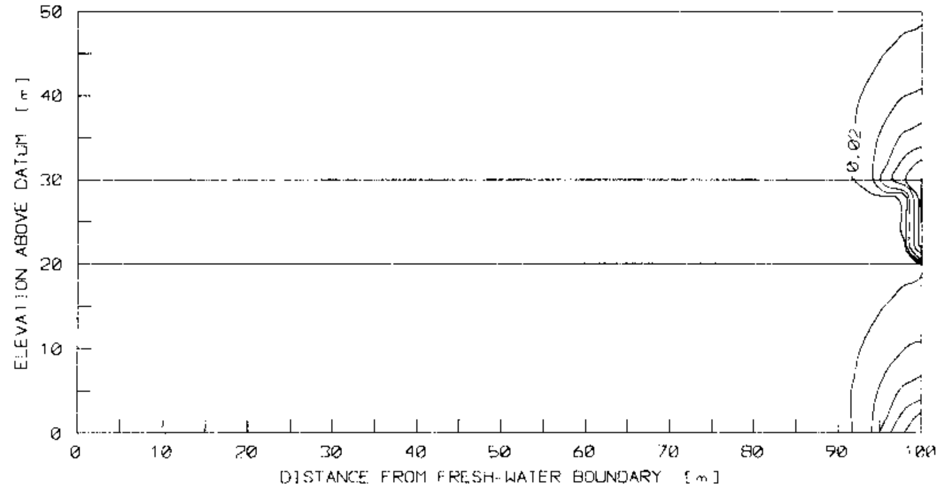



**Fig. 5.5** Comparison of effect of permeability on saltwater intrusion in a layered aquifer system; (A) Isochlors for the cross-section when permeabilities for the top, middle and bottom layers are $k_T$=1.02x10$^{-10}$ m$^2$, $k_M$=1.02x10$^{-12}$ m$^2$, and $k_B$=1.02x10$^{-9}$ m$^2$ respectively, and (B) Isochlors for the cross-section when permeabilities for the top, middle and bottom layers are $k_T$=1.02x10$^{-11}$ m$^2$, $k_M$=1.02x10$^{-13}$ m$^2$, and $k_B$=1.02x10$^{-9}$ m$^2$ respectively

[A]

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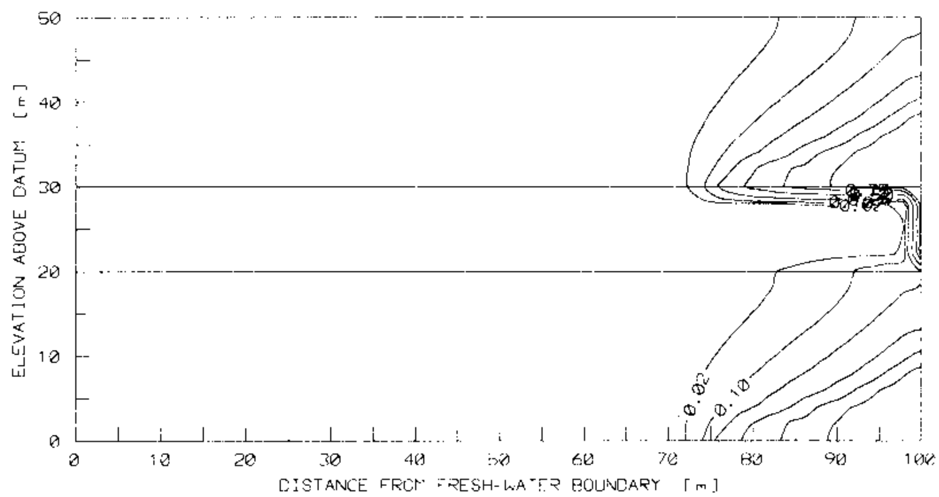



**Fig. 5.6** Comparison of effect of influx at the fresh-water boundary on saltwater intrusion in a layered aquifer system ($k_T$=1.02x10$^{-9}$ m$^2$, $k_M$=1.02x10$^{-13}$ m$^2$, and $k_B$=1.02x10$^{-9}$ m$^2$); (A) Isochlors for the cross-section when fresh-water injection rate, $Q_{IN}$=8 kg/s, and (B) Isochlors for the cross-section when fresh-water injection rate, $Q_{IN}$=2 kg/s (one-fourth the value of case A).

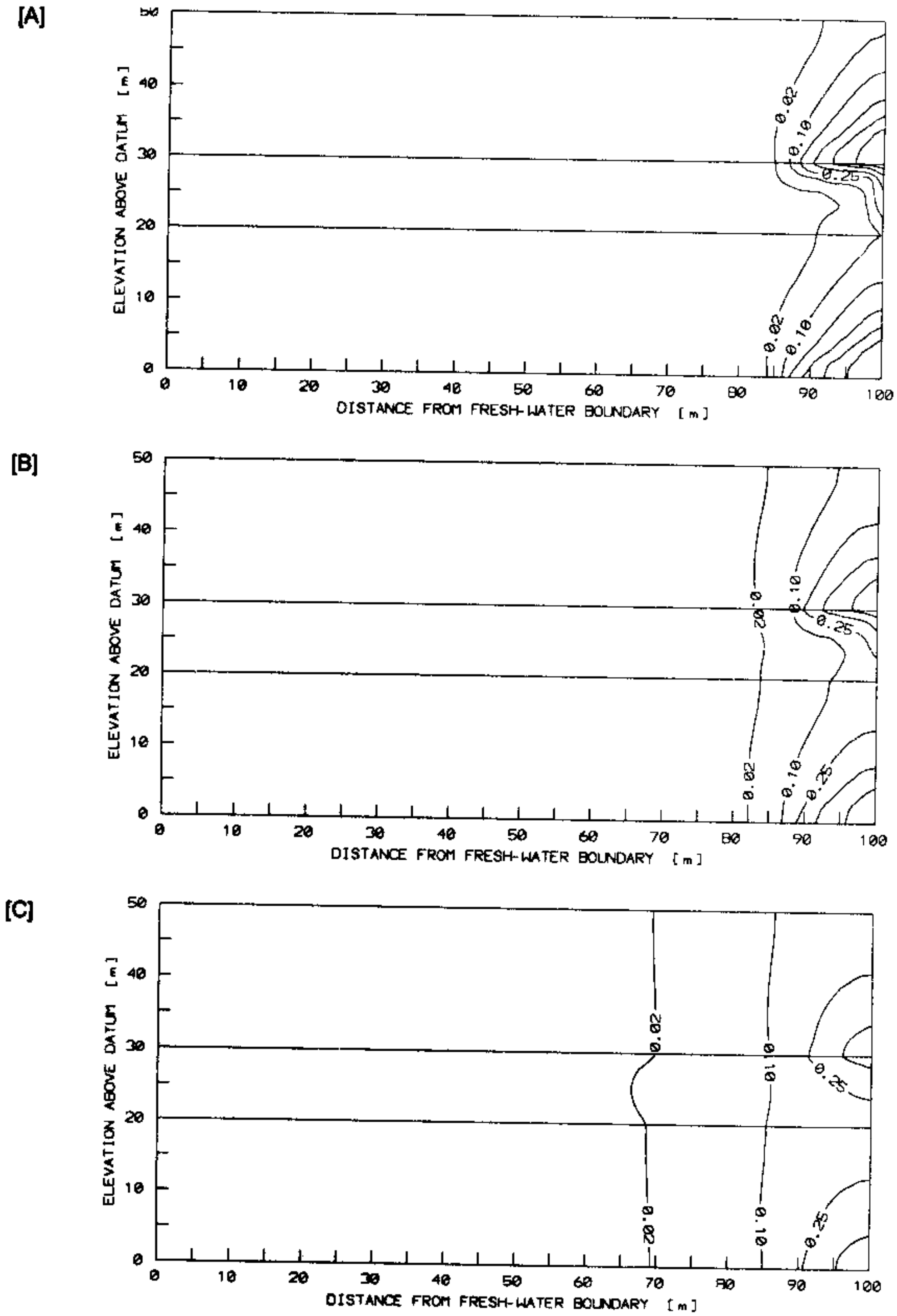
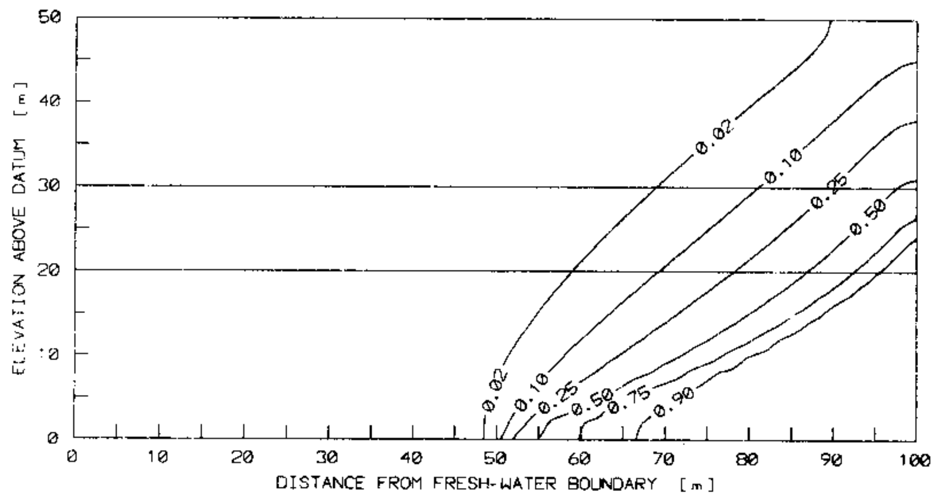



**Fig. 5.7** **Comparison of effect of dispersivities on saltwater intrusion in a layered aquifer system ($k_T = k_B = 1.02\times10^{-9}$ m², and $k_M = 1.02\times10^{-12}$ m². Saltwater intrusion profiles when (A) $\alpha_L = \alpha_T = 2$m, (B) $\alpha_L = \alpha_T = 4$m, and (C) $\alpha_L = \alpha_T = 10$m**

[A]




[B]

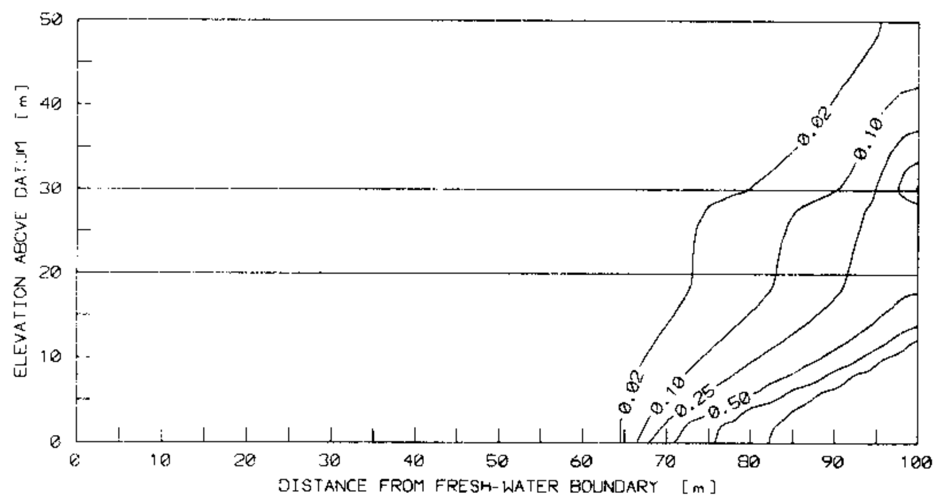



**Fig. 5.8-1** Comparison of saltwater intrusion profiles in a layered aquifer system with permeability varying for the confining layer; Permeability for the other layers is $k_T = k_B = 1.02 \times 10^{-9}$ m$^2$. (A) Isochlors for the cross-section when permeabilities for the confining layer, $k_M = 1.02 \times 10^{-9}$ m$^2$, and (B) Isochlors for the cross-section when permeabilities for the confining layer, $k_M = 1.02 \times 10^{-10}$ m$^2$.

[C]

[D]

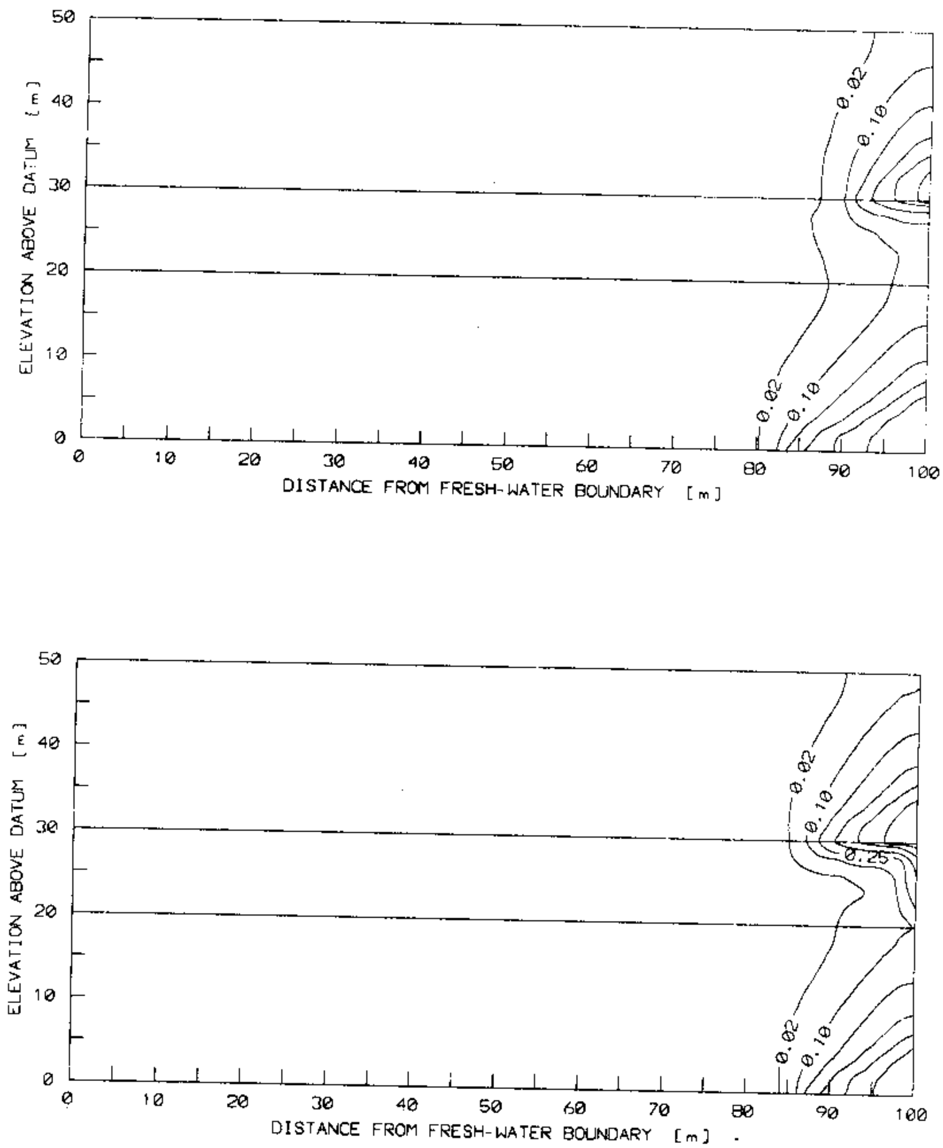
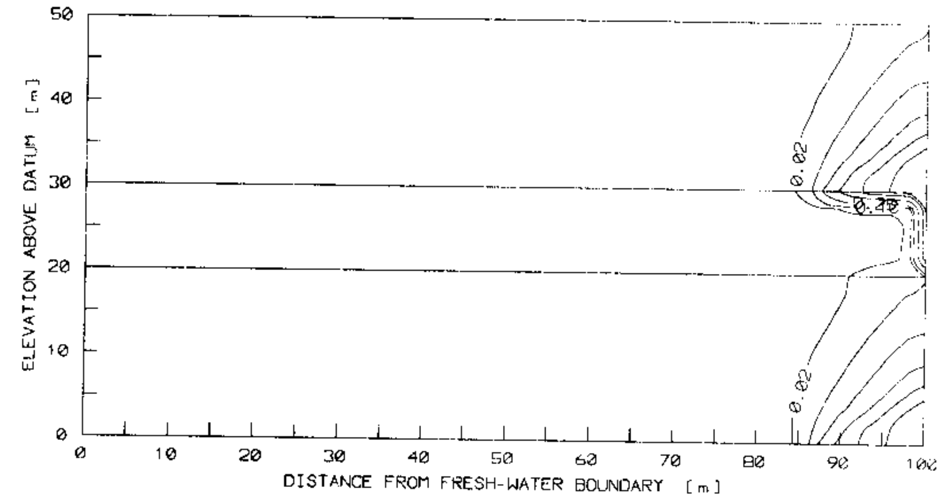



**Fig. 5.8-2** Comparison of saltwater intrusion profiles in a layered aquifer system with permeability varying for the confining layer; Permeability for the other layers is $k_T = k_B = 1.02 \times 10^{-9}$ m². (C) Isochlors for the cross-section when permeabilities for the confining layer, $k_M = 1.02 \times 10^{-11}$ m², and (D) Isochlors for the cross-section when permeabilities for the confining layer, $k_M = 1.02 \times 10^{-12}$ m².

[E]




[F]

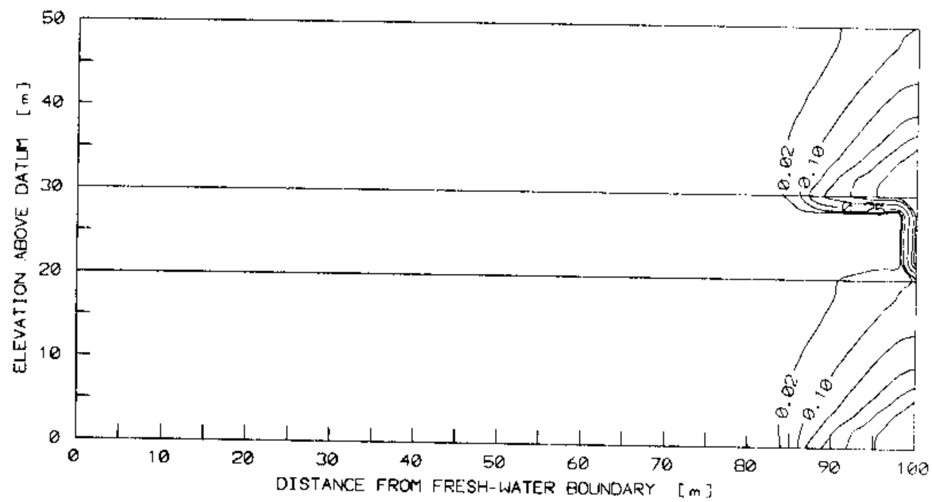
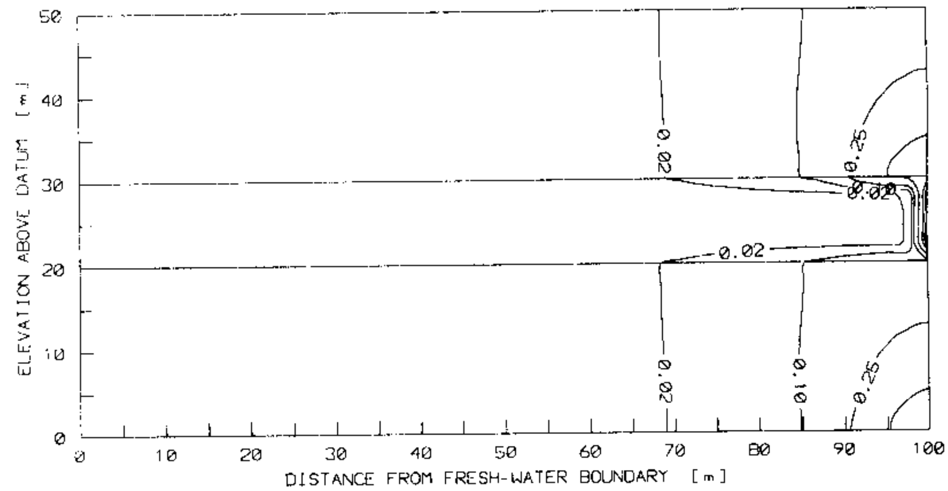



**Fig. 5.8-3** Comparison of saltwater intrusion profiles in a layered aquifer system with permeability varying for the confining layer; Permeability for the other layers is $k_T = k_B = 1.02\times10^{-9}$ $m^2$. (E) Isochlors for the cross-section when permeabilities for the confining layer, $k_M=1.02\times10^{-13}$ $m^2$, and (F) Isochlors for the cross-section when permeabilities for the confining layer, $k_M=1.02\times10^{-16}$ $m^2$.

[A]




[B]

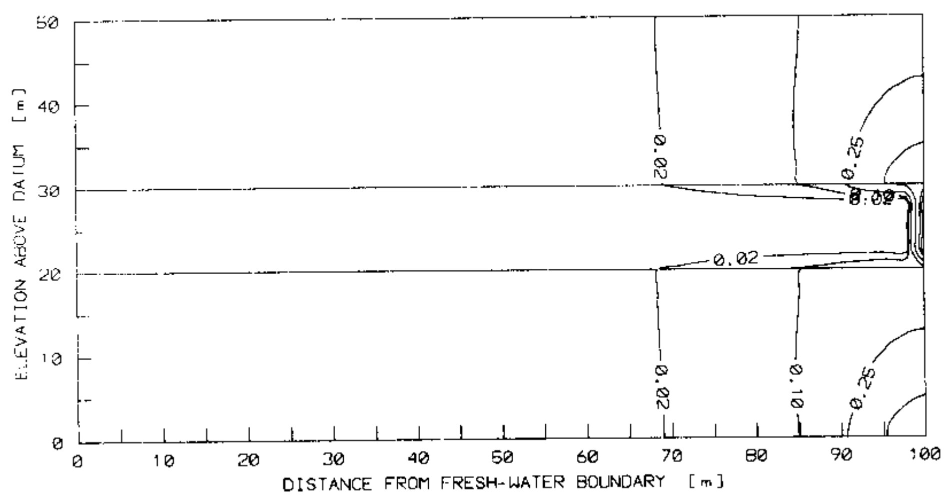



**Fig. 5.9** Comparison of saltwater intrusion profiles in a layered aquifer system with material-independent dispersivity and material-dependent dispersivities; (A) Intrusion profile with dispersivities $\alpha_L$=$\alpha_T$=10m throughout the system, and (B) Intrusion profile with dispersivities $\alpha_L$=$\alpha_T$=1.0m for the confining layer and $\alpha_L$=$\alpha_T$=10m elsewhere. Permeability for the confining layer, $k_M$=1.02x$10^{-16}$ $m^2$ and $k_T$= $k_B$= 1.02x$10^{-9}$ $m^2$.

# 6.0 SUMMARY AND CONCLUSION

Salinewater intrusion is a major problem in coastal regions affecting the quality of water supply. Quantitative understanding of the pattern of movement and mixing between fresh and salinewater, and of the factors that influence these processes, is required to manage and protect the freshwater resources in the coastal regions. A sustainable groundwater management approach in coastal region should aim at maintaining acceptable spatial and temporal equilibrium of saltwater ingress in the aquifer system. In order to realise this, analysis of the saltwater intrusion problem at regional scale is necessary. Prognostic analyses may be carried out based on field observations and hydrogeology of the aquifer system. Remedial measures may be evaluated and implemented based on such analyses. Mathematical modelling of flow and solute transport in coastal aquifer system can be a useful tool for the purpose.

In the present study, a hypothetical set-up of a homogeneous and a multi-layered coastal aquifer system is simulated using the USGS finite element model SUTRA for different boundary conditions and aquifer parameters. The saltwater intrusion profiles for steady-state/ transient conditions are obtained and analysis of results presented in the preceding section. The influence of changes in the permeabilities of aquifers and aquitards, changes in flux at the boundaries, and changes in dispersivities in the medium on the intrusion profiles are investigated. The effect of material-independent/ material-dependent dispersivities are also subjected to analysis. It is observed that permeability of the medium, dispersivity in the medium and influx at the boundaries affect the extend and intensity of saltwater intrusion in a coastal aquifer system. However, material-dependent dispersivity in a multilayered aquifer system did not make discernible changes in the intrusion profile compared to that with material-independent dispersivitiy for the present set-up.

In layered coastal systems, the scale of horizontal movement is usually very different from the scale of movement through confining units. This requires that dispersivities used to describe the system under investigation reflect the difference in scale. For adequate simulation of saltwater intrusion in a coastal aquifer, flow-direction-dependent dispersivity (equivalently a material-dependent dispersivity also could be used) may be required. It has been reported (*Reilly, 1990*) that in order to reproduce staggered transition zones in the saltwater intrusion profiles, consistent with theoretical studies and field investigations, it is required to use flow-direction-dependent dispersivity/ material or position-dependent dispersivity. The case investigated presently neither showed any staggered zones in the profile nor there was any noticeable difference between the profiles obtained by use of material-independent dispersivity and material-dependent dispersivity for the layered aquifer system. One reason could be the small lateral extent of the present simulated section wherein the values of dispersivity can not vary largely in the aquifer portion and aquitard portion. The difference between dispersivities of the aquifer and aquitard portions for the present case is only 9m. Whereas in one of the investigations (*Reilly, 1990*), the material dependent dispersivity was 500 times smaller (for the aquitard) than that in the aquifer portion of the coastal aquifer system, which is extending to 20 km landwards.

The investigations employing the model SUTRA bring forth some insight into the behaviour of saltwater intrusion profiles in a multilayered coastal aquifer system with varying boundary conditions or aquifer parameters. SUTRA is a powerful tool for the simulation of density-dependent solute transport processes in a porous medium. However, application of the model SUTRA is limited to two-dimensional aquifer systems only since it can not account for the variations in the third dimension. As such, it is inappropriate to model aquifer systems with three-dimensional boundary conditions and flow characteristics. Similarly, simulation of pumping stresses on saltwater intrusion in a coastal aquifer system is also difficult. To simulate three-dimensional processes in a coastal aquifer system, the finite-difference model HST3D (*Kipp, 1987*) or the finite-element model SALTFLOW (*Molson and Frind, 1994*) may be employed.

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