Technical University of Denmark

Vejen injektionsfelt: Dispersion

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Vejen Injektionsfelt: DISPERSION

RAPPORT M5/6 DECEMBER 1991

LOSSEPLADSPROJEKTET

FORORD

Denne rapport omhandler de aktiviteter vedrørende dispersion, der er foregået indenfor lossepladsprojektets M5 og P4 projekter. Som led i disse projekter er der ved injektionsfeltet ved Vejen foretaget injektion af tritium og klorid med henblik på at undersøge transport- og dispersionsmekanismer i samme type grundvandsmagasin, som i området omkring Vejen losseplads, er forurenet med perkolat.

Rapporten består af en kortfattet præsentation af de vigtigste resultater, og som bilag er inkluderet en artikel, hvor data og resultater er mere udførligt præsenteret og diskuteret.

Der rettes en tak til Isotopcentralen, ATV, for assistance i forbindelse med indhentning af myndighedsgodkendelser, injektion samt analyse for tritiumindhold.

SAMMENFATNING

Ved injektionsfeltet ved Vejen er der foretaget injektion af tritium og klorid med henblik på at undersøge transport- og dispersionsmekanismer i samme type grundvandsmagasin, som i området omkring Vejen losseplads er forurenet med perkolat. På grundlag af koncentrationsmålinger udført på et stort antal vandprøver, som er indsamlet fra et tæt net af observationsboringer, er der konstateret en lille dispersion i alle tre hovedretninger, og de afledte dispersiviteter er væsentligt mindre end, hvad hidtil har været anvendt i ingeniørmæssig praksis. For kloridfanens vedkommende blev der konstateret en densitetseffekt tæt ved injektionspunktet, som gav anledning til en neddykning af fanen.

Der er opstillet en 3-dimensional strømnings- og transportmodel for det undersøgte grundvandsmagasin. Modellen er sammenkoblet med en 1-dimensional model for umættet vandstrømning for at medregne indflydelsen af de sæsonmæssige fluktuationer i nedsivningen. På grundlag af en række følsomhedsanalyser er der identificeret følgende værdier for dispersiviterne: langsgående dispersivitet i horisontal retning 0.45 m, tværgående dispersivitet i horisontal retning 0.001 m, langsgående dispersivitet i vertikal retning 0.05 m og tværgående dispersivitet i vertikal retning 0.0005 m.

Der er opnået en særdeles god overensstemmelse mellem simuleringerne af transporten og dispersionen af de to tracere og de overordnede observerede forløb. Derimod kan der optræde afvigelser, når der foretages sammenligninger på meget mindre skala i form af gennembrudskurver fra specificerede positioner i grundvandsmagasinet. Dette er imidlertid at forvente, fordi de observerede gennembrudskurver er påvirket af de lokalspecifikke geologiske forhold, som der ikke er taget hensyn til i modellen.

ENGLISH SUMMARY

Bitsch, K., Jensen, K. Høgh and Bjerg, P.L. (1991): Large-scale dispersion experiments in a sandy aquifer in Denmark. Lossepladsprojektet, Rapport M5.

A large-scale natural gradient dispersion experiment was carried out in a sandy aquifer in the western part of Denmark in order to examine the dispersion processes in a geological environment typical for that part of the country. Tritium and chloride were used as tracers injected as a slug and continuously over a 37 day period, respectively.

The transport and dispersion of the two plumes were monitored by water sampling in a dense three-dimensional network of piezometers. For both plumes a marked spreading was observed in the longitudinal direction while the spreading in the transverse horizontal and transverse vertical directions was very small. However, the chloride plume experienced an initial sinking due to gravitational instabilities, created by density contrasts between the injected solution and the native groundwater.

The transport parameters of the convection dispersion equation (CDE) were investigated by applying an optimization model based on the analytical solution to the CDE to observed break-through curves of tritium.

No clear trend with travel distance for the distances examined could be found suggesting that the asymptotic stages are reached within short distances from the point of injection.

A three-dimensional numerical model for flow and transport was applied to the aquifer in order to identify the dispersivity parameters more closely. The model was coupled to a one-dimensional unsaturated flow model to account for the seasonality in recharge. On the basis of a number of trial simulations the following "best-fit" dispersivity parameters were identified: longitu-

dinal horizontal 0.45 m, transverse horizontal 0.001 m, longitudinal vertical 0.05 m, and transverse vertical 0.0005 m.

The numerical model simulations compared excellent to the observations of the water table fluctuations and to the overall behaviour of the tracer plumes. However, on a more detailed basis when breakthrough curves are compared discrepancies were present due to the existence of local heterogeneities.

INDHOLDSFORTEGNELSE

1. INDLEDNING

Transport af opløste ikke-reaktive forureningsstoffer i grundvand regnes traditionelt at være bestemt af de to processer konvektion og dispersion. Konvektion refererer til den transport, som sker med middelbevægelsen af grundvandet, og dispersion beskriver transporten, som skyldes de lokale hastighedsvariationer omkring middelbevægelsen, Freeze og Cherry (1979). Disse hastighedsfluktuationer skyldes de altid tilstedeværende inhomogeniteter i de geologiske lagfølger.

Den klassiske matematiske model for transport og spredning af opløste stoffer i porøse medier er konvektions-dispersionsligningen, som er udledt under antagelse af, at dispersionsprocessen kan beskrives ved Ficks diffusionslov, Bear (1972). I ligningen indgår som parametre dispersiviteter, som repræsenterer spredningen på langs og på tværs af strømningsretningen. Konvektions-dispersionsligningen er oprindeligt udledt for en skala repræsenterende det "representative elementary volume (REV)", jfr. Bear (1979), hvilket til alle praktiske formål kan antages at svare til skalaen i laboratorieopstillinger. Imidlertid har ligningen i stort omfang været anvendt til beskrivelse af stofspredningen i felten, hvor dispersiviteterne så er forhøjet en størrelsesorden eller mere for at beskrive den større spredning, som den heterogene geologiske opbygning giver anledning til.

Dispersiviteterne har i den forbindelse typisk været anvendt som kalibreringsparametre. Først er der foretaget en kalibrering af en strømningsmodel på grundlag af hydrogeologiske data, primært transmissiviteter og potentialer, hvorved der er etableret en beskrivelse af den konvektive udbredelse. Dernæst er en stoftransportmodel kalibreret ved at justere på dispersiviteterne, indtil der på grundlag af skøn for kildestyrke opnås en god beskrivelse af de foreliggende koncentrationsmålinger i det påvirkede magasin. Da det altid er vanskeligt at kvantificere kildestyrkens historiske udvikling, og da der oftest kun foreligger et mindre antal koncentrationsmålinger, er ovennævnte metode til bestemmelse af dispersiviteterne forbundet med betydelig usikkerhed.

I Lallemand-Barris og Reandecerf (1978) samt Gelhar et al. (1985) er der foretaget en sammenstilling og diskussion af en række feltmålinger af den langsgående dispersivitet. Af disse sammenstillinger fremgår, at dispersiviteten tilsyneladende er skalaafhængig, og at der er tale om en betydelig spredning på resultaterne selv inden for samme aflejringstype og for samme transportafstande. Den fysiske forklaring på disse observationer henføres til jordlagenes heterogene opbygning, og den deraf afledede variation i de hydrauliske parametre og herunder specielt den hydrauliske ledningsevne. Dette betyder, at for større transportafstande vil forureningsfanen blive udsat for flere og flere inhomogeniteter, og dermed skal introduceres en større dispersivitet for at beskrive den heraf afledte spredningsmæssige effekt. Tilsvarende gør sig gældende, at desto mere inhomogent magasin, der er tale om, desto større dispersivitet skal anvendes.

I forbindelse med en række teoretiske undersøgelser, hvor den hydrauliske ledningsevne opfattes som en stokastisk variabel, er der etableret sammenhænge mellem dispersivitet og variation i hydraulisk ledningsevne, se fx Dagan (1982), Dagan (1984), Gelhar og Axness (1983), Gelhar et al. (1979) og Matheon og de Mar~~d~~sily (1980). Disse teoretiske arbejder har endvidere påvist, at dispersionsprocessen i visse tilfælde ikke kan beskrives ved en Ficks diffusionsanalogi i nærfeltet, fordi dispersiviteten vokser mod en asymptotisk værdi, som måske først nås efter transportafstande på flere hundrede meter.

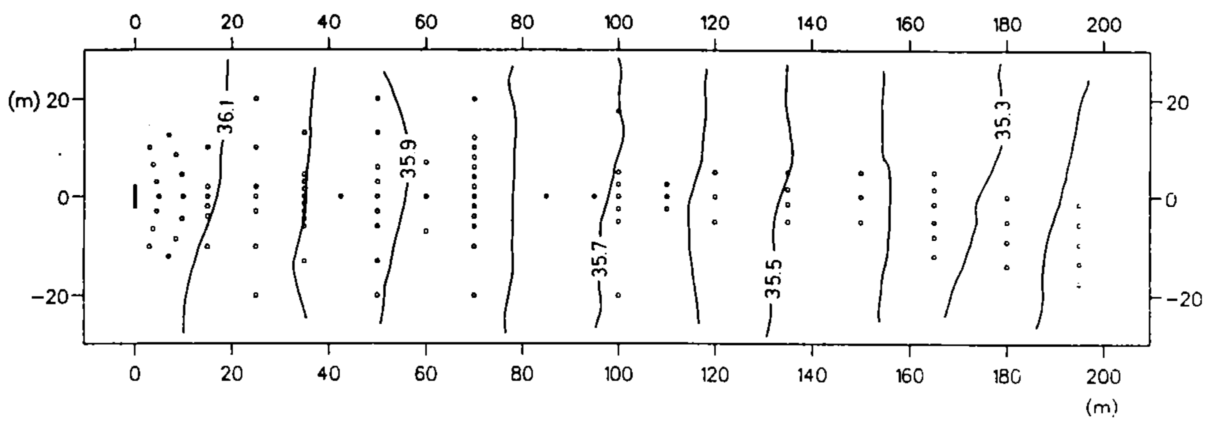
Generelt kan siges, at der er en række uafklarede forhold omkring anvendelse af konvektions-dispersionsligningen til beskrivelse af forureningsspredning i naturlige grundvandsmagasiner og herunder ikke mindst omkring bestemmelsen af dispersiviteten. Dette har foranlediget, at der i udlandet har været udført kontrollerede dispersionsforsøg med henblik på at undersøge disse forhold på grundlag af veldokumenterede data. De tre kendteste forsøg er

Borden Air Force Base, Freyberg (1986) og Mackay et al. (1986), Cape Cod, Garabedian et al. (1988) og Twin Lake, Killey et al. (1987).

Der har ikke tidligere været udført sådanne forsøg i Danmark, og det blev derfor besluttet at udføre et dispersionsforsøg som led i lossepladsprojektet med henblik på at undersøge dispersionsforholdene i en typisk dansk aflejringstype (hedeslettesand). Tracerlokaliteten blev placeret så tæt ved pilotlossepladsen som muligt for dermed tillige at etablere viden af specifik relevans for modelleringen af forureningsudbredelsen fra lossepladsen, se Refsgaard et al. (1991).

2. FORSØGSMÆSSIGE FORHOLD

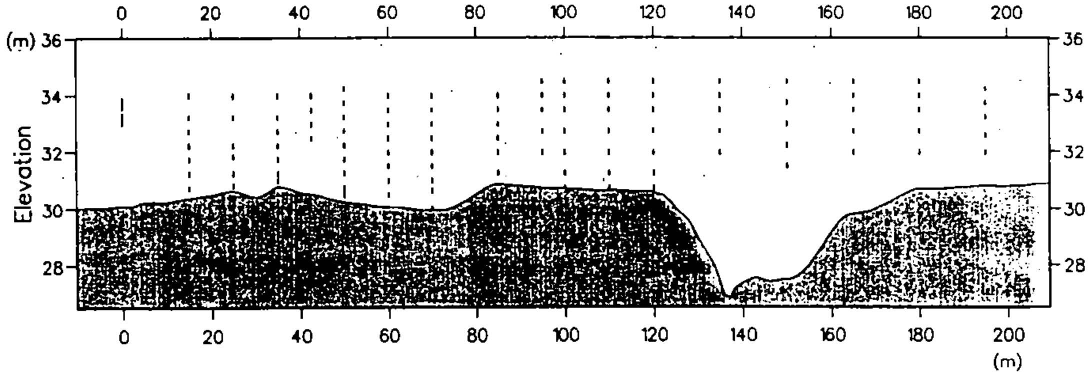
Tracerfeltet, som er placeret sydvest for pilotlossepladsen, har en udstrækning på 200 m på langs og 40 m på tværs af strømningsretningen. Der er i alt etableret ca. 100 prøvetagningslokaliteter inden for feltet med op til 7 prøvetagningssteder over dybden, Fig. 1 og 2. Alle prøvetagningsfiltre har en længde på 0.25 m og er installeret i adskilte rør, som ved rammeteknik er placeret i de enkelte dybder. I den opstrøms ende af feltet er placeret 5 boringer med 0.5 m filtre (jvf. Fig. 1), hvor tracerinjektionen er foretaget.



Figur 1. Horisontal placering af prøvetagningslokaliteter samt potentialbillede.

Grundvandsspejlet er placeret ca. 5 m under terræn, og reservoiret er begrænset nedadtil af et tæt lerlag i ca. 10 m dybde, således at den mættede lagtykkelse for det øverste reservoir er ca. 5 m, se Bjerg et al. (1991).

Der er observeret sæsonmæssige fluktuationer i grundvandsstanden på maksimalt 1 m, men da vandspejlsfluktuationerne i observationsboringer stort set er i fase, introduceres ingen væsentlig tværgående strømning på tværs af hovedstrømningsretningen. Fig. 1 viser potentialbilledet pr. 14.2.1990, hvoraf fremgår, at strømningsretningen er tæt på at være sammenfaldende med orienteringen af tracerfeltet.



Figur 2. Vertikal placering af prøvetagningssteder.

Den hydrauliske ledningsevne er bestemt ved slug-test og beskrevet af Hinsby et al. (1991) og Bjerg et al. (1991a). Der er observeret en relativt lille rumlig variation i den hydrauliske ledningsevne $K(\sigma^2_{lnk} = 0.38)$. Endvidere er måleresultaterne kun korreleret indenfor små afstande (længdekorrelation $\lambda < 2.5$ m).

Porøsiteten er bestemt til at være af størrelsesordenen 0.35-0.40, Bjerg et al. (1991b), og den effektive porøsitet vurderes til 0.30.

Der er foretaget injektion af to forskellige ikke-reaktive tracere i to omgange. Det egentlige dispersionsforsøg blev udført med tritium (H-3) som tracer. Dette sporstof blev valgt, fordi det er muligt at opnå store koncentrationskontraster, uden at der derved introduceres densitetseffekter. Anvendelse af tritium kræver til gengæld, at de sundhedsmæssige forhold overvåges nøje. Doseringen blev foretaget 1. marts 1989 ved til hver af de 3 midterste boringer at tilføre 50 l vand over ca. 10 minutter, hvori der er opløst $1.55 \cdot 10^9$ Bq H-3.

I forbindelse med det efterfølgende tracerforsøg med uorganiske salte Bjerg og Christensen (1991) blev doseret klorid, som også kan opfattes om et konservativt stof, og dets bevægelse vil derfor også afspejle dispersionsforholdene. I modsætning til doseringen af tritium, som skete momentant, blev de uorganiske salte tilført kontinuert over 37 dage fra 1. maj 1989 til 6. juni 1989, og alle 5 doseringsrør blev taget i anvendelse. På doseringstidspunktet var der en formodning om, at tritiumfanen var blevet indfanget i et grovere sandlag, hvilket i øvrigt senere blev bekræftet ved jordprøveudtagning, og det blev derfor besluttet at nedramme doseringsfiltrene yderligere 0.5 m. Den samlede kloridnedpumpning var 48 kg med en middelnedpumpning på 9.0 l/time svarende til en koncentration på ca. 6000 mg/l.

Det fremgår heraf, at de to tracerforsøg vedrørende dispersion komplementerer hinanden for så vidt angår sporstoftype, doseringsmetode samt det påvirkede område af grundvandsmagasinet.

De to tracerskyers udbredelse er kortlagt ved at måle koncentrationen i vandprøver, som er udtaget med vacuumudstyr efter passende renpumpning.

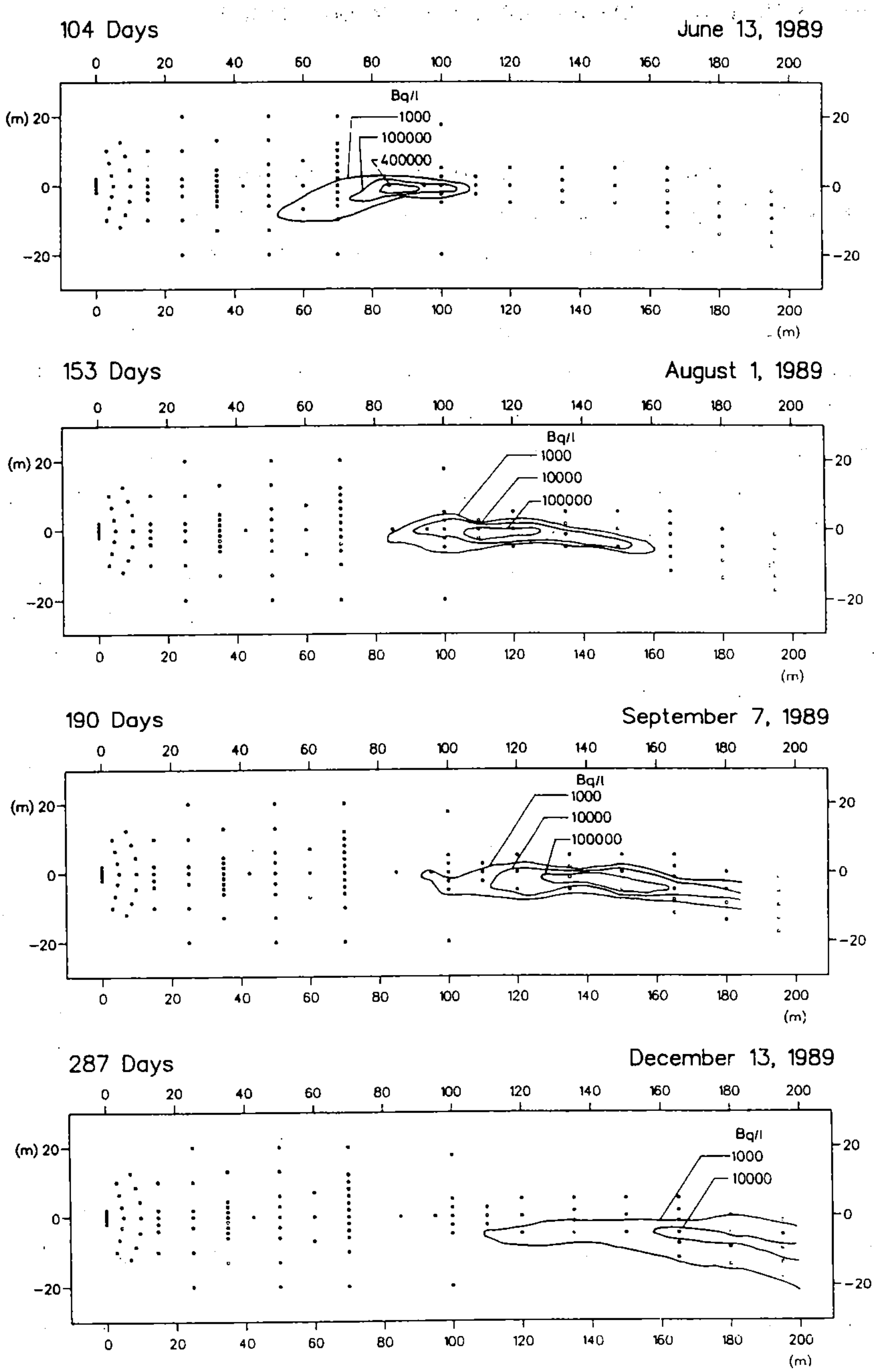
3. OBSERVERET UDBREDELSE AF TRITIUM OG KLORID

3.1 Tritium

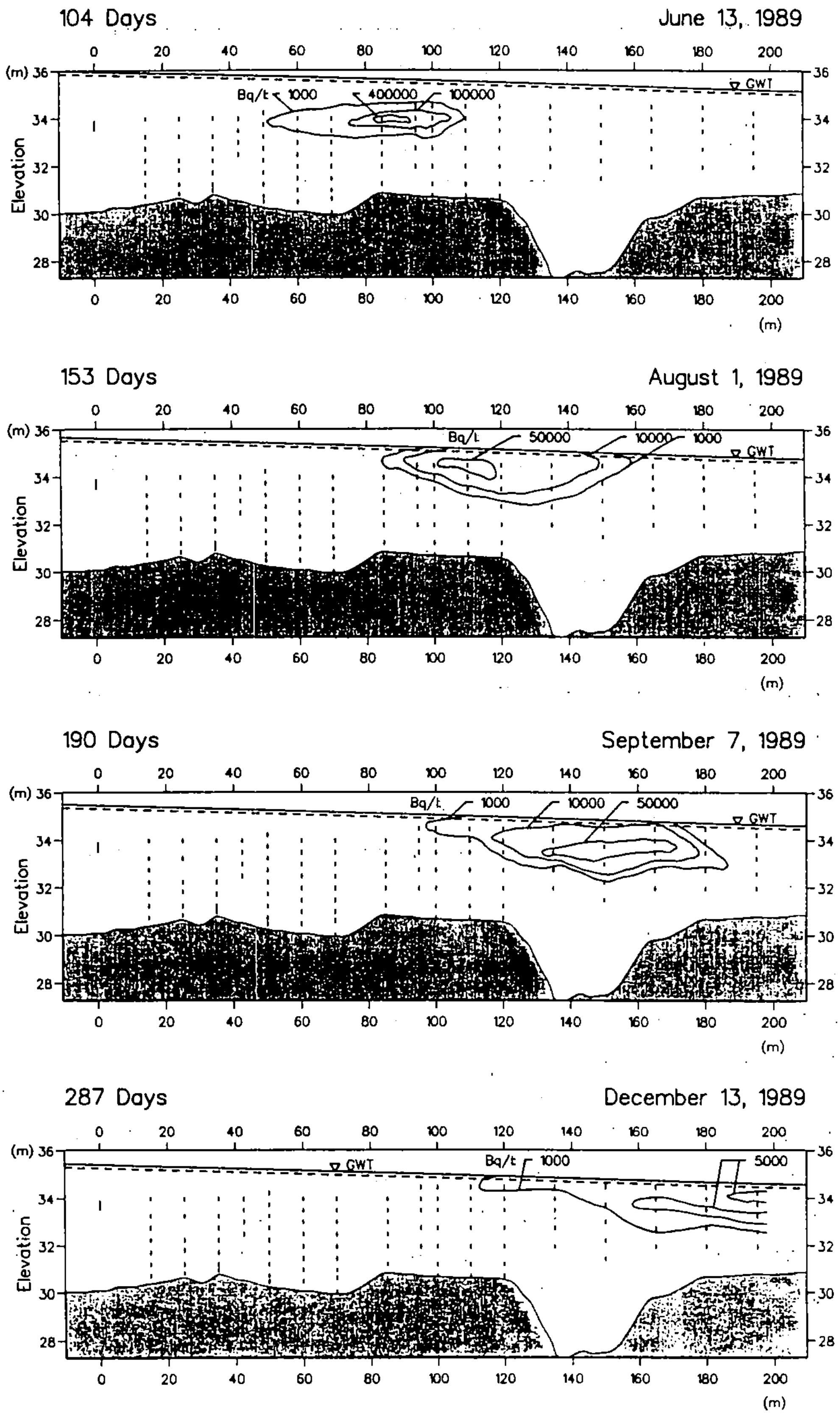
Tritiumskyen udbredte sig i grundvandsmagasinet med en meget større hastighed og en væsentligt mindre dispersion end forventet, hvilket betød, at de boringer, som blev etableret i første fase, ikke alle havde en hensigtsmæssig placering. Endvidere var prøvetagnings- og analyseprogrammet ikke designet optimalt i starten, hvilket tilsammen betød, at faneudbredelsen de første 50 m ikke blev kortlagt i alle detaljer. De indvundne erfaringer omkring udbredelseshastighed førte til, at de videre prøvetagningskampagner blev væsentligt mere intensive end oprindeligt planlagt, og videre foranledigede den meget beskedne dispersion, at antallet af observationsrør blev udvidet og i øvrigt placeret meget tættere. Disse løbende revisioner i undersøgelsesprogrammet betød, at for afstande udover 50 m blev tritiumudbredelsen kortlagt meget detaljeret både rumligt og som gennembrudskurver.

I Fig. 3 er vist den horisontale udbredelse af tritiumskyen til udvalgte tidspunkter i transportforløbet. De angivne koncentrationsværdier er et mål for den totale tritiummængde, som er til stede i vertikalsnit. Af figuren fremgår at stofskyen stort set bevæger sig langs med det etablerede undersøgelsesområde, og først når skyen forlader feltet, sker der en svag ændring i retningen, hvilket er i overensstemmelse med potentialbilledet, Fig. 1. Den gennemsnitlige udbredelseshastighed af skyens massemidtpunkt kan beregnes til ca. 0.75 m/dag. Det fremgår videre af figuren, at der sker en betydelig stofspredning i longitudinal retning, som resulterer i en gradvis udstrækning af skyen med en heraf følgende formindskelse i maksimalkoncentrationer. Den transversale spredning på tværs af hovedstrømningsretningen er derimod meget lille.

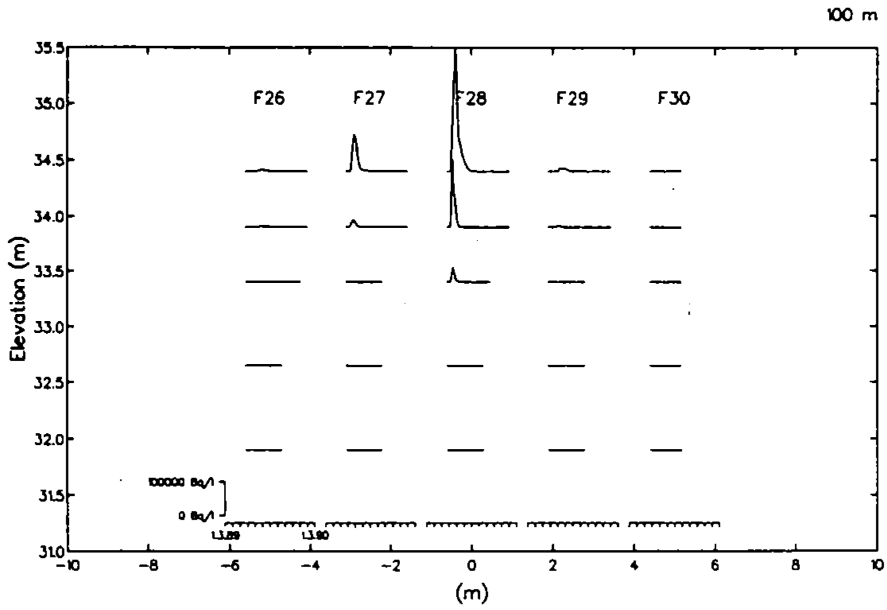
Fig. 4 illustrerer udbredelsen af tritium i et vertikalsnit, som er placeret langs tritiumskyens længdeakse. Der konstateres en relativ beskeden spredning over dybden og specielt bemærkes, at



Figur 3.Horisontal udbredelse af tritium til udvalgte tidspunkter.



Figur 4. Vertikal udbredelse af tritium til udvalgte tidspunkter.



Figur 5. Gennembrudskurver for tritium i filtre placeret i et tværsnit 100 m nedstrøms injektionsstedet.

skyen mod forventning har tendens til at bevæge sig op mod grundvandsspejlet.

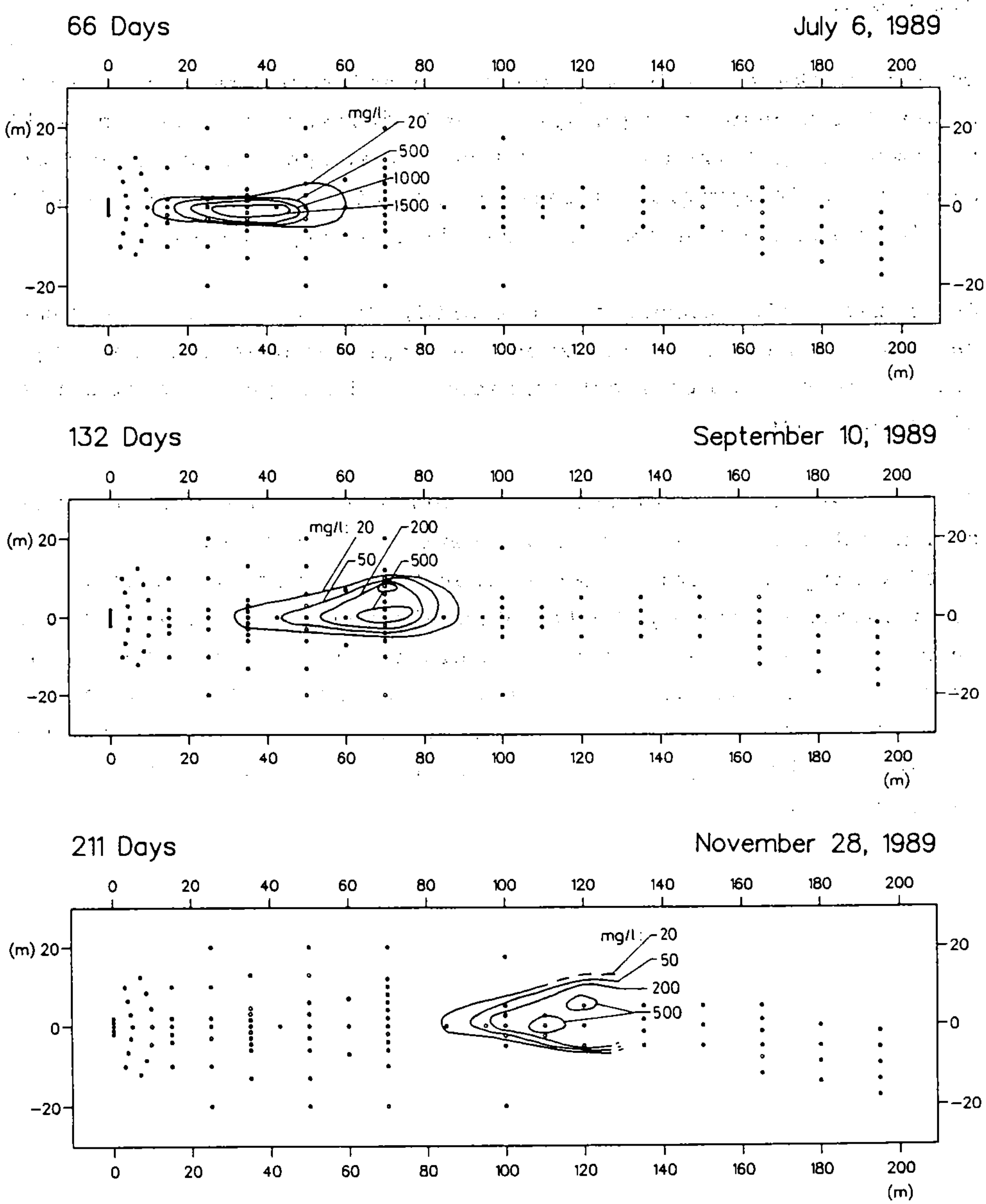
I Fig. 5 er illustreret de observerede gennembrudskurver for alle filtre placeret i et snit 100 m nedstrøms injektionsstedet. Af figuren ses, at filtrene stort set omslutter tritiumskyen under dens passage gennem snittet undtagen tæt ved grundvandsspejlet. De øverste filtre i F27 og F28 er begge stærkt påvirket, og det er derfor sandsynligt, at der passerer tracer tættere mod grundvandsspejlet. Ellers ses filtrene i den midterste søjle F28 at være mest påvirkede - dog formodes massemidtpunktet at passere et sted mellem F27 og F28. De præsenterede kurver samt de fleste af de øvrige længere nedstrøms følger stort set Gauss-fordelinger. I visse af de yderste filtre langs skyens højre afgrænsning optræder dog gennembrudskurver med to toppunkter, hvilket kunne indicere, at skyen tidligt i transportforløbet kan have fulgt to transportveje.

3.2 Klorid

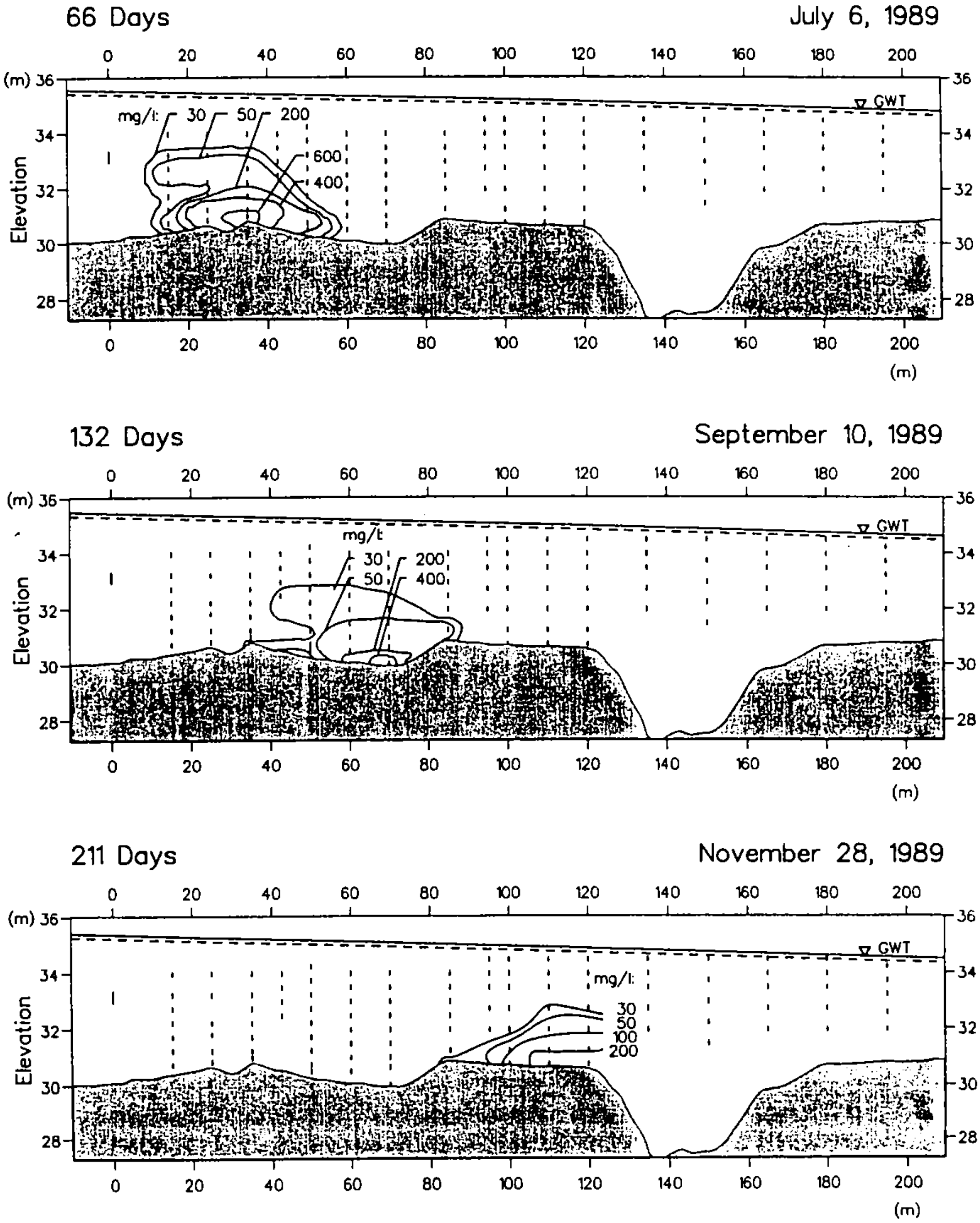
De uorganiske salte blev doseret 2 måneder senere, og da kendskabet til transport- og dispersionsforholdene på dette tidspunkt var væsentligt forbedret, var det muligt at opstille et mere optimalt moniteringsprogram, således at det initielle spredningsforløb her blev kortlagt bedre end i det første tracerforsøg.

Den horisontale udbredelse af klorid, Fig. 6, udviser de samme karakteristika som tritiumskyens: en udpræget dispersion i longitudinal retning og en meget beskeden spredning på tværs af strømningsretningen.

I Fig. 7 er vist fordelingen i et vertikalsnit placeret i langsgående retning. Heraf ses at den vertikale fordeling for klorid, i modsætning til tritium, har de største koncentrationer lige over det impermeable lerlag. Dette udbredelsesmønster skyldes, at traceropløsningen har en forholdsvis høj densitet (Δ = 0.006), og at injektionen foretages med et mindre overtryk (ca.0.05 m), således at de tilsatte salte i selve injektionsområdet føres lodret mod den impermeable afgrænsning, og først herefter føres med grundvandsstrømmen.



Figur 6.Horisontal udbredelse af klorid til udvalgte tidspunkter.



Figur 7. Vertikal udbredelse af klorid til udvalgte tidspunkter.

4. DISPERSIONSANALYSE

Der er foretaget en kvantitativ analyse af dispersionen ved at tilpasse en analytisk løsning til konvektions-dispersionsligningen til gennembrudskurverne for tritium. Som følge af den beskedne spredning over dybden betragtes kun den horisontale dispersion ved at analysere de vertikalt integrerede gennembrudskurver.

Under antagelse af at tracertilførslen sker som en momentan punkt-injektion i en to-dimensionel planparallel strømning, kan koncentrationsfordelingen beskrives ved (se Bear (1979)):

$$C(x,y,t) = \frac{M}{4\pi nbt(D_L D_T)^{0.5}} \exp\left(-\frac{(x-ut)^2}{4D_L t} - \frac{y^2}{4D_T t}\right)$$

hvor

- C - koncentration
- M - tilført masse
- n - porøsitet
- b - mættet lagtykkelse
- u - konvektiv hastighed
- D_L - longitudinal dispersionskoefficient
- D_T - transversal dispersionskoefficient
- x,y - horisontale koordinater
- t - tid

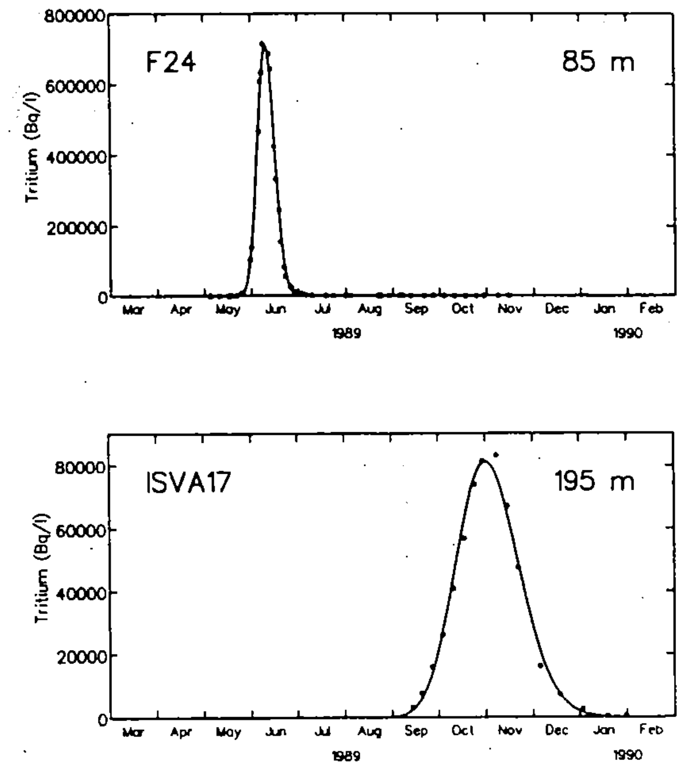
Dispersionskoefficienterne er under de givne forudsætninger relateret til dispersivitetskoefficienterne efter følgende simple relationer:

$$D_L = \alpha_L u$$
$$D_T = \alpha_{TH} u$$

hvor

- α_L - longitudinal dispersivitet
- α_{TH} - transversal horisontal dispersivitet

Ved tilpasningen af ovenstående ligning til de observerede gennembrudskurver er anvendt en optimeringsalgoritme beskrevet i Sauty og Kinzelbach (1988a, 1988b). De heraf afledte dispersiviteter udviste kun en mindre variation fra punkt til punkt for afstande udover 50 m. Det har ikke været muligt at identificere en afstandsafhængighed i resultaterne, hvilket fører til den konklusion, at det asymptotiske regime var nået for de undersøgte afstande. I Fig. 8 er vist eksempler på kalibreringsresultatet.



Figur 8. Eksempler på tilpasning af konvektions-dispersionsmodel til vertialintegrerede tritiumkoncentationer i afstandene 85 m og 195 m.

For de horisontale dispersiviteter i langsgående og tværgående retninger blev identificeret repræsentative værdier på henholdsvis 0.45 m og 0.02 m. Forudsætningerne bag den anvendte simple analytiske model er ikke helt opfyldt i det konkrete tilfælde, hvilket betyder, at specielt den transversale dispersivitet kan være estimeret for højt. Man ser da, at de fundne dispersiviteter er væsentligt mindre end de parameterværdier, der sædvanligvis har være anvendt i ingeniørmæssig praksis i forbindelse med grundvandsmodellering. De blev endvidere bekræftet i forsøget med klorid og er i øvrigt i god overensstemmelse med værdier opnået i udenlandske tracerforsøg og harmonerer i øvrigt med observationer af en række forureningsfaner, som har udvist en meget lille dispersion, se Gelhar (1986).

5. TRE-DIMENSIONAL STRØMNINGS- OG STOFTRANSPORTMODEL

5.1 Numerisk model

De indsamlede data om geologi og hydraulisk ledningsevnefordeling har dannet grundlag for opstilling af en tre-dimensional numerisk strømnings- og stoftransportmodel med henblik på en mere detaljeret analyse af spredningen af tritium og klorid i den undersøgte område. Den tre-dimensionale grundvandsmodel i SHE (Ammentorp og Refsgaard, 1990) er anvendt. Modellen løser strømningsligningen og stoftransportligningen ved hjælp af numeriske tilnærmelser (finite-difference). For strømningsmodellen er den primære parameter fordelingen af hydrauliske ledningsevne, mens transportmodellen opererer i sin beskrivelse af dispersion med en dispersionstensor bestående af i alt fire komponenter:

α_{LH} - landsgående dispersivitet i det horisontale plan
α_{TH} - tværgående dispersivitet i det horisontale plan
α_{LV} - landsgående dispersivitet i det vertikale plan
α_{TV} - tværgående dispersivitet i det vertikale plan

5.2 Modelanvendelse

Til beskrivelse af strømnings- og transportforholdene i forsøgsområdet er anvendt et 220 × 30 horisontalt, 9 vertikalt modelnet med netstørrelserne 1.0 m horisontalt og 0.5 m vertikalt til at diskretisere området, således at der totalt opereres med 54936 numeriske beregningspunkter.

Den øverste randbetingelse i form af nedsivning af nedbør er beregnet på grundlag af daglige observationer af nedbør og potentiel fordampning under anvendelse af en én-dimensional model for umættet vandstrømning (Jensen, 1983).

Under antagelse af hydrostatisk trykfordeling angives det hydrauliske trykniveau som randbetingelse langs modelranden.

Modellens nedre afgrænsning er bestemt af den lavpermeable silt/ler aflejring (fvf. Fig. 2).

5.3 Homogen tre-lagsmodel

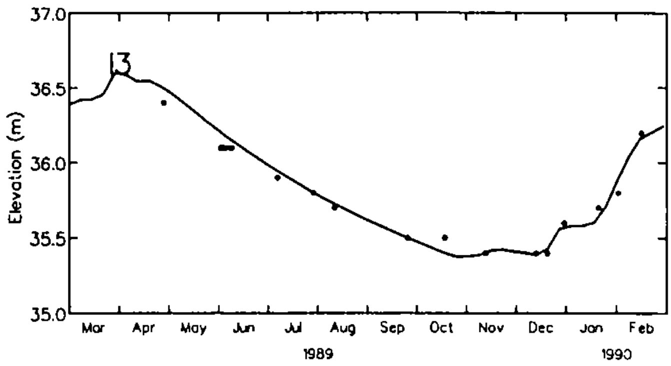
De første simuleringer er baseret på en antagelse om, at grundvandsmagasinet består af tre horisontale homogene sandaflejringer. Hydrauliske parametre, samt mægtighed af de tre aflejringer er angivet i Tabel 5.1. Da aquiferen er dannet i et postglacialt aflejringsmiljø skønnes det, at den vertikale hydrauliske ledningsevne er 50 gange mindre den horisontale. 0.20 og 0.001 er anvendt som magasintal under henholdsvis frie og artesiske forhold. Den effektive porøsitet er sat til 0.30.

Kote (m)	K_g (m/s)	Interval (m/s)	$\sigma^2_{\ln K}$	λ (m)	θ	θ_e
33.0-34.5	5.6×10^{-4}	$1.3-15.7\times10^{-4}$	0.20	2.5	0.38	0.30
32.0-33.0	4.4×10^{-4}	$0.8-12.3\times10^{-4}$	0.41	1.0	0.38	0.30
31.0-32.0	6.1×10^{-4}	$1.6-22.5\times10^{-4}$	0.29	1.0	0.38	0.30
Global	5.1×10^{-4}		0.37			

Tabel 5.1 Hydrauliske parameter (K_g - geometrisk middelværdi af hydraulisk ledningsevne, $\sigma^2_{\ln K}$ - variansen af lnK, λ - horisontal korrelationslængde, θ - porøsitet, θ_e - skønnet effektiv porøsitet).

Trods denne forenkling af aquiferen er der opnået en meget fin overensstemmelse mellem observerede og simulerede potentialer, se Fig. 9.

Dispersiviteter bestemt af den simplificerede analytiske analyse diskuteret tidligere blev anvendt som udgangspunkt for de første transportsimuleringer. Dette resulterede i en for stor transversal spredning sammenlignet med den observerede, medens den longitudinale komponent var i overensstemmelse med den observerede. En efterfølgende sensitivitetsanalyse af dispersiviterne blev udført, og den resulterede i følgende værdier: α_{LH} = 0.45 m, α_{TH} = 0.001 m, α_{LV} = 0.05 m, α_{TV} = 0.0005 m.



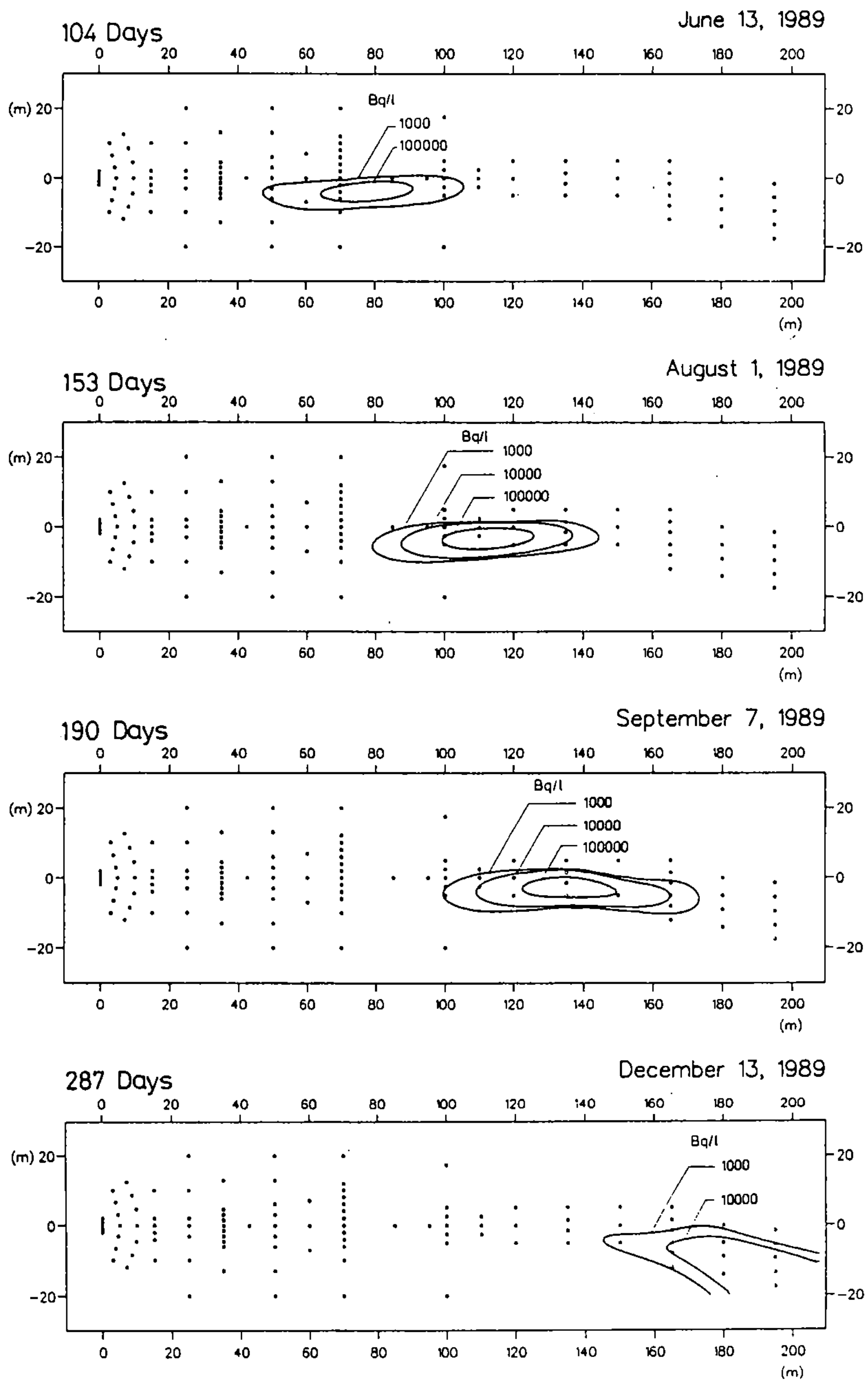
Figur 9. Observeret og simuleret potentialetidsserier i injektionsboringen I3.

Udvalgte resultater af sensitivitetsanalysen er vist i Bilag 1.

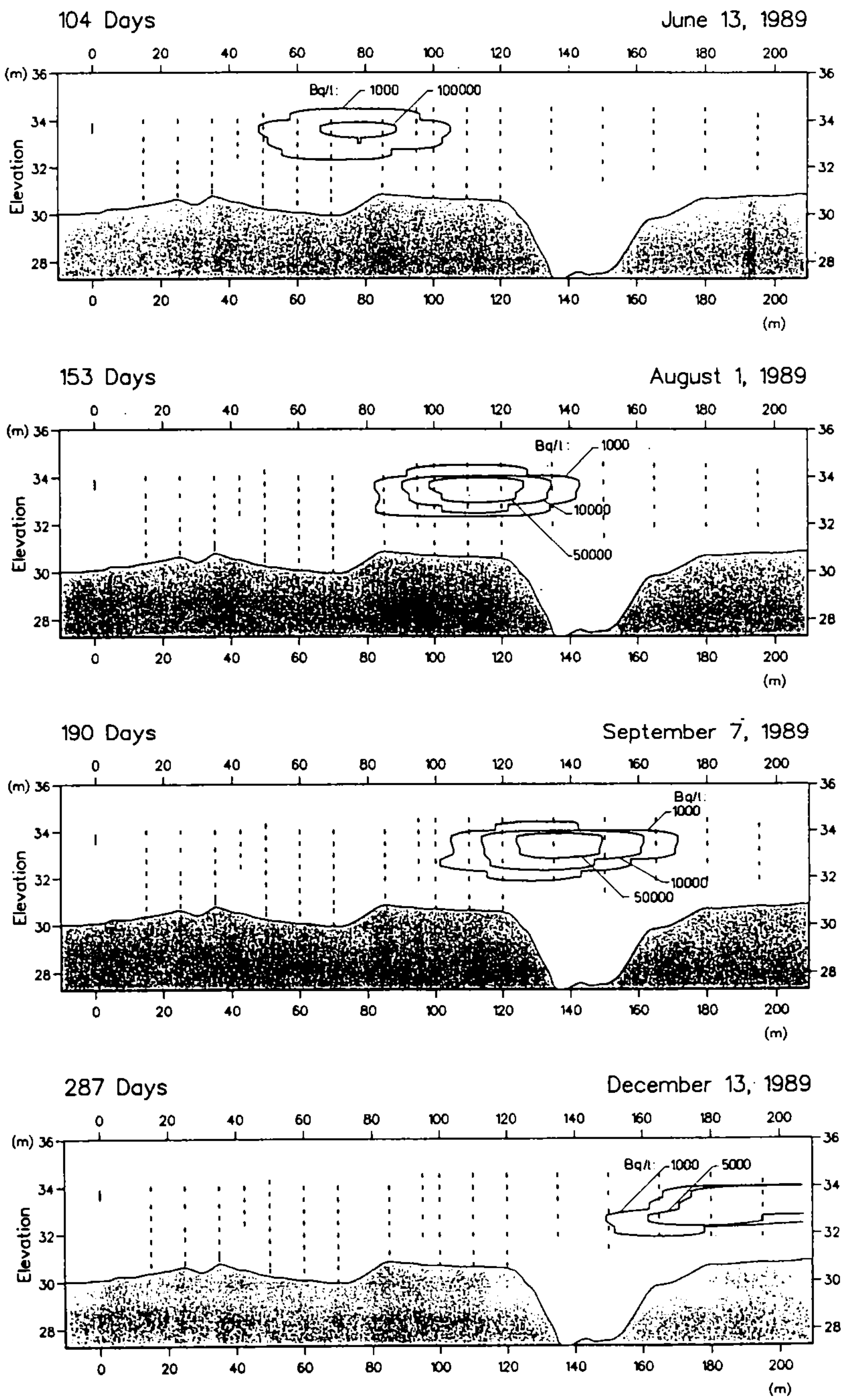
Transportsimuleringer med ovenstående dispersiviteter er vist i Fig. 10 og 11. Af disse fremgår, at der er god overensstemmelse med den observerede udbredelse, se Fig. 3 og 4, hvilket gælder såvel transporthastighed som spredning horisontalt og vertikalt.

Det andet eksperiment, som indebar injektion af uorganiske kloridsalte, var udsat for en initiel vertikal fortrængning som følge af densitetskontrasten mellem traceren og grundvandet. Da den numeriske model ikke muliggør simulering af spredning, som skyldes hydrodynamiske instabiliteter, er der taget hensyn til den initiale vertikale opblanding ved numerisk at injicere traceren vertikalt i et forhold beregnet af peak-koncentrationerne observeret i 15 m nedstrøms injektionspunktet.

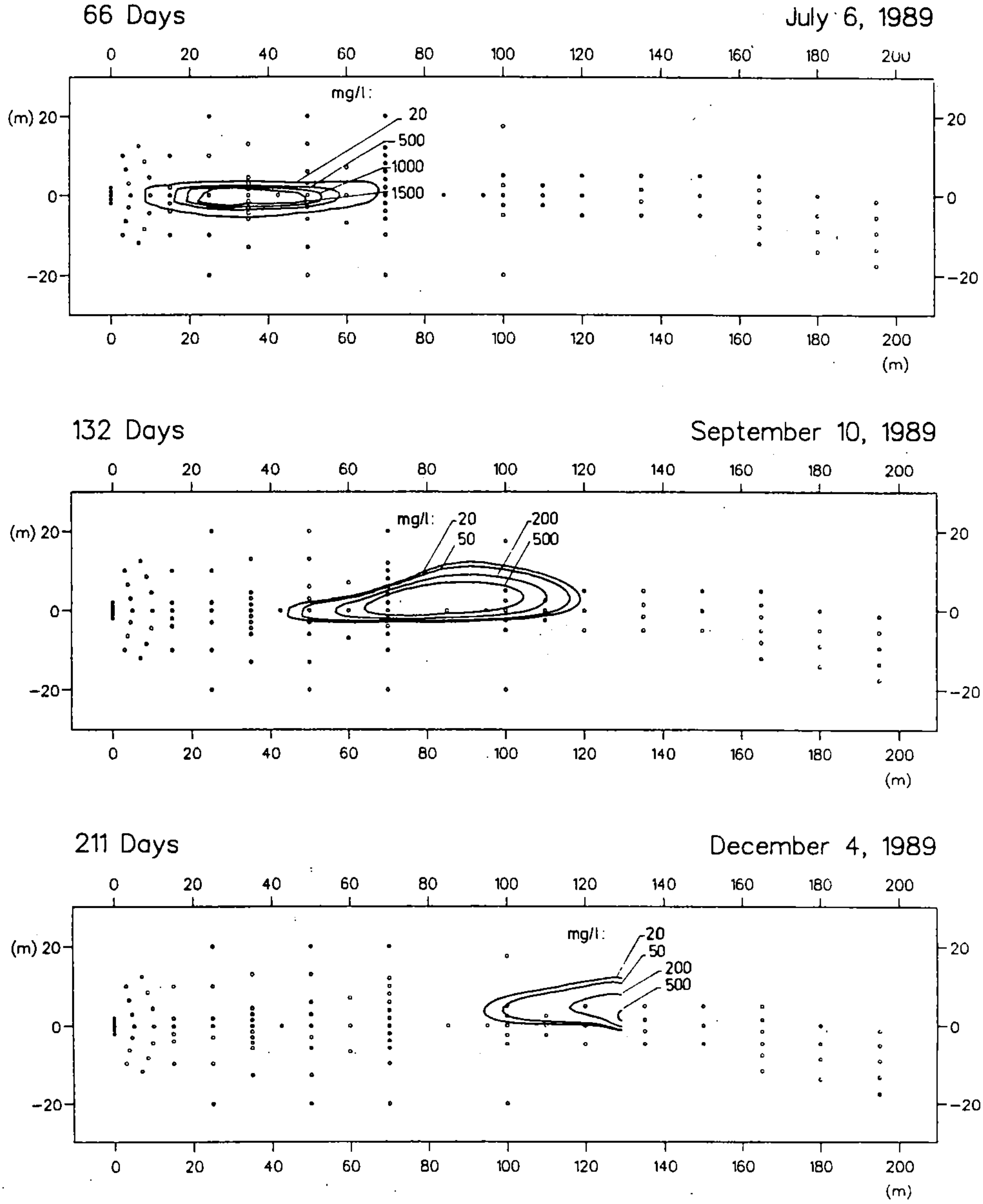
Transportsimuleringer med dispersivitetsværdier som anvendt til beregning af spredningen af tritium er vist i Fig. 12 og 13. Sammenlignet med den observerede udbredelse vist i Fig. 6 og 7 ses, at både de horisontale som de vertikale udbredelsesmønstre stemmer



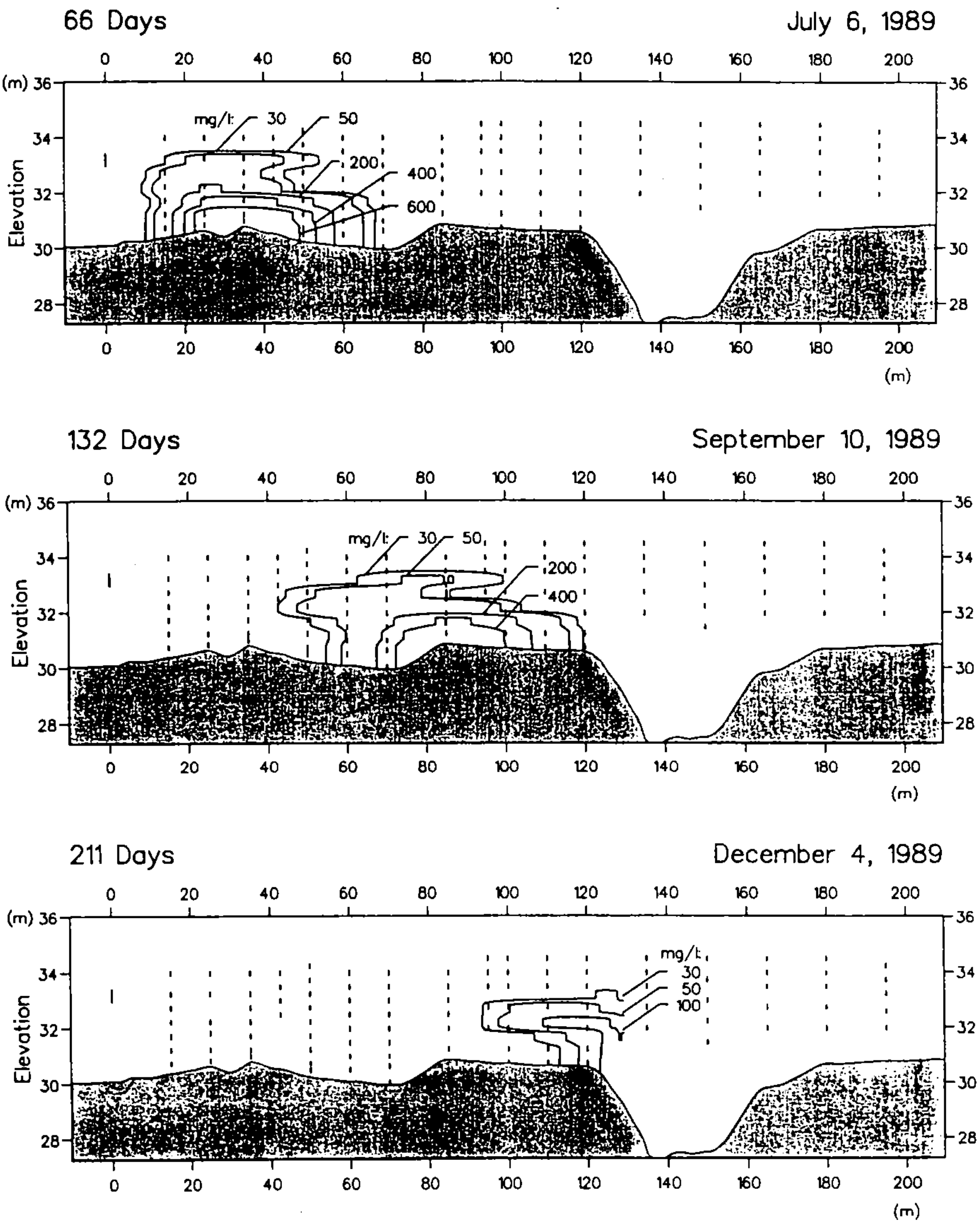
Figur 10. Simuleret horisontal udbredelse af tritium til udvalgte tidspunkter.



Figur 11. Simuleret vertikal udbredelse af tritium til udvalgte tidspunkter.



Figur 12. Simuleret horisontal udbredelse af klorid til udvalgte tidspunkter.



Figur 13. Simuleret vertikal udbredelse af klorid til udvalgte tidspunkter.

5.4 Heterogen tre-lagsmodel

Modelanalysen, hvor aquiferen blev betragtet som et homogent tre-lagssystem, viste meget fin overensstemmelse mellem simuleringer og målinger, hvad gælder det overordnede spredningsmønster. En sammenligning på en mere detaljeret skala mellem simulerede og målte gennembrudskurver viste, at de målte koncentrationer lokalt er påvirket af inhomogeniteterne, som ikke er medtaget i den numeriske model. For at analysere dette fænomen nærmere, blev der ved hjælp af Turning band metoden (Mantoglou og Wilson, 1982) genereret en realisation af fordelingen af den hydrauliske ledningsevne, som repræsenterer en heterogen sandaquifer med middelværdi, varians og korrelationslængde, som angivet i Tabel 5.1.

Denne hydrauliske ledningsevnefordeling er anvendt som input til den numeriske model. Trods små værdier for både varians og korrelationslængde gav det anledning til en større spredning, og det var derfor muligt at reducere den langsgående dispersivitet i horizontal retning til 0.10 m. Denne dispersivitet repræsenterer dermed dispersionen indenfor et numerisk beregningselement.

KONKLUSION

Der er gennemført to kontrollerede tracerforsøg med henholdsvis tritium og klorid, og udbredelsesmønstret for begge stoffer er karakteriseret ved en lille dispersion på tværs af strømningsretningen. Der blev målt en middelstrømningshastighed på ca. 0.75 m/dag, og v.h.a. en tre-dimensional numerisk model blev dispersiviteterne estimeret til 0.45 m, 0.001 m og 0.005 m i henholdsvis longitudinal, transversal horisontal og transversal vertikal retning. Disse værdier, som i øvrigt er i overensstemmelse med resultater fra udenlandske tracerforsøg, er meget lavere end de, som hidtil har været anvendt i ingeniørmæssig praksis.

Den dominerende indflydelse af den konvektive transport på faneudbredelsen stiller øgede krav til antal og placering af moniteringboringer. Da forureningsfanens transportveje kan påvirkes af lokale geologiske forstyrrelser, uden at dispersionen forøges i væsentlig grad, kan den forureningspåvirkede del af grundvandsmagasinet være meget skarpt afgrænset både horisontalt og vertikalt i "forureningskanaler". Dette vanskeliggør selvsagt identifikationen af det forurenede område med forøgede krav til antallet af boringer, hvilket med al tydelighed er demonstreret i Lossepladsprojektet.

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LARGE-SCALE DISPERSION EXPERIMENTS IN A SANDY AQUIFER IN DENMARK: OBSERVED TRACER MOVEMENTS AND NUMERICAL ANALYSIS

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ABSTRACT

A large-scale natural gradient dispersion experiment was carried out in a sandy aquifer in the western part of Denmark in order to examine the dispersion processes in a geological environment typical for that part of the country. Tritium and chloride were used as tracers injected as a slug and continuously over a 37 day period, respectively.

The transport and dispersion of the two plumes were monitored by water sampling in a dense three-dimensional network of piezometers. For both plumes a marked spreading was observed in the longitudinal direction while the spreading in the transverse horizontal and transverse vertical directions was very small. However, the chloride plume experienced an initial sinking due to gravitational instabilities, created by density contrasts between the injected solution and the native groundwater.

The transport parameters of the convection dispersion equation (CDE) were investigated by applying an optimization model based on the analytical solution to the CDE to observed break-through curves of tritium.

No clear trend with travel distance for the distances examined could be found suggesting that the asymptotic stages are reached within short distances from the point of injection.

A three-dimensional numerical model for flow and transport was applied to the aquifer in order to identify the dispersivity parameters more closely. The model was coupled to a one-dimensional unsaturated flow model to account for the seasonality in recharge. On the basis of a number of trial simulations the

following "best-fit" dispersivity parameters were identified: longitudinal horizontal 0.45 m, transverse horizontal 0.001 m, longitudinal vertical 0.05 m, and transverse vertical 0.0005 m.

The numerical model simulations compared excellent to the observations of the water table fluctuations and to the overall behaviour of the tracer plumes. However, on a more detailed basis when breakthrough curves are compared discrepancies were present due to the existence of local heterogeneities. The effect of the hydraulic conductivity fluctuations was investigated by simulating the evolution of the tracer plume in a single realization of the hydraulic conductivity field generated by the turning bands method.

1. INTRODUCTION

Transport behaviour of non-reactive solutes in groundwater is generally considered to be governed by the two principal processes: advection and dispersion, which describe the role of hydrodynamics in transport and dilution of soluble substances. Advection refers to the mean movement of the solute in the flowing groundwater, while dispersion describes the solute spreading about the mean motion caused by local fluctuations in velocity (Freeze and Cherry, 1979).

The classical model of transport in groundwater is the advection-dispersion equation, in which dispersion is considered to be analogous to a Fickian diffusion process (Bear, 1972). This model was originally developed at the scale of a representative elementary volume (REV), where the dispersion parameter, dispersivity, is regarded as a unique and measurable property of the medium at the pore-scale continuum. However, the model has been widely applied to large-scale regional transport problems simply by augmenting the dispersivity parameter in order to account for the enhanced mixing caused by the heterogeneity of the hydraulic properties in aquifer systems. In this way the dispersivity is essentially used as a lump parameter which accounts for all the unknown fluid velocity variations related to the aquifer heterogeneity.

The dispersivity value is usually determined by calibration of the advection-dispersion model to observed concentrations. In practical situations sufficient concentration data will generally not be available for a reliable determination of the dispersivity, and furthermore the history of the contamination source is often unknown, which implies that the value obtained by calibration becomes very uncertain.

Analysis of solute behaviour in natural field environments have indicated that the dispersive spreading and dilution behave non-Fickian over the initial travel distances from the source, and that the dispersivity increases with the scale of the transport problem, see e.g. discussions by Anderson (1979) and Gilham and Cherry (1982). Various reviews and compilations of field-scale observations of longitudinal dispersivities (Lallemand-Barres and Peaudecerf, 1978; Gelhar et al., 1985; Kinzelbach, 1986) have all shown the scale effect, and furthermore it has been shown that the dispersivity exhibits a wide range of variation for the same type of aquifer and scale of transport. The physical explanation of these phenomena is that with increasing travel distance the contaminant plume is exposed to more and more aquifer heterogeneity, and consequently larger dispersivities are encountered.

The recent theoretical studies within contaminant transport have emphasized the significance of spatial variability of hydraulic conductivity and the uncertainty always encountered when a mapping of aquifer properties is attempted. By treating the natural heterogeneity in a stochastic sense, stochastic forms of the groundwater flow and transport equations have been developed in which the hydraulic parameters appear as random variables. These studies including those by Gelhar et al. (1979), Matheron and de Marsily (1980), Smith and Schwartz (1980), Dagan (1982, 1984), Gelhar and Axness (1983) have demonstrated the influence of hydraulic conductivity variations on dispersive mixing. The theoretical work has also indicated that in heterogeneous aquifer systems non-Fickian behaviour with a growing dispersivity is experienced during the initial phase of the transport process, and that Fickian behaviour with a constant dispersivity is reached asymptotically as the dispersion process develops. The theories suggest that the transition zone may involve travel distances of more than 10 correlation lengths (maybe hundreds of meters) before the asymptotic dispersivity is reached.

As mentioned above several field observations on dispersion behaviour have been reported in the literature, but as pointed out by Gelhar et al. (1985) the reliability of many of the reported dispersivities can be questioned. Three comprehensive and rather unique large-scale tracer tests can be mentioned: Borden Air Force Base (Mackay et al., 1986; Freyberg, 1986; Sudicky, 1986), Cape Cod (Garabedian et al., 1988, Le Blanc et al. (1991), Garabedian et al (1991) and Twin Lake (Killey and Moltyaner, 1988; Moltyaner and Killey, 1988a, Moltyaner and Killey, 1988b). By establishing very detailed information on the hydrogeological conditions and the spreading patterns of solutes, these field tests have provided new insight into the dispersion process, and the two first mentioned have also served the purpose of verification basis for the stochastic theories. However, in none of these studies a three-dimensional deterministic model analysis of the plume movements was attempted.

The purpose of the study reported here was to carry out a tracer experiment at a site extensively equipped with observation piezometers in order (1) to examine the dispersion processes in a sandy aquifer typical for the geological conditions in the western part of Denmark and with particular reference to a contaminant plume from an old landfill located about 600 m from the dispersion site serving the purpose of a outdoor large-scale laboratory facility for contamination studies; (2) to determine the dispersivity of the aquifer; (3) to predict and compare the dispersivity from the statistical properties of the hydraulic conductivity variation; and (4) to produce a detailed and accurate data base for validation of three-dimensional numerical simulations of groundwater flow and tracer transport.

Two natural gradient tests were made using tritium and chloride as tracers applied in two different injection modes. The tracer tests are in some ways complementary to the other tests mentioned with respect to the geological and experimental conditions.

In this paper we describe the experimental site and conditions under which the tracers are applied, sampled and analysed. The geological and hydrogeological conditions are discussed and investigations of the hydraulic conductivity distribution are summarized. The results of the tracer experiments are demonstrated as horizontal and vertical distributions at different times during the developments of the plumes and the transport parameters evaluated from the data. Finally, we introduce a three-dimensional numerical finite difference model for non-steady flow and transport and simulation results are demonstrated and compared to measurements of water table fluctuations and tracer concentrations.

2. EXPERIMENTAL SITE

A 200 m long and 40 m wide area was allocated for the experiment oriented with the longest side parallel to the prevailing groundwater flow direction. The monitoring system consisted of a dense network of piezometers with ports at various levels installed concurrently with the development of the plume. Fig. 1 shows a plan diagram of the sampling network involving a total of approximately 100 sampling locations, and a vertical diagram of the vertical sampling ports involving up to seven levels at a given horizontal location. The horizontal spacing of the multilevel sampling locations varied between 5 to 15 m in longitudinal direction and most typically between 1 and 5 m in transverse direction. The vertical spacing of the sampling ports varied typically from 0.2 to 0.5 m.

All sampling piezometers were established in separate wells to avoid cross-contamination during sampling. The installation was accomplished by driving to the desired level. Some piezometers were established by driving a casing into the soil and subsequently install a 1.6 cm PVC tube at the desired depth followed by withdrawal of the casing. Other sampling tubes were made of 2.5 cm diameter iron metal with a filter placed at the front which enabled them to be driven directly to the desired depth. All piezometers are equipped with 25 cm screens. The injection wells are of a larger diameter (5 cm) with 50 cm screens. The piezometers installed in a semicircle arrangement near the injection wells (cf. Fig. 1) are all screened over 2.5 m because they were only used for control purposes.

3. AQUIFER CHARACTERISTICS

3.1 Geological conditions

The experimental site is located in the western part of Denmark on the peninsula Jutland. The area was formed during the latest glacial period by a river system carrying meltwater and sediments from a rather stationary glacial front placed north-south in the middle of the peninsula. A huge outwash plain was hence created in the western part composed of layers of fine-grained, medium-grained and coarse-grained sand depending on the settling conditions which prevailed at the individual locations. Although the aquifer is generally considered to be fairly homogeneous, discontinuous lenses of coarser-grained as well as silty formations have been observed which may be of potential importance for the transport behaviour.

The local geology at the experimental site has been described by Bjerg et al. (1991) on the basis of 31 sediment cores. A low-permeable clay layer at approximately 10 m depth defines the lower boundary of the aquifer. The surface of the layer is undulating between levels 30 and 31 m except at the distance of 135-155 m downgradient the injection wells (cf. Fig. 1) where the clay surface dips. However, in general a shallow 5 m aquifer horizon is available for the tracer experiment.

The aquifer may be divided into three structural sand layers, cf. Fig. 2: (1) a layer below level 31 m deposited in eroded channels in the clay surface; (2) a layer between levels 31 and 33 m showing cross-bedding; and (3) a layer between levels 33 and 35 m showing through-bedding. The sand fraction of all three layers is medium to coarse-grained (mean grain size 0.56 mm), however, in all layers silty inhomogeneities can be found particularly in the intermediate layer.

3.2 Hydraulic parameters

The hydraulic conductivity distribution in the aquifer was investigated using conventional slug tests in the 2.5 cm diameter tubes, Hinsby et al. (1991). Single-well response tests were carried out on the piezometers by raising the water table to a given level using a vacuum pump, and after equilibrium was achieved the vacuum was released and the rate of decline of the water table monitored. The falling-head data were analyzed and the hydraulic conductivity derived using the method developed by Dax (1987).

The hydraulic conductivity K has a global geometric mean of $5.1 \cdot 10^{-4}$ m/s and a ln(K) variance of 0.37 assuming a lognormal distribution, Bjerg et al. (1991). Note that this mean value is between the Borden Site value of $9.75 \cdot 10^{-5}$ m/s (Sudicky, 1986) and the Twin lake value of about $5.0 \cdot 10^{-5}$ m/s (Killey and Moltyaner, 1988) on the one side and the Cape Cod Site value of $1.4 \cdot 10^{-3}$ m/s (Garabedian et al., 1988) on the other, while the ln(K) variance of 0.38 corresponds exactly to the Borden Site.

The data for the hydraulic conductivity is summarized in Table 1. As it appears from the table three layers with different statistical parameters can be identified thus supporting the three-layer geological model discussed above. The horizontal correlation length has been estimated in the range of 1.0-2.5 m. This value corresponds to the correlation length of 2.8 m found at the Borden Site (Sudicky, 1986) which has a comparable geological history. The data for the total porosity were obtained from measurements on sediment samples and by cone penetration tests while the effective or dynamic porosity was estimated as a fraction of the full porosity (see eg. Marsily, 1986).

3.3 Groundwater flow system

The groundwater flow in the study area occurs under unconfined conditions and the average water table depth is approximately 5.0 m below the soil surface.

The groundwater is recharged by the precipitation in excess of the evapotranspiration from the grass-covered area. During the period of investigation (March 1989 - March 1990) the recharge was estimated to app. 350 mm/year based on simulations using a one-dimensional unsaturated flow model as described below. Over a longer time span the mean annual recharge was estimated to 550 mm/year. The recharge varies over the season which imposes seasonal fluctuations to the flow system.

The water table was measured during a number of campaigns using the network of piezometers shown in Fig. 1. Seasonal fluctuations of about 1.0 m were observed with highest levels in early spring and lowest levels in late fall. The fluctuations over a one-year period for selected wells are shown in Fig. 3. All piezometers shown responded similarly to the seasonal changes in recharge, and no significant phase differences were observed. Hence, the flow directions are supposed to remain fairly stationary, and transients in flow behaviour are expected not to contribute significantly to the dispersion process.

Vertical head gradients were very small, and the differences observed were within the range of measurement and levelling errors. In Fig. 3 a water table configuration map established on the basis of measurements from February 14, 1990, is shown, and this map therefore essentially represents the flow conditions prevailing over the season as well as over the aquifer depth. The dominant flow direction conforms rather closely to the orientation of the field site. Furthermore, the diagram seems to indicate that the hydraulic gradient is fairly uniform over the area (4.5‰ on the average) thus supporting the observation that the hydraulic properties are rather uniform.

4. EXPERIMENTAL PROCEDURE

4.1 Tracer applications

The objective of the first tracer study was to investigate the large-scale physical transport and dispersion behaviour, and hence the tracer should reflect the groundwater flow as accurately as possible. As outlined by e.g. Gaspar and Oncescu (1972), Unesco (1980), and Davis et al. (1985) a number of requirements to the field tracer need to be considered. Such requirements include easy solubility, large contrasts between background concentration and injected tracer, no density effects, no retardation, and detectable and measurable at small concentrations. Given all these considerations we selected tritium (H) as HTO as the primary tracer mainly for contrast and density reasons. Tritium has been viewed as a near-ideal tracer, because it forms part of the water molecule and travels with the groundwater, although Kaufman and Orlob (1956) have reported some retardation. The major disadvantage is the toxicity for which reason careful consideration of the safety aspects is required.

The injection in the first experiment was designed to approximate an instantaneous pulse in a well-defined flow field with minimal disturbance of the natural flow. The tracer was injected in three wells with 1 m spacing transversely to the flow direction, Fig. 1, each screened over a 0.5 m interval. At the time of injection (March 1, 1989) the screened intervals were located 2.4 - 2.9 m below the water table corresponding to 5.5 - 6.0 m below ground surface (elevation 33.4 - 33.9 m).

A 50 l solution of $1.55 \cdot 10^9$ Bq H-3 was injected to each of the injection wells over less than 30 minutes, and thus a total of $4.66 \cdot 10^9$ Bq H-3 was released to the groundwater. The solution volume applied was chosen to ensure that the mass of tritium was distributed properly around the injection wells.

The initial movement of the tritium plume showed very little transverse dispersion and the horizontal transport velocity was very high, which could suggest that the plume was entrapped in a high-permeable layer. In order to investigate whether these observations were representative of the geological conditions at the injection site, it was decided to drive the screens of the injection wells additional 0.5 m for the second tracer experiment.

This second experiment was designed to study the ion-exchange processes in the aquifer (Bjerg and Christensen, 1991). The movement of the chloride plume is analyzed in this paper assuming that this constituent behaves as a non-reactive tracer.

The experiment was carried out by injecting groundwater spiked with sodium chloride (NaCl) and potassium chloride (KCl) continuously over 37 days starting on May 1, 1989. To increase the lateral dimension of the plume five injection wells with 1 m spacing were used. The average pumping rate was 9.0 litres per hour and the total volume and mass of chloride amounted to 8 m^3 and 48 kg respectively corresponding to a chloride concentration of approximately 6000 mg/l. The total mass of all injected compounds was 85 kg or a total concentration of 10600 mg/l, and the density of the injected fluid was 1.005 g/cm^3 corresponding to a relative density difference Δ of 0.0055 at 10°C.

4.2 Sampling and analysis

Water samples were collected up to four times a week for tritium analysis and on a daily basis for chloride analysis during the most intensive campaigns of the experiment in order to determine the position of the tracers and to accurately define the breakthrough curves at various locations within the field site.

Sample volumes were extracted by suction using a vacuum pump from each of the piezometer tubes considered relevant at the time of sampling. The wells were pumped prior to water sampling to ensure that the ambient groundwater at the piezometer screen was sampled. Water samples for tritium analysis were pumped directly into 20 ml glass bottles, and the concentrations were measured using direct liquid scintillation on a Packard Pico Flour-water cocktail. Chloride concentrations were determined by a ferricyanid method modified from Standard Methods (1985) using a Technicon Auto Analyzer.

A total of approximately 13.000 water samples were collected of which subsets of 4.900 and 4.000 were analyzed for tritium and chloride respectively.

5. OBSERVED TRACER MOVEMENTS

5.1 Tritium

Contour maps of vertically integrated tritium concentrations at 104, 153, 190 and 287 days after injection are presented in Fig. 4. The concentrations shown represent the total tritium mass within the verticals diluted in a 0.5 m aquifer layer. The contours are established by a combination of computer and hand contouring. This illustration gives a good indication of the bulk mass location in the horizontal plane and hence an estimation of the mean velocity and trajectory of the migrating pulse. On the basis of the contour maps the rate of horizontal movement can be estimated to about 0.75 m/day. The direction of the tracer movement follows the projected path derived from the water table configuration including the slight deflection of the trajectory occurring towards the downstream end of the field site (see Fig. 12).

A significant spreading in the longitudinal direction is observed resulting in an ever increasing length of the tracer cloud and decreasing peak concentration. On the other hand, the increase in the lateral dimension of the tracer zone in the horizontal plane is very little.

Due to the unexpected high travel velocity of the plume, the initial plume behaviour was not mapped in great details because the sampling program was not appropriately designed at that time. However, the subsequent dispersion test with chloride was successful on the short distances in view of the acquired experiences, and data from this test can therefore supplement the missing information.

Fig. 5 shows the concentration distribution in a vertical section placed along the longitudinal axis of the plume. The contouring is done on the basis of data projected onto the cross-section from the measurement positions located nearby. A rather small vertical spreading is observed. Note that no downward movement of the plume takes place indicating that the migration is not affected by density contrasts. In fact, on the contrary the centre of mass seems to move horizontally and even a little upwards as indicated in the second graph. It is unlikely that this behaviour is caused by evaporation from the water table and we explain it by interferences of local heterogeneities.

In Fig. 6 break-through curves are compiled for the various levels at selected positions along the longitudinal axis. Most of the curves mirror the shape of a Gaussian distribution, although some of the responses in the downstream direction have a bimodal shape. This appearance is probably caused by a slight difference in the trajectories taken by different parts of the plume. The curves display several properties to be anticipated like a gradually broadening of the break-throughs and decreasing peaks. It is also evident that the tracer tends to concentrate around very few measuring levels.

5.2 Chloride

The horizontal movement of chloride behaved in many ways similar to the tritium plume as shown in Fig. 7. The longitudinal dimensions are of the same magnitude and also the lateral dispersions are of the same order although the chloride plume tends to be a little more wide due to the sinking of the plume and the influence of the impermeable clay layer as discussed below. The horizontal velocity of the center of mass is approximately 0.7

m/day which is a little less than the velocity of the tritium plume.

In vertical direction the movement of the chloride plume was completely different from the behaviour observed in the first tracer experiment. As shown in Fig. 8 large concentrations are observed just above the clay layer and the bulk mass of chloride is found significantly below the level of injection. Note that the plume tends to conform to the same shape during migration.

Fig. 9 demonstrates breakthrough curves at different vertical sections from the injection location and also this figure clearly shows the downward movement of the plume which we observed took place right after injection. Two mechanisms may be responsible for this behaviour: (1) vertical velocity components caused by the driving head applied during injection and (2) density-driven transport and convective instabilities. During the period of injection a driving head of less than 5 cm was observed in the injection wells, so we attribute the vertical displacement to the density contrast between the injected fluid and the native groundwater. Garabedian et al. (1987) and Freyberg (1986) both report on sinking due to density differences for contrasts much less than in the present case and in a recent study by Schincariol and Schwartz (1990) the sinking of a denser fluid was clearly demonstrated for velocity and density conditions comparable to our case. They also observed the development of gravitational instabilities for large plume concentrations, a phenomenon which also contributes to enhanced spreading of solute perpendicular to the ambient flow field.

6. ANALYSIS OF DISPERSIVITY PARAMETERS

We have analyzed the behaviour of the dispersivity parameters on the basis of breakthrough curves by fitting an analytical solution of the advection-dispersion equation to the observed data. Sudicky et al. (1983) and Moltyaner and Killey (1988 a,b) have used a solution describing the migration of a tracer released as a rectangular parallelpiped while others (e.g. Leland and Hillel, 1982) have applied the solution for the case of an instantaneous point injection. All these analytical solutions are based on the assumption that the flow is unidirectional with a constant velocity since it is not possible to accommodate velocity variations between and within the various sedimentary sequences or transient variations into analytical models. Hence, whatever analytical model which is applied it will inevitably only provide an approximate description of the transport and dispersion processes taking place in the field and the derived dispersivity parameters may therefore only be considered as approximate.

We have constrained the analysis to the tritium observations because the problem of sinking of the chloride plume and the approximations of the adopted analytical model makes the chloride data less attractive. In the following approximate analysis we have furthermore focused on the horizontal components of the dispersivity tensor, because the vertical spreading of the tritium plume was rather small. Hence, the analysis is based on the total mass of tracer present in the verticals. A parameter identification model developed by Sauty and Kinzelbach (1988 a,b) has been used to identify the transport parameters at a number of observation points in the horizontal. The model uses the Rosenbrock (Rosenbrock, 1960) and the Powell optimization (Powell, 1964) methods concurrently, and it allows for optimization of flow velocity, flow direction, longitudinal and transverse dispersivities in a two-dimensional uniform flow field.

For an instantaneous injection of a tracer slug in a two-dimensional uniform flow field at coordinate origin, the concentration distribution is described by (Bear, 1979):

$$C(x,y,t) = \frac{M}{4\pi nbt(D_{LH}D_{TH})^{0.5}} \exp\left(-\frac{(x-ut)^2}{4D_{LH}t} - \frac{y^2}{4D_{TH}t}\right) \qquad (1)$$

where

- C - concentration
- M - injection mass
- n - porosity
- b - aquifer thickness
- u - flow velocity (parallel to x axis)
- D_{LH} - longitudinal dispersion coefficient
- D_{TH} - transverse horizontal dispersion coefficient
- x,y - horizontal space coordinates
- t - time coordinate

The dispersion coefficients are related to the dispersivity coefficients by:

$$D_{LH} = \alpha_{LH}\, u$$

$$D_{TH} = \alpha_{TH}\, u$$

where

- α_{LH} - longitudinal dispersity
- α_{TH} - transverse horizontal dispersivity

The solution has been extended by Sauty and Kinzelbach (1988 a,b) to consider the direction of flow by introducing a coordinate transformation into a coordinate system related to the flow direction.

Assuming that the vertically integrated tritium concentration data can be described by this extended analytical equation, the transport parameters have been optimized in a two-step procedure. First the flow direction is determined for each line of wells placed transversely to the prevailing flow direction by including the integrated observations from all wells of the specific line in the computer optimization process. In the second step the identified flow directions are kept fixed while flow velocity and dispersivities are optimized for the individual observation wells. The results are summarized in Table 2 for those observation points where well-defined break-through curves can be established. Note that the lateral dispersivity will be overestimated using the present approach, because the injected tracer has a lateral dimension of 2 m at the release point, and this is not accounted for in the analytical model. However, the results are still valid for an initial screening of the variation within the experimental area.

In Fig. 10 are shown some typical matches to observed breakthrough curves indicating that it is possible to match the analytical solution fairly closely to observations.

As indicated in Table 2 the transport parameters vary somewhat between the observation points which is an indication of geological heterogeneity present in the aquifer not accounted for in the present rather simple analysis. Yet, the variation for all parameters is rather small. The optimized horizontal displacement velocity varies between 0.58 m/day and 0.88 m/day with an average value of 0.75 m/day. The values listed in the table suggest that the velocity is slightly above the average value in the upstream end and slightly below average further downstream.

For the longitudinal and transverse horizontal dispersivities no clear trend with travel distance can be found as reported by Freyberg (1986) and Garabedian et al. (1988). The optimized values for the location listed in Table 2 vary more or less arbitrarily around the mean values of 0.42 m and 0.02 m for the longitudinal and transverse dispersivity, respectively, thus indicating that the asymptotic stage of the development of the dispersivity parameter is reached for the distances examined. The variation appearing in Table 2 can be explained by the aquifer heterogeneity, which then gives rise to different dispersivities, because the actual flow trajectories are not included in the analysis.

The dispersivities obtained in this study seem rather small for this particular scale when compared to values reported elsewhere (e.g. Gelhar et al., 1985) and the values often applied in engineering practice. Yet they are consistent with the magnitudes obtained in the Borden and Cape Cod cases.

Although small values are obtained for the dispersivities in this study, they may in reality be a little enlarged due the identification method. Velocity variations over the aquifer thickness may enhance the longitudinal dispersivities because the analysis is based on vertically integrated concentrations. Also seasonal fluctuations in the flow regime as well as the initial lateral dimension of the injected tracer may introduce an artificial increase in the dispersivities. In a subsequent paragraph we will apply a three-dimensional numerical model which provides a more realistic description of the field conditions in order to verify or adjust the parameters found by the present rather simplified analysis.

Gelhar and Axness (1983) have developed theoretical expressions for the macroscopic dispersivity tensor. Of particular interest is the asymptotic values which for the two-dimensional case is given by

$$A_{11} = \sigma^2_{lnK} \cdot \lambda_{lnK}$$
$$A_{22} = \sigma^2_{lnK}(\alpha_1 + 3\alpha_2)/8 \qquad (2)$$

where σ^2_{lnK} represents the variance of the logarithmic transformed hydraulic conductivity; λ_{lnK} is the correlation length; and α_1 and α_2 are the local dispersivities.

Using the data on the correlation structure of the hydraulic conductivity field (σ^2_{lnK} = 0.37, $\lambda_{lnK} \approx$ 1.5 m) and assuming that the local dispersivities are of the order of a few mm (α_1 = 0.005 m, α_2 = 0.0005 m), the theoretically derived asymptotic macrodispersivities are

$$A_{11} = 0.55\ m$$

$$A_{22} = 3 \cdot 10^{-4}\ m$$

The longitudinal dispersivity conforms rather closely to the average value listed in Table 2, while the theoretical value for the transverse dispersivity is much smaller. However, as mentioned above the average transverse dispersivity given in Table 2 is probably too high and in fact the theoretical value is not very far from the value identified in the numerical analysis discussed below.

The increase in dispersivity with travel distance has not been examined, because we are not able to recover reliable breakthrough data for the initial phase of the experiment with tritium. The analysis suggests that the asymptotic value of dispersivity is already reached at the smallest distance (50 m) from which complete breakthrough data are available. This observation conforms with the theoretically derived expressions for the development of longitudinal dispersivity with displacement distance, according to which the asymptotic stage is reached after approximately 10 correlation lengths (Gelhar and Axness, 1983).

The ideal method for analyzing the transport and dispersion characteristics of a tracer experiment is a spatial moment analysis, where the moments define integrated measures of total mass, mean velocity, and dispersion of the plume. Moments are estimated on the basis of the point observations using some numerical integration techniques. The moment analysis method has been successfully used both in the Borden and Cape Cod experiments as described by Freyberg (1986) and Garabedian et al. (1988) respectively. Application of this method requires a very dense sampling network in order to accurately derive the moments. Although the present field test also includes a large number of observation points, it is not as dense as for the two other sites. Due to the limited extension of the plume, the "snapshots" of three-dimensional spatial distribution of the tracer concentration at particular times are not very accurately defined because only a relatively small number of observation wells are affected, and hence it is not feasible to apply this technique in our study.

7. NUMERICAL SIMULATIONS OF FLOW AND TRACER TRANSPORT

7.1 NUMERICAL MODEL

A three dimensional numerical model with a refined discretization was applied for accurately simulating the movement of the tracer plumes. Using a numerical model it is possible to incorporate all the data collected on both the geological stratification, and the hydraulic conductivity distribution and to consider the seasonal fluctuations of recharge.

We have applied the three-dimensional finite-difference model developed as part of the European Hydrological System (SHE), Ammentorp and Refsgaard (1990).

The flow description of the model is based on the governing equation for three-dimensional Darcy-type flow (Freeze and Cherry, 1979):

$$S\frac{\partial h}{\partial t} = \frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial h}{\partial x_j}\right) - R \qquad i,j = 1,\ 2,\ 3$$

where

- h - hydraulic head
- K - hydraulic conductivity
- S - specific storage
- R - sink term
- x - spatial coordinates
- t - time

In the numerical model this equation is approximated by a set of coupled algebraic equations which are obtained by applying the water balance equation and Darcy's law in finite difference forms to each node in the solution domain assuming that flow occurs in directions between the specific node and its six direct neighbour nodes. The equations are formulated in an implicit scheme where the internode hydraulic conductivity is obtained as the harmonic mean. The system of linear finite difference equations are solved iteratively using a modified Gauss-Seidel method (Thomas, 1973).

The transport of solutes in groundwater is described by solving the advection-dispersion equation:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(Cu_i) - S \qquad i,j = 1,\ 2,\ 3$$

where

C - concentration of solute
D - dispersion coefficient
u - seepage velocity
S - sink term
x - spatial coordinates
t - time

The dispersion coefficient is traditionally related to the groundwater velocity using Scheidegger's (1961) equation:

$$D_{ij} = \alpha_{ijmn}\frac{u_m u_n}{|u|} \qquad i,\ j,\ m,\ n = 1,\ 2,\ 3$$

where

α - dispersivity
u - seepage velocity
$|u|$ - magnitude of seepage velocity

In order to simplify the dispersion description only the diagonal terms of the dispersion tensor are considered. Due to symmetry and physical reasons four components of the dispersivity tensor are defined: α_{LH} (longitudinal horizontal dispersivity), α_{LV} (longitudinal vertical dispersivity), α_{TH} (transverse horizontal dispersivity) and α_{TV} (transverse vertical dispersivity).

Under these assumptions the advection-dispersion is solved by finite-difference techniques using an explicit third-order accurate interpolation scheme as described by Ekebjærg and Justesen (1989). This scheme is mass conservative and enables simulation of sharp convective fronts without smearing from numerical dispersion. Due to the explicit formulation the time step is constrained by requirements to maximum allowable advective and dispersive transport distances.

7.2 Model application

The affected part of the aquifer has been divided into a large number of cells to form the finite difference grid. The horizontal grid spacing is 1.0 m while 0.5 m is used for the vertical spacing in the region transversed by the plumes. This results in 220 × 30 nodes in the horizontal and with 9 levels in the vertical a total of 59,400 numerical elements are involved in the computations, Fig. 11. The numerical discretization has been defined as a balance between requirements to spatial resolution and computer turn-over time.

The upper boundary condition in the form of recharge to the water table is generated by applying a one-dimensional unsaturated flow and evapotranspiration model developed by Jensen (1983). On the basis of daily observations of rainfall and potential evapotranspiration and site-specific soil hydraulic properties, the model predicts the water flux at the level of the water table which hence constitutes the inflow to the groundwater model.

The boundary conditions along the vertical planes which border the model region in the horizontal directions are prescribed hydraulic heads assuming that hydrostatic conditions apply. The fluctuations in hydraulic heads along the model boundary are generated by applying the two-dimensional flow model of the U.S. Geological Survey's method of characteristics code (Konikow and Bredehoeft, 1978) to the regional aquifer surrounding the experimental site. The boundaries of the regional model are placed along creeks when possible and otherwise far away from the area of interest. The fluctuations in recharge are also here predicted by the unsaturated flow model.

The lower confinement of the model is provided by the layer of low-permeable silt/clay sediments, Fig. 11.

The timesteps used in the numerical model are of the order of 7 days for the flow and 7 hours for the transport computations, respectively.

7.3 Simulation results (homogeneous three-layer model)

The first series of model simulations are based on the assumption that the aquifer is composed of three homogeneous layers. The values for the hydraulic conductivity and the thickness of the individual layers are listed in Table 1. Since the aquifer is composed of alluvial deposits we assume that the vertical hydraulic conductivities are 50 times smaller than the horizontal values. This anisotropy factor is consistent with the factor applied in a large-scale model study in the same area, Jensen et al. (1991). For the specific storage coefficient a value of 0.20 is specified in the upper discretization blocks containing the water table (unconfined conditions) while a value of 0.001 is applied in blocks where the hydraulic head level is above the level of the upper confinement (artesian conditions). For the kinematic porosity a value of 0.30 is assumed. All the simulation results presented below are based on transient flow conditions.

On the basis of this simplified geometry of the aquifer and the boundary conditions discussed above very accurate simulations of the water table configuration (Fig. 12) as well as of the seasonal fluctuations (Fig. 13) are obtained.

For the transport simulations we applied in the first attempt the values for the horizontal dispersivities found by the simplified analytical analysis discussed above. However, as anticipated this resulted in a much more pronounced transverse dispersion than observed while the longitudinal component compared reasonably to the observations. A sensitivity analysis was subsequently carried out in order to identify the values for the dispersivities which gave the best match to the observed concentrations. Some selected results of this analysis are included below.

Fig. 14 presents simulation results for different values of α_{LH} and by comparing with the observed spreading shown in Fig. 4 it is seen that the most accurate simulation is obtained for a dispersivity value of the order of 0.45 m, which also conforms closely to the result of the analysis discussed in section 6. As shown by the figure the simulation results are sensitive to the longitudinal horizontal dispersivity within the range of variation examined here which as far as the upper bound is concerned does not exceed the likely variation when compared to the reviews by Gelhar et al. (1985) and Lallemand-Barries and Peaudecerf (1978).

The longitudinal dispersivity in vertical direction has virtually no effect on the simulation results because of insignificant vertical flow components. Hence, it is not possible to identify this parameter with reasonable accuracy on the basis of the present experiment and the value listed above is set somewhat arbitrary.

The sensitivity to the transverse horizontal dispersivity α_{TH} is shown in Fig. 15 displaying the simulation results for some selected values. By also comparing this figure to Fig. 4 it is evident that the parameter has to be assigned a very low value in order to match the observed spreading. In relation to the previous analytical analysis we have to reduce α_{TH} by an order of one magnitude, partly because the lateral dimension of the injection is now taken into account, but also due to the fact that the spatial and dynamic variations in the flow lines are considered in the numerical model. Although the figure does not show any significant difference in the simulation results for the cases of α_{LH} = 0.0 and α_{LH} = 0.001 m, the simulations compared slightly better to observations in the last case when evaluated more detailed on the basis of breakthrough curves. The value for α_{TH} suggested in this study is lower than found in the Borden and Cape Cod cases, but it conforms closer to the value predicted by the stochastic theory developed by Gelhar et al. (1985).

Similarly for the transverse vertical dispersivity α_{TV} an extremely low value is required in order to match simulations and observations, cf. Fig. 16 and Fig. 5. Also for this parameter we observe a significant effect on the simulation results and a value which essentially only represents molecular diffusion needs to be introduced in order to reproduce the steep-sided plume observed. This finding is consistent with the results by Frind et al. (1989).

On the basis of this sensitivity analysis we identified the following "best-fit" parameters: α_{LH} = 0.45 m, α_{TH} = 0.001 m, α_{LV} = 0.05 m, α_{TV} = 0.0005 m. It should be emphasized that these parameters have not been identified in a stringent optimization process but on the basis of a number of trial simulations. Hence, they should not be considered as definite numbers but rather as indications of the order of magnitude.

The simulation results based on the above values for the dispersivity parameters are shown in Figs. 17, 18 and 19. Fig. 17 presents contour plots of the vertically averaged tritium concentration at various times after injection and Fig. 18 shows concentration distributions of the tritium plume in vertical sections on the longitudinal axis of the plume at the same times. These figures provide an overview of the overall behaviour of the simulated tritium plume and by comparing to the observed behaviour shown in Figs. 6 and 7 it is seen that there is a good agreement as far as travel velocity and spreading in horizontal and vertical directions are concerned.

When compared on a more detailed scale as in Fig. 19 which displays observed and simulated breakthrough curves in piezometers located in vertical sections placed perpendicular to the longitudinal axis at various distances from the injection point, the discrepancies between the observed data and the numerical results become more apparent. In general the simulated breakthrough curves mirror the shapes of the observed ones rather closely both with respect to arrival times, base lengths on the time axis and peak concentrations. However, the spatial locations of the breakthroughs laterally as well as vertically within the cross-sections displayed are not in exact agreement. In the distance of 100 m the phenomenon of upward movement of the plume is clearly displayed, because the breakthrough of the bulk part of the plume takes place approximately 1.0 m above the level of injection, and this phenomenon is obviously not reflected in the model simulations. Also discrepancies on the lateral direction are apparent from the figure such as in the distance of 195 m from injection point. The discrepancies disclosed by the figure we attribute to the presence of local small-scale intraformational heterogeneities not accounted for in the hydraulic conductivity distribution introduced in the model. Such heterogeneities will locally influence the concentration distribution, however, the effects seem to average out on a larger scale. It is an impossible task to map the three-dimensional spatial distribution of the hydraulic properties in all details and consequently we cannot expect that the model is able to provide a complete resolution of the concentration variation observed at the individual point locations within the aquifer transversed by the tracer. However, on an overall basis the model has reproduced the characteristics of the observed tracer distribution and the results suggest that dispersivities of magnitudes similar to those obtained in small-scale laboratory systems can be applied to field studies in alluvial aquifers if the overall structure of the sedimentary layers is defined.

The second experiment involving chloride as a tracer suffers from the problem of initial vertical displacement of the plume due to hydraulic head differences and density contrasts between the tracer solution and the native groundwater. While the head effect can be accounted for in the numerical model we are not able in a rigorous way to describe the spreading produced by the hydrodynamic instabilities due to the presence of the higher-density tracer solution over the lower-density native groundwater.

As discussed previously the density driven vertical displacement of the solute plume takes place immediately below the injection point leading to high concentrations just above the less-permeable clay layer. Furthermore, the experimental data indicate that the vertical shape of the plume remains essentially unchanged over the duration of the experiment, see Fig. 8. In order to account for the initial density driven displacement in the numerical model we have adjusted the injection mode in a pragmatic way by injecting the tracer solution over the vertical in proportion to the peak concentrations observed over the vertical 15 m downstream of the injection point.

Using the same dispersivity parameters as for the tritium simulations, the predictions of the movement of the chloride plume are shown in Figs. 20-22. By comparing the simulation results to the observations presented in Figs. 7 and 8 it is seen that both the horizontal and vertical shapes of the simulated plume compare rather well to the configurations observed. Also the predicted horizontal displacement velocity compares favourably to the observed characteristics during the initial phase of the experiment (up to a travel distance of about 60 m), however, in the later phase the displacement velocity is somewhat overestimated.

Fig. 22 compares predicted and observed breakthrough curves at various positions in cross-sections placed in the near field. As shown by the figure an excellent accordance is obtained for the travel distances shown. For longer distances the time of arrivals are slightly offset, however the shape of the curves are still in good agreement. Hence, the chloride data has confirmed the best fit dispersivity parameters obtained from the tritium simulation. This suggests that the parameters also are valid in the lower part of the aquifer.

7.4 Simulation results (heterogeneous three-layer model)

The numerical model analysis discussed in the previous section was based on the assumption that the aquifer under investigation is composed of three structural sand layers with uniform hydraulic properties within the individual layers. For the transport distances examined the simulation of the plume movements based on this rather simple conceptualization of the geological composition were in good agreement with the experimental data for dispersivity values comparable to those obtained in small-scale systems. However, the analysis also suggested that the concentration observations locally are influenced by small-scale intraformational heterogeneity which were not considered in the numerical model.

In order to investigate the influence on contaminant transport of the small-scale local variations in the hydraulic conductivity the parameter is treated as a random variable. The relevant statistical parameters for characterizing the spatial variation of the hydraulic conductivity include the mean, the standard deviation and the covariance.

Due to excessive computer commitments of the three-dimensional flow and transport model it was not feasible to perform a traditional Monte Carlo analysis involving a large number of realizations and instead we have only analyzed the movement of the tracer plume in a single realization.

Because of the large transport distance of the plume in comparison with the horizontal correlation scale of the hydraulic conductivity field, it was assumed that the transport characteristics of the simulated plume represented the ensemble average. The same approach has been used by Ababou et al. (1989) and Sudicky (1990).

In order to generate random three-dimensional hydraulic conductivity fields with prescribed statistical properties the turning band method developed by Mantoglou and Wilson (1982) was used. It was assumed that the aquifer is composed of three statistically independent sedimentary layers with the statistical properties (mean, variance and correlation length) listed in Table 1. Further, it was assumed that the spatial correlation structure of the log-transformed hydraulic conductivity fluctuations could be described by an exponentially decaying function. No data was available for the correlation length in vertical direction and therefore we estimated this parameter to 0.15 m on the basis of a comparative analysis to the structural data given by Sudicky (1986) and Hess et al. (1991).

The code developed by Tompson et al. (1987) was used to generate a realization of the hydraulic conductivity fields with the statistical properties described above. Point-values of hydraulic conductivity were generated on a grid with 1.0 m spacing in the horizontal direction and 0.10 m in the vertical. The vertical discretization was decreased in comparison with the homogeneous case in order to preserve the statistical properties of the lnK field. The random field was not conditioned at the measurement locations, because of the small number of measurements present (250) in relation to the total number of grid elements involved (244.000) and the small correlation lengths of the hydraulic conductivity fluctuations. A visual impression of synthesized aquifer is given in Fig. 23 which indicates that a more tortuous flow pattern will be present at the local scale.

The single realization of the hydraulic conductivity field served as input to the numerical model, and for this particular case the flow field was assumed to be time-invariant. In the first simulation the same dispersivity parameters as for the homogeneous case were introduced and the two simulations are compared in Figs. 24 and 25. As shown in the figure the fluctuations of the generated lnK field have introduced some irregularities in the concentration distributions, however, the mean travel velocity and direction of the tracer plume are nearly the same in the two simulations. The longitudinal dimension of the plume is larger in the heterogeneous case, while the horizontal transverse and vertical dimensions of the plume have not increased significantly.

The increased dispersion in the heterogeneous case is due to the disturbances introduced by the fluctuations in the hydraulic conductivity field. In accordance with the higher resolution of the flow solution, lower values for the dispersivity parameters could be introduced. We made a few trial simulations with smaller values for the longitudinal dispersivity and as also shown in Figs. 24 and 25, a value of 0.10 m results in a dispersion pattern which is very close to the observed pattern. This dispersivity represents the dispersion created by the heterogeneity at a scale below the selected modelling scale.

8. SUMMARY AND CONCLUSIONS

A large-scale natural gradient experiment on solute transport in groundwater was carried out using tritium and chloride as tracers. The objective was to study the transport and dispersion behaviour in a sandy aquifer contaminated by leachate from an old landfill located about 600 m from the dispersion field site. The aquifer is typical for the geological conditions in the western part of Denmark.

The aquifer at the site is unconfined with the water table located approximately 5 m below the ground surface. A low-permeable clay layer at approximately 10 m depth defines the lower boundary. The water table fluctuated about 1.0 m over the season, however, all wells responded similarly, and the flow direction therefore remained fairly constant during the experiment.

The statistical characteristics of the hydraulic conductivity distribution were determined on the basis of slug tests. Due to the alluvial origin of the aquifer low values were obtained for both the variance (0.37) and the correlation length (in the range of 1.0 - 2.5 m).

A 200 m long and 40 m wide experimental area was designed with orientation along the groundwater flow direction. A dense three-dimensional piezometer network was established concurrently with the development of the tracer plumes in order to accurately determine the position of the tracers.

Tritium was selected as the primary tracer because of its detectability in low concentrations, and it proved very suitable for the experiment. Tritium was injected as a slug of $4.66 \cdot 10^9$ Bq in total, and water sampling was carried out several times a week in order to accurately define the break-through curves.

In a second tracer experiment chloride together with other inorganic constituents were injected continuously over 37 days. Also this plume was monitored by sampling several times a week. The plume experienced a vertical displacement at the point of injection due to density contrasts and therefore this experiment was less suitable for detailed investigations of the dispersion characteristics.

Apart from the initial sinking of the chloride plume, both tracer plumes behaved similarly by showing a predominantly spreading in longitudinal horizontal direction while very small spreadings occurred in transverse horizontal and vertical directions.

The number of piezometers affected at a given time was not large enough to enable application of the moment analysis method. Instead the transport parameters were evaluated on the basis of breakthrough curves for vertically integrated tritium concentrations using an optimization procedure based on a simple analytical solution to the advection-dispersion equation. For the travel distances examined (larger than 50 m) the dispersivities showed no significant trend to increasing values with increased distance from the point of injection suggesting that the asymptotic stage was reached. The longitudinal dispersivity identified conformed well to the value estimated on the basis of a stochastic theory of dispersion.

A numerical three-dimensional model was applied to the aquifer in order to identify the dispersivities more closely. The model was coupled to a one-dimensional model for unsaturated flow to generate the seasonal variation of recharge to the water table. Assuming a three-layer structural geological model with uniform hydraulic properties very accurate simulations were obtained of the seasonal fluctuations of the water table within the experimental area.

On the basis of trial simulations the following "best-fit" dispersivity parameter were identified: α_{LH} = 0.45 m, α_{TH} = 0.001 m, α_{LV} = 0.05 m, α_{TV} = 0.005 m. The longitudinal horizontal dispersivity is of the same magnitude as found in the Borden and Cape Cod tracer experiments while the transverse dispersivities in this experiment are smaller. In general the dispersivities found in this study are smaller than listed in previous compilations, see e.g. Gelhar et al. (1985).

Using the dispersivities listed above good agreement was obtained between the numerical simulations and observations of the overall behaviour of both tracer plumes. On a more detailed scale at the level of breakthrough curves in the individual piezometers some discrepancies were present due to the disturbances created by local geological heterogeneities.

A single realization of the hydraulic conductivity field was generated using the turning band simulator to mimic the heterogeneity in the hydraulic properties. Because of the large transport distance involved in relation to the correlation scale of the fluctuations in the hydraulic conductivity, the single realization was presumed to be an analogue of the real aquifer. Due to the increased flow resolution it was possible to reduce the longitudinal dispersivity to a value of 0.10 m which consequently represents the dispersion created by the heterogeneity at a scale below the modelling scale.

The above conclusions show that a three-dimensional numerical model based on the classical advection-dispersion with dispersivities of magnitudes similar to those obtained in small-scale systems can be applied to field systems for prediction of the overall plume behaviour in aquifers of alluvial origin if the structural geological layers are accounted for. By considering the intra-structural heterogeneity of the hydraulic conductivity field in the model for this particular aquifer, the longitudinal dispersivity could be further decreased.

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LIST OF TABLES

Table 1. Hydraulic parameters for three structural layers of the aquifer (K_g - geometric mean of hydraulic conductivity, $\sigma^2_{\ln K}$ - variance of lnK, λ - horizontal correlation length, θ - full porosity, θ_e - estimated effective porosity).

Level (m)	Kg (m/s)	Range of variation (m/s)	$\sigma^2_{\ln K}$	λ (m)	θ	θ_e
33.0-34.5	5.6	$1.3 - 15.7 \times 10^{-4}$	0.20	2.5	0.38	0.30
32.0-33.0	4.4	$0.8 - 12.3 \times 10^{-4}$	0.41	1.0	0.38	0.30
31.0-32.0	6.1	$1.6 - 22.5 \times 10^{-4}$	0.29	1.0	0.38	0.30
Global	5.1		0.37			

Table 2. Computer optimized transport parameters. (θ - flow direction, V - convective velocity, α_{LH} - longitudinal horizontal dispersivity, α_{TH} - transverse horizontal dispersivity).

Observation well	θ°	V(m/day)	α_{LH}(m)	α_{TH}(m)
f18	-1.35	0.63	0.42	0.056
f19	-1.35	0.88	0.52	0.065
f21	-0.21	0.62	0.13	0.076
f22	-0.21	0.88	0.57	0.007
* f22	-0.21	0.86	0.35	0.010
f24	0.0	0.84	0.13	0.013
f25	0.0	0.82	0.41	0.012
f26	-0.31	0.73	1.85	0.015
* f26	-0.31	0.68	0.45	0.014
f27	-0.31	0.83	0.26	0.068
f28	-0.31	0.86	0.32	0.004
f29	-0.31	0.73	0.55	0.007
f31	-1.17	0.78	0.27	0.038
f32	-1.17	0.77	0.49	0.023
f34	-0.79	0.60	0.83	0.009
* f34	-0.79	0.61	0.39	0.008
f35	-0.79	0.80	0.47	0.005
ISVA1	-0.85	0.70	1.99	0.006
* ISVA1	-0.85	0.79	0.20	0.004
ISVA2	-0.85	0.74	0.48	0.040
ISVA3	-0.85	0.66	0.20	0.003
ISVA5	-1.79	0.79	0.55	0.020
ISVA6	-1.79	0.78	0.29	0.019
ISVA8	-1.36	0.79	0.52	0.005
ISVA9	-1.36	0.76	0.18	0.004
ISVA12	-1.13	0.78	0.46	0.026
ISVA14	-1.13	0.77	1.40	0.026
* ISVA14	-1.13	0.81	0.48	0.018
ISVA15	-1.36	0.72	1.98	0.007
* ISVA15	-1.36	0.79	0.48	0.006
ISVA16	-2.8	0.78	1.99	0.009
* ISVA16	-2.8	0.82	0.40	0.007
ISVA17	-2.8	0.79	0.66	0.037
ISVA18	-2.8	0.76	0.43	0.006
ISVA19	-2.8	0.73	0.78	0.013
ISVA20	-2.8	0.68	0.70	0.024
ISVA21	-1.13	0.64	0.76	0.041
ISVA22	-1.36	0.58	0.44	0.028
Mean		0.75	0.42	0.023

* Fitting not successful

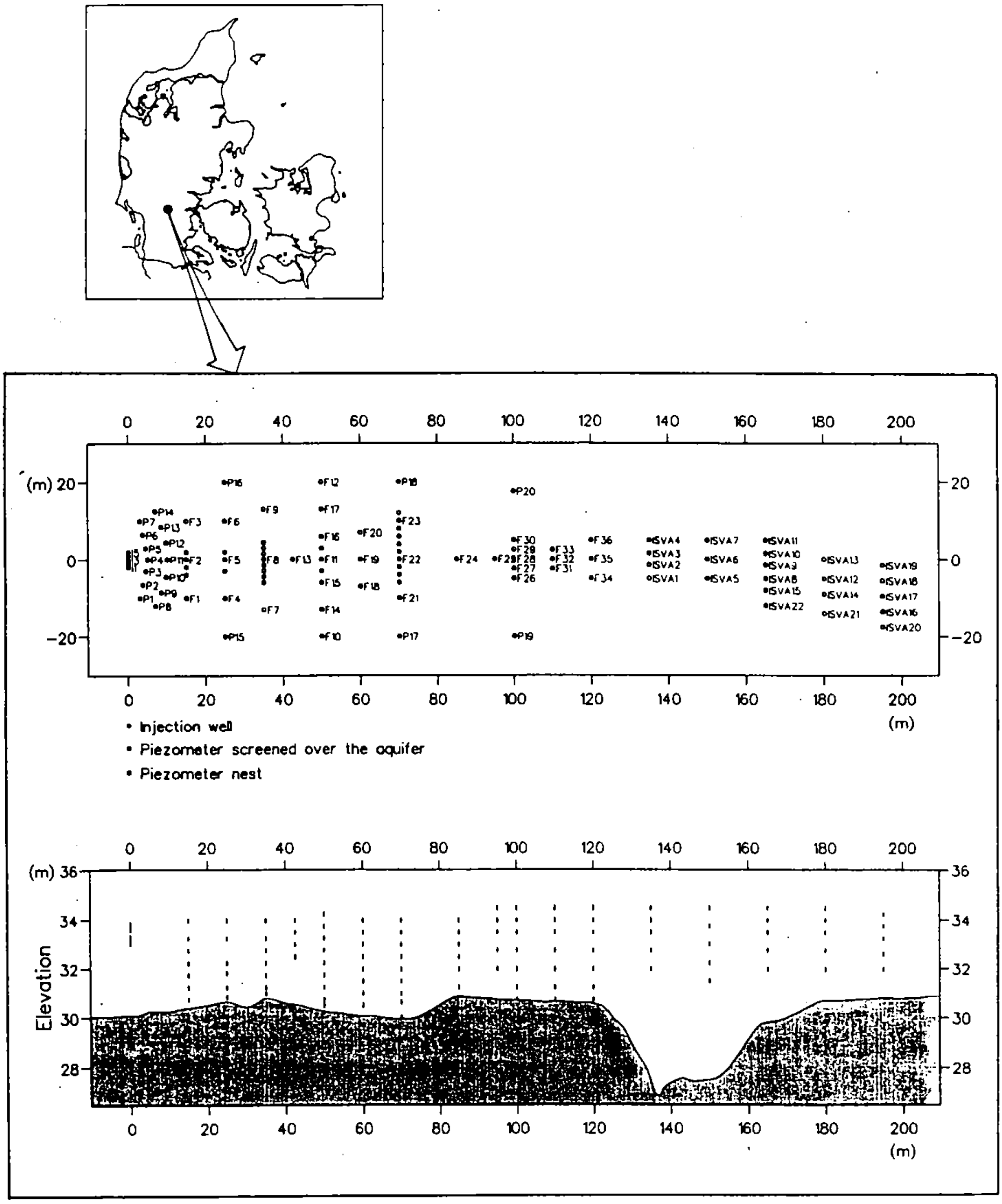

Figure 1. Plan and vertical diagram of sampling and monitoring locations.

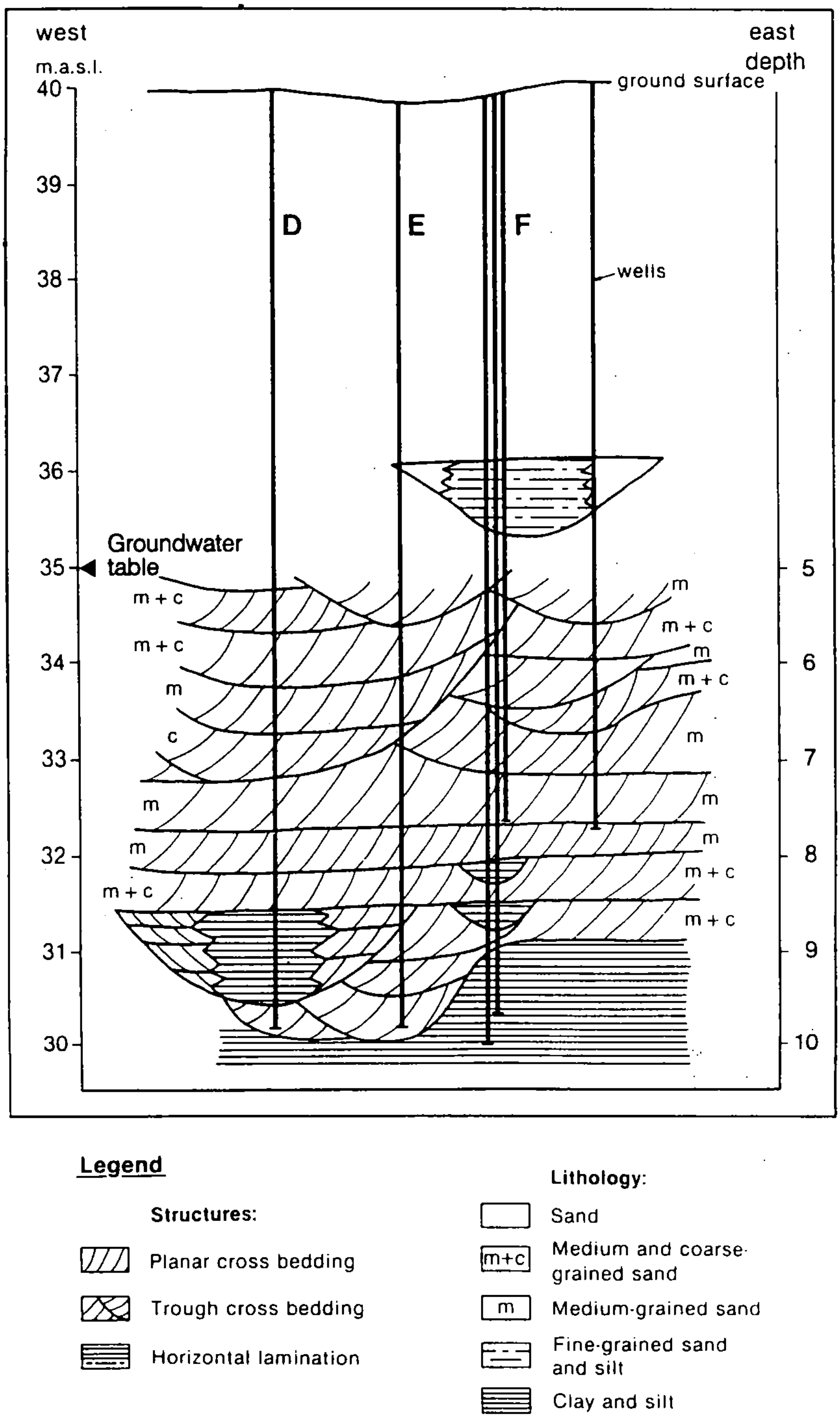

Figure 2. Stratigraphy of the aquifer.

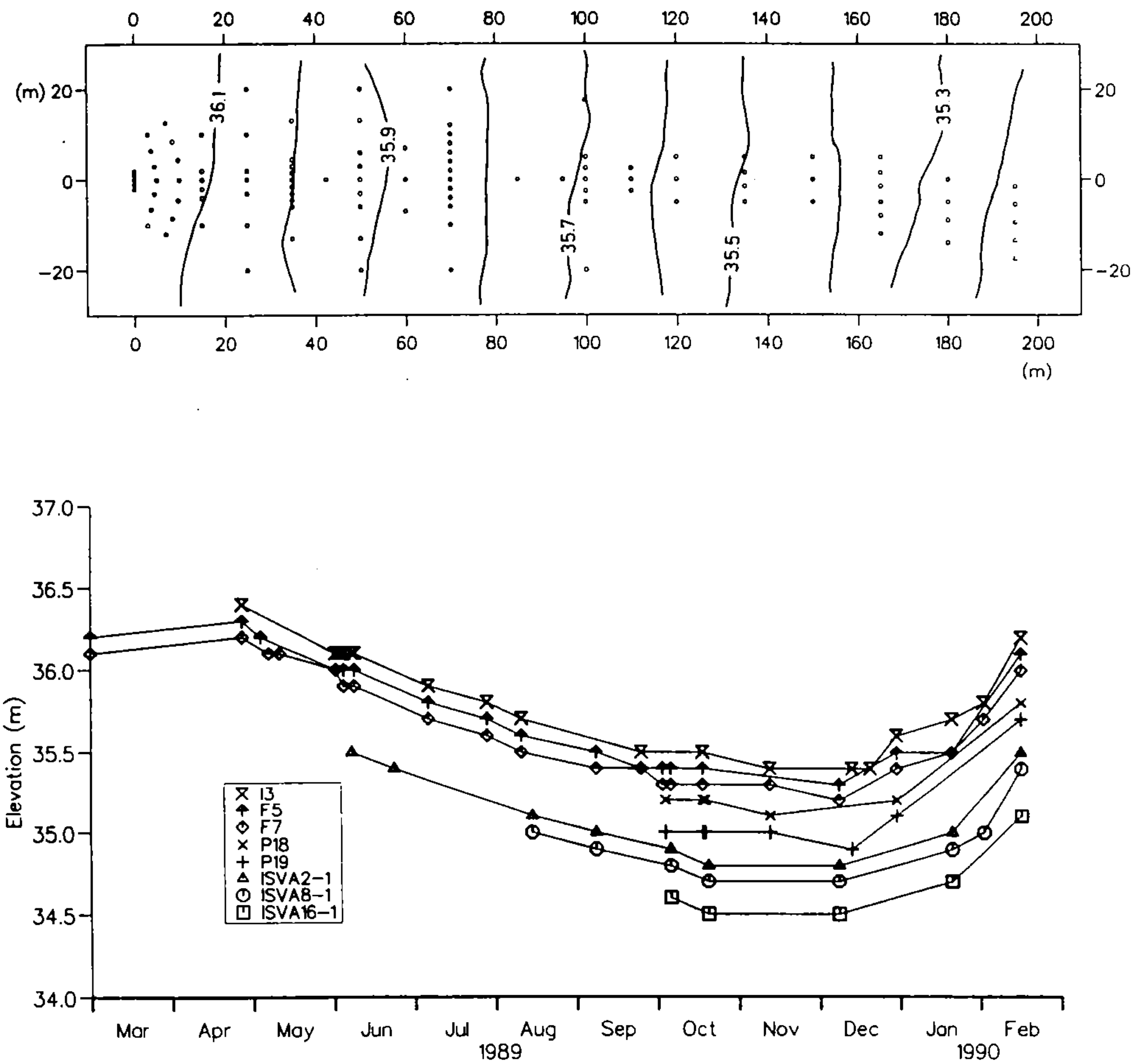

Figure 3. Water table configuration (February 14, 1990) and seasonal fluctuations of the water table in selected observation wells.

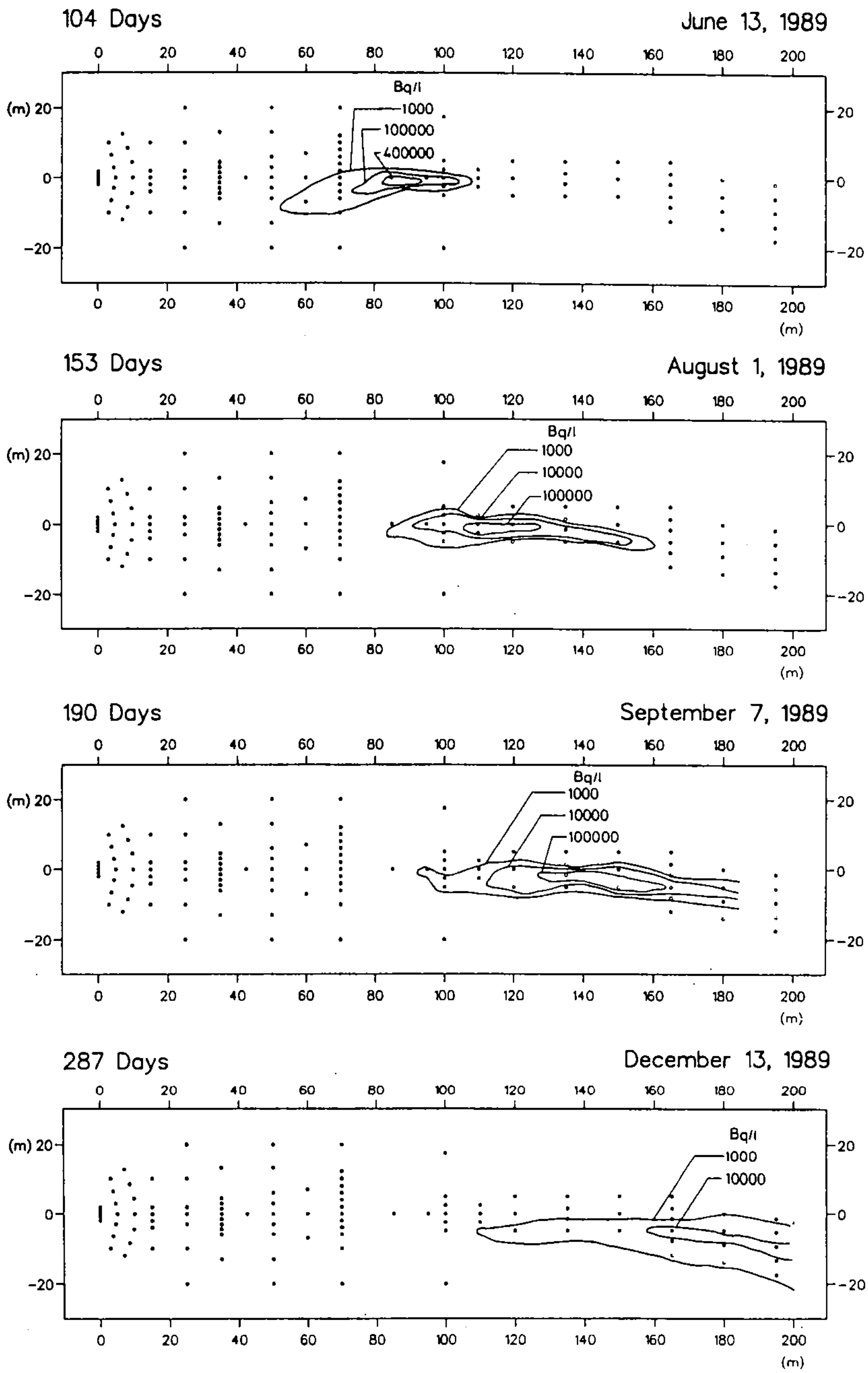

Figure 4. Horizontal distribution of vertically integrated tritium concentrations.

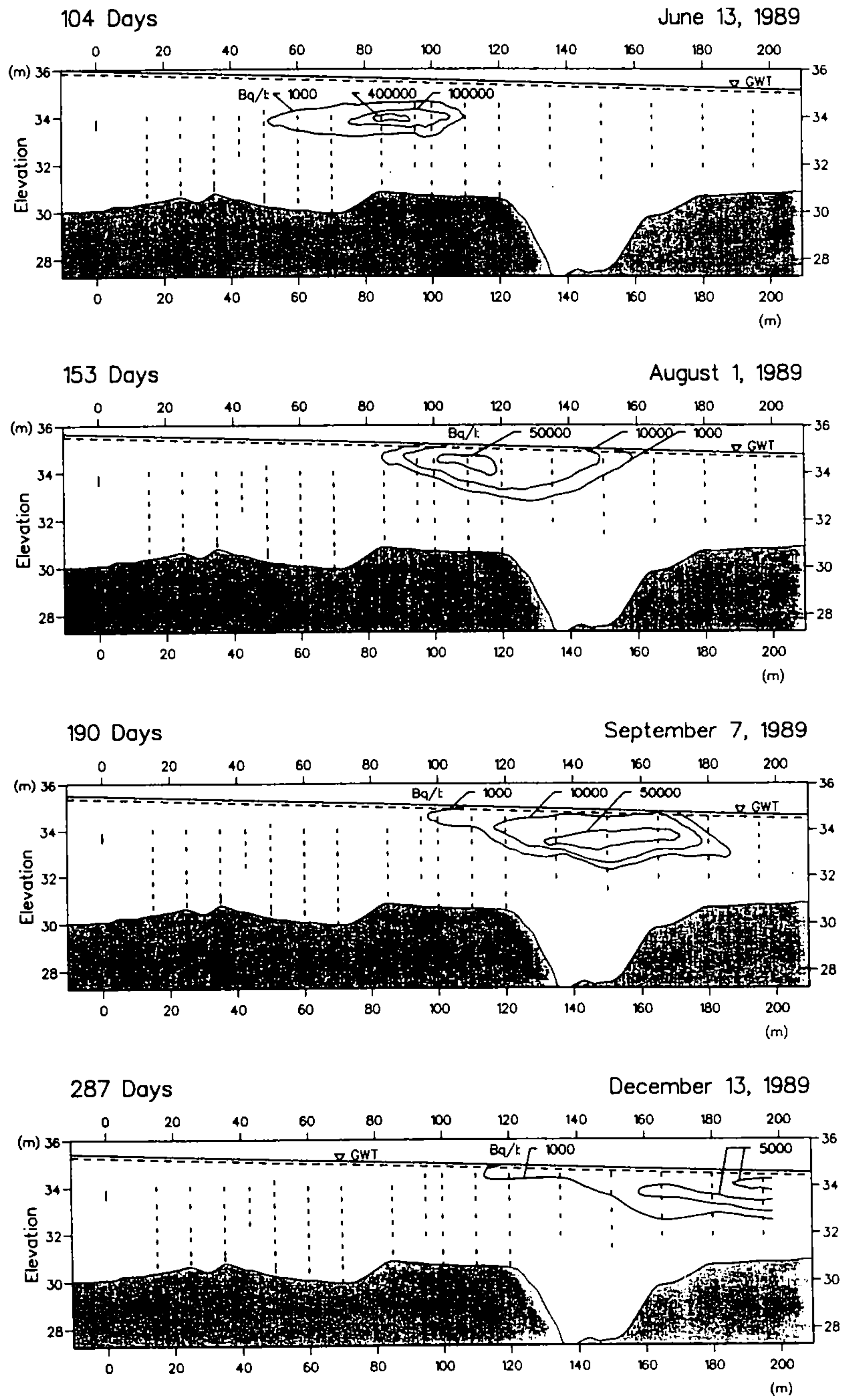

Figure 5. Distribution of tritium concentrations in a vertical section along the longitudinal axis of the plume.

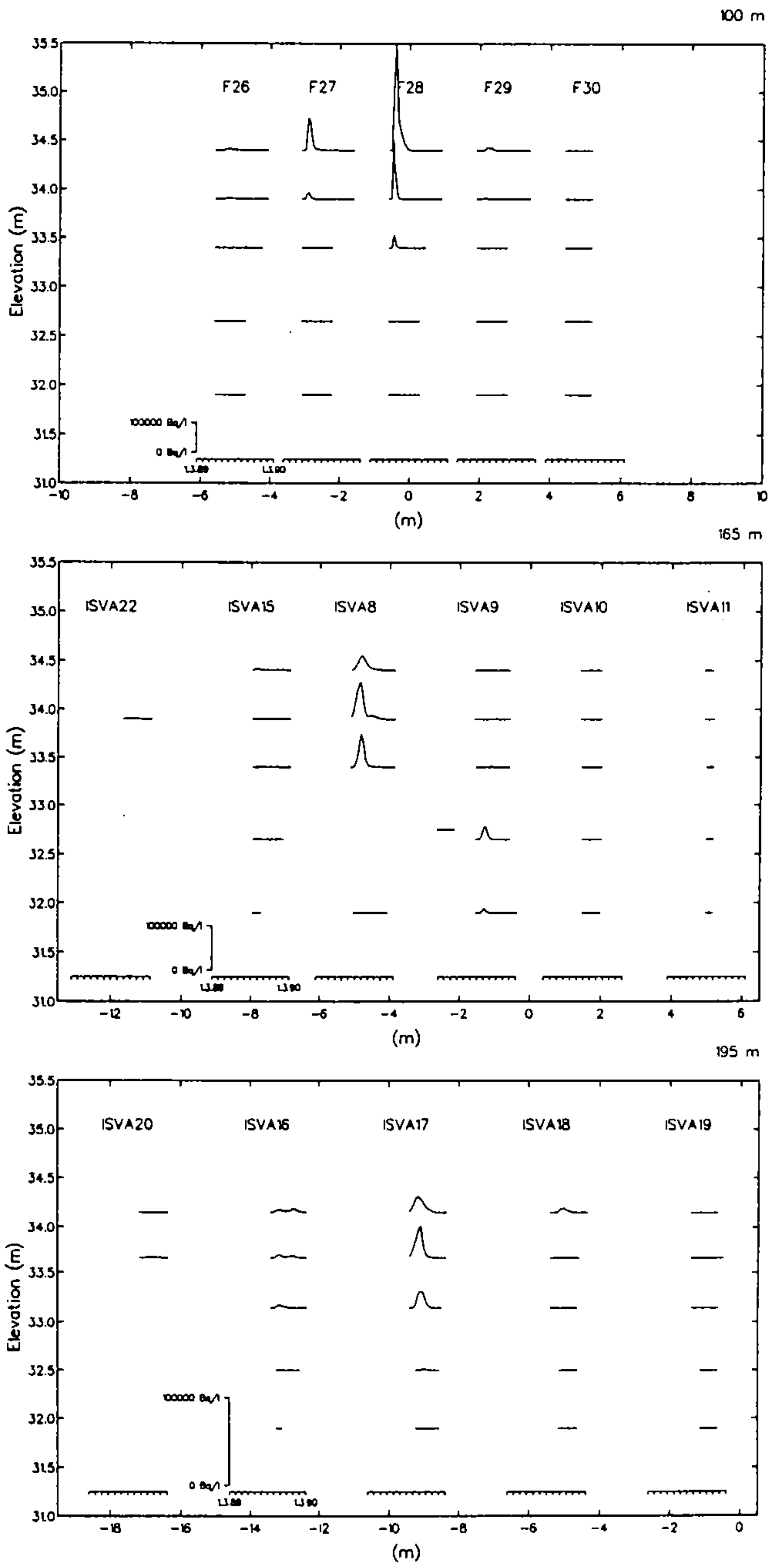

Figure 6. Breakthrough curves of tritium in screens placed in vertical planes perpendicular to the longitudinal axis at different distances from injection wells.

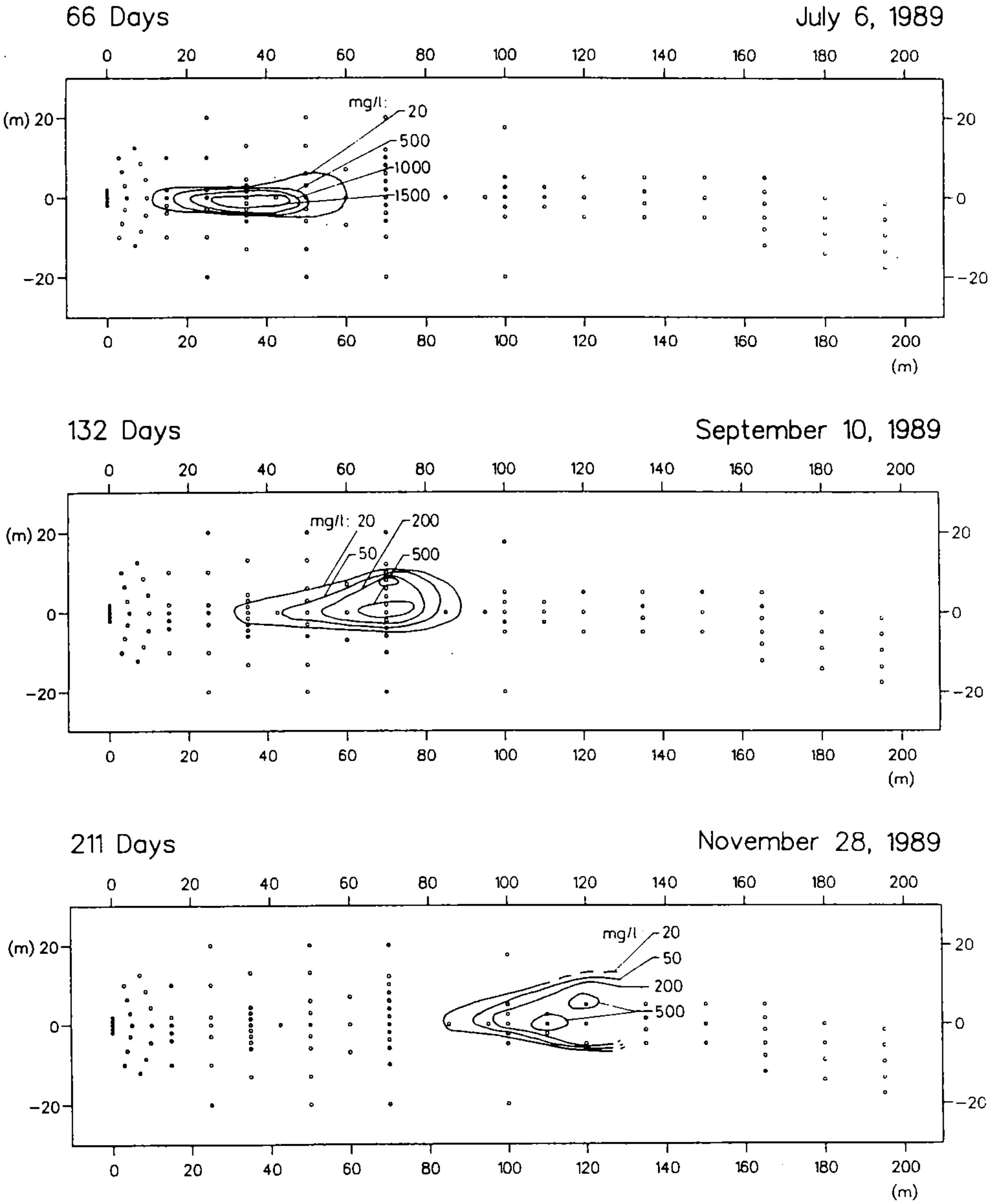

Figure 7. Horizontal distribution of vertically integrated chloride concentrations.

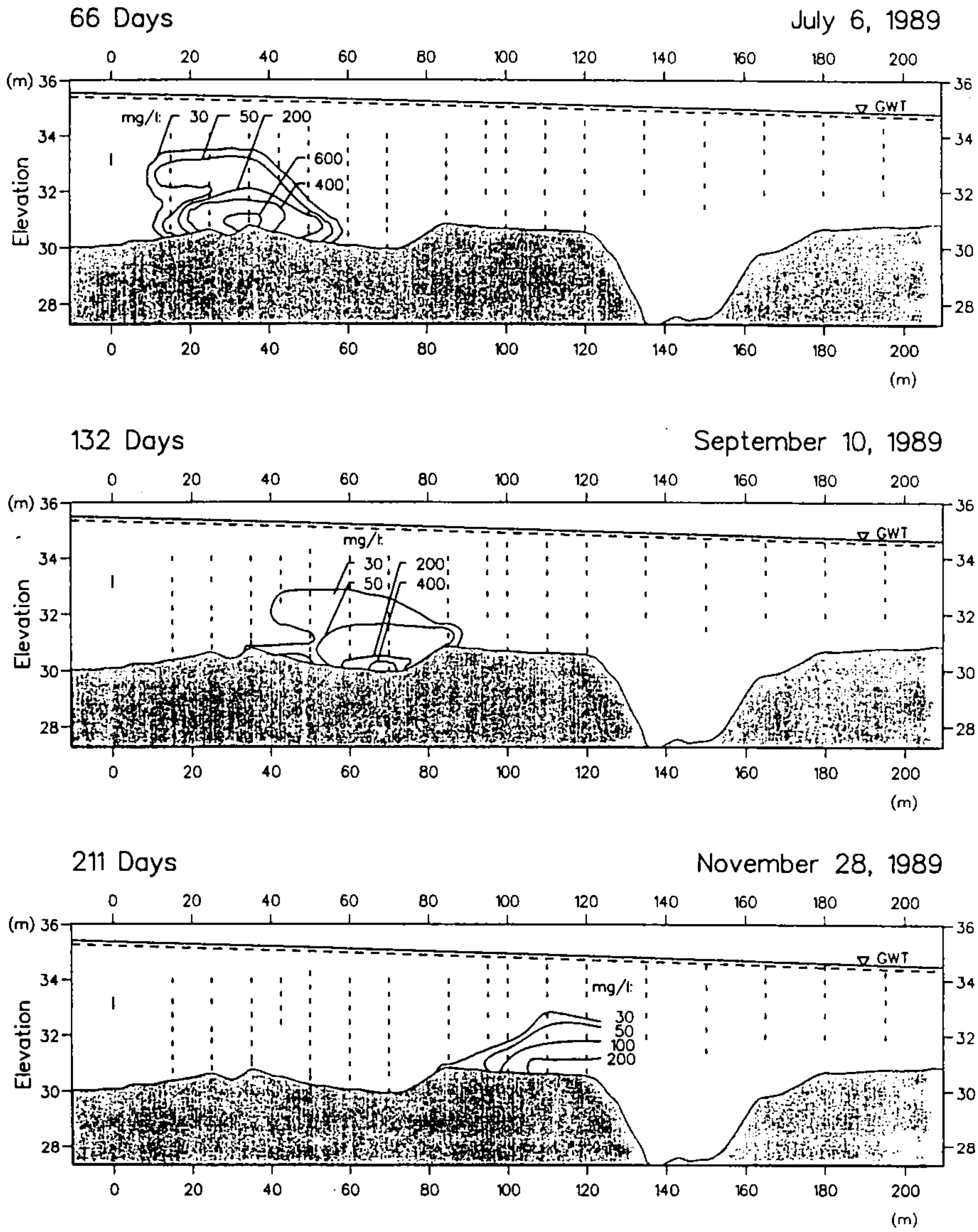

Figure 8. Distribution of chloride concentrations in a vertical section along the longitudinal axis of the plume.

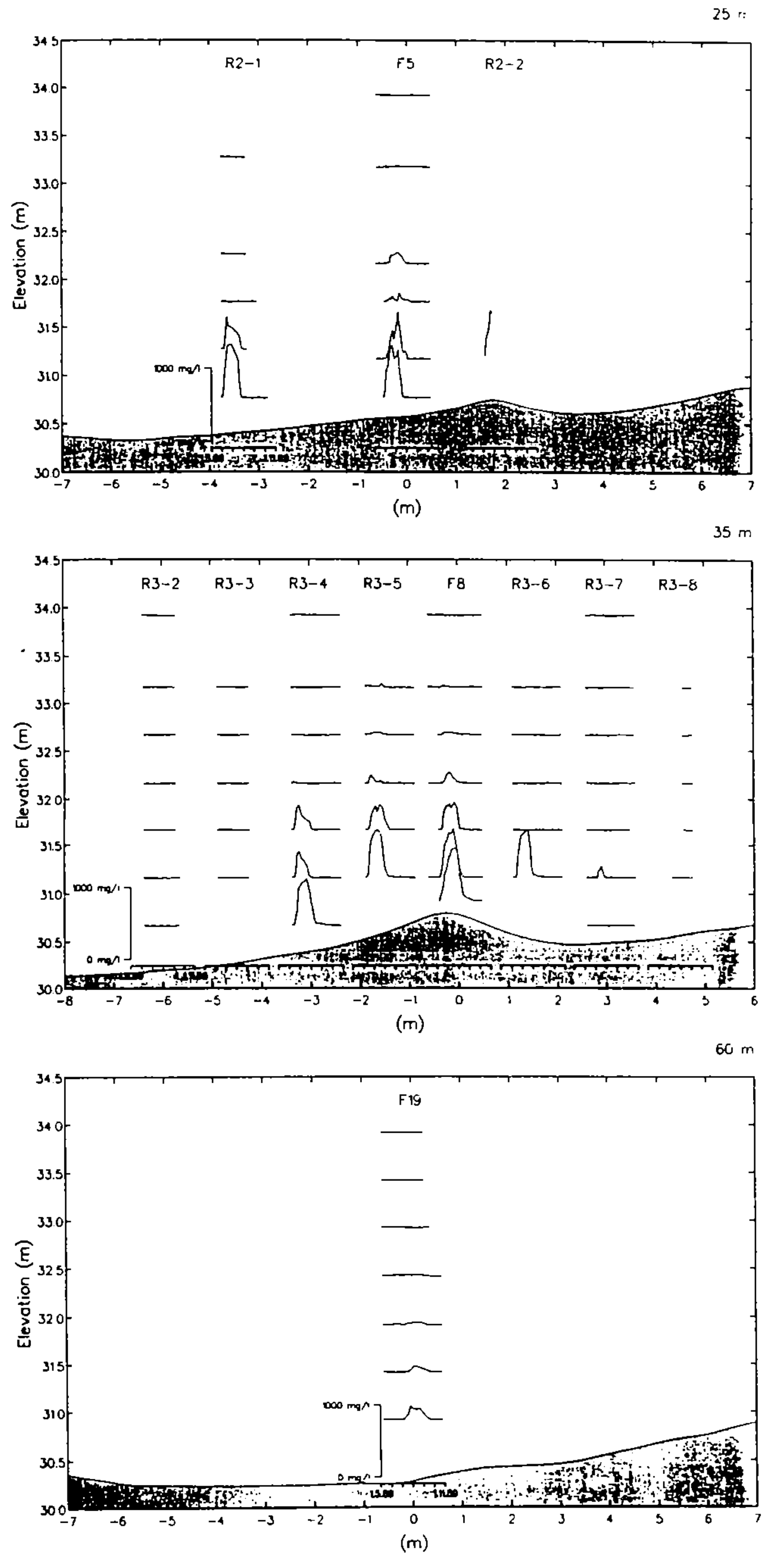

Figure 9. Breakthrough curves of chloride in screens placed in vertical planes perpendicular to the longitudinal axis at different distances from injection wells.

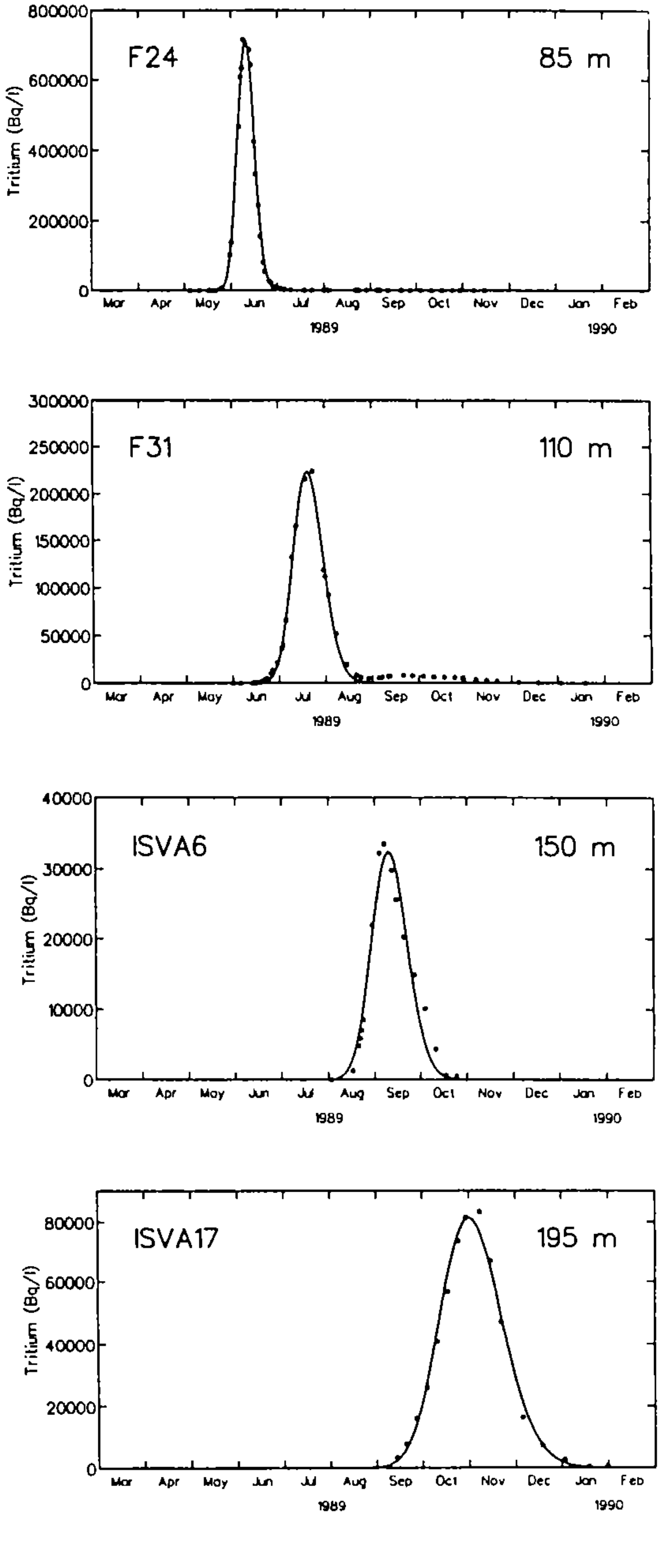

Figure 10. Observed and fitted breakthrough curves of vertically integrated tritium concentrations.

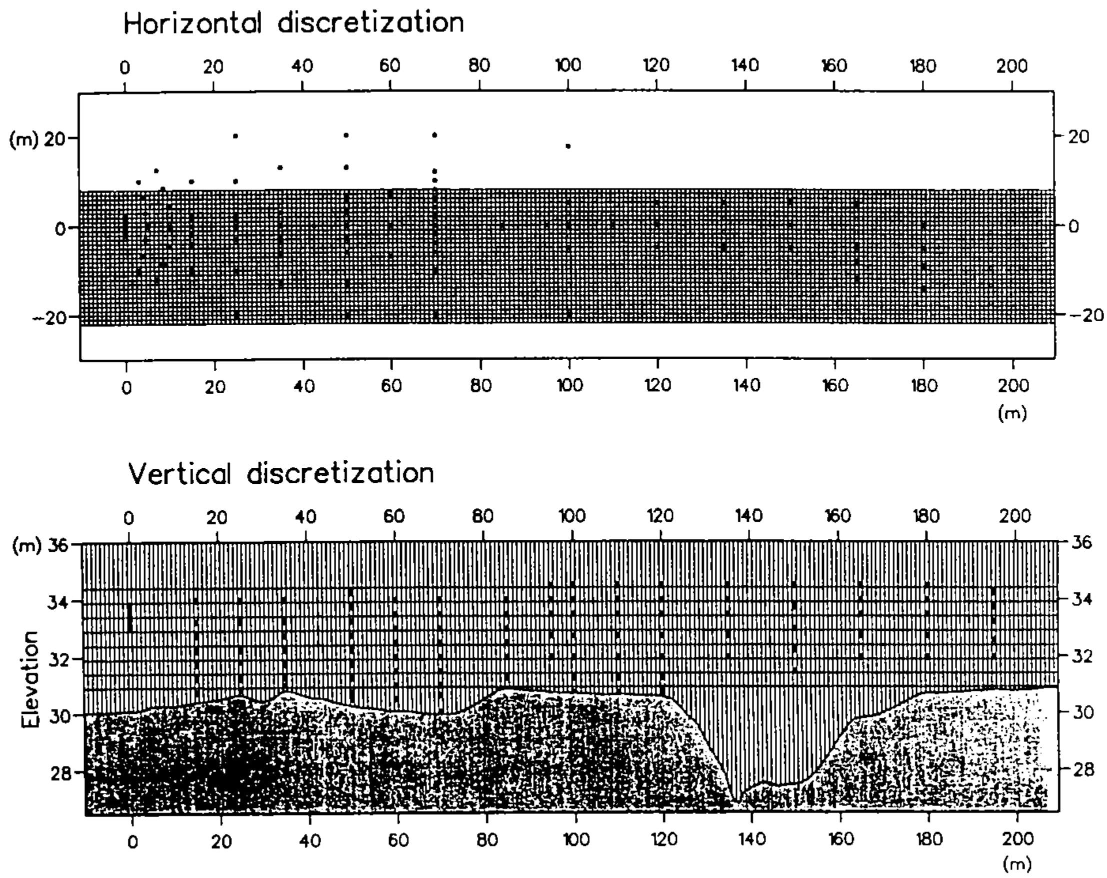

Figure 11. Horizontal and vertical discretization in numerical model.

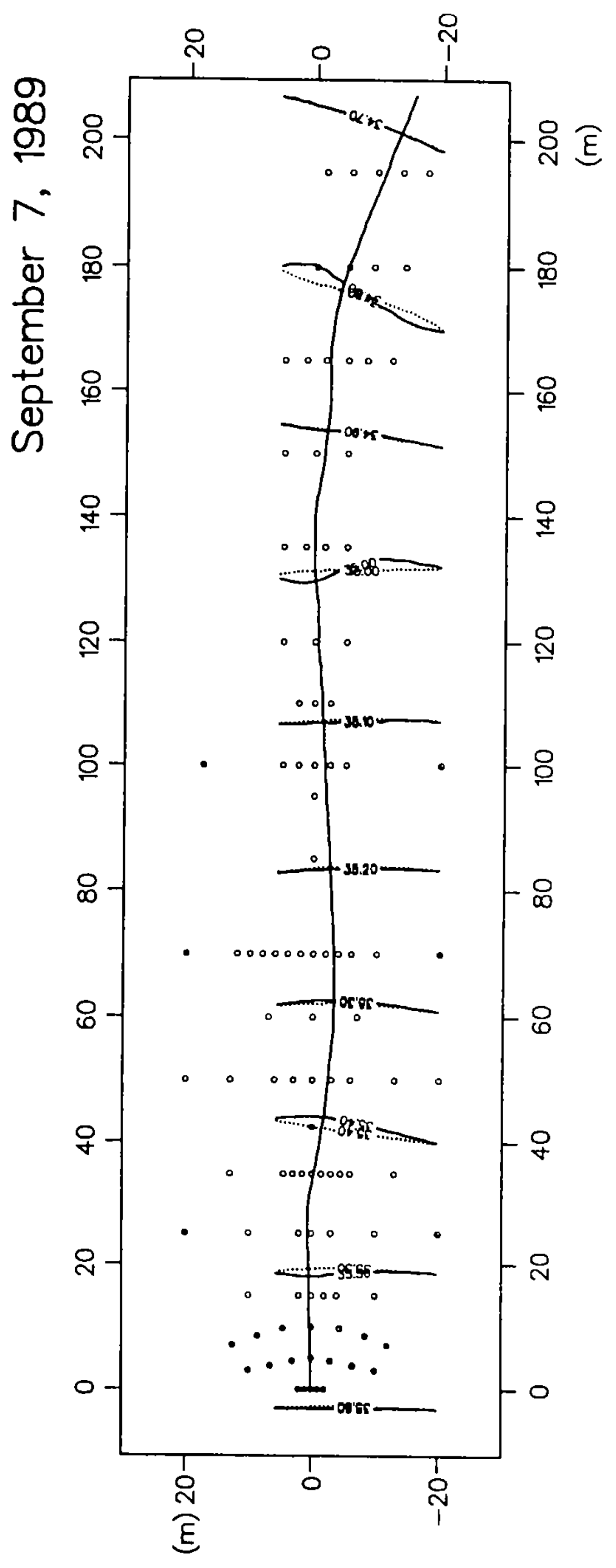

Figure 12. Observed and simulated water table configuration and flow trajectory.

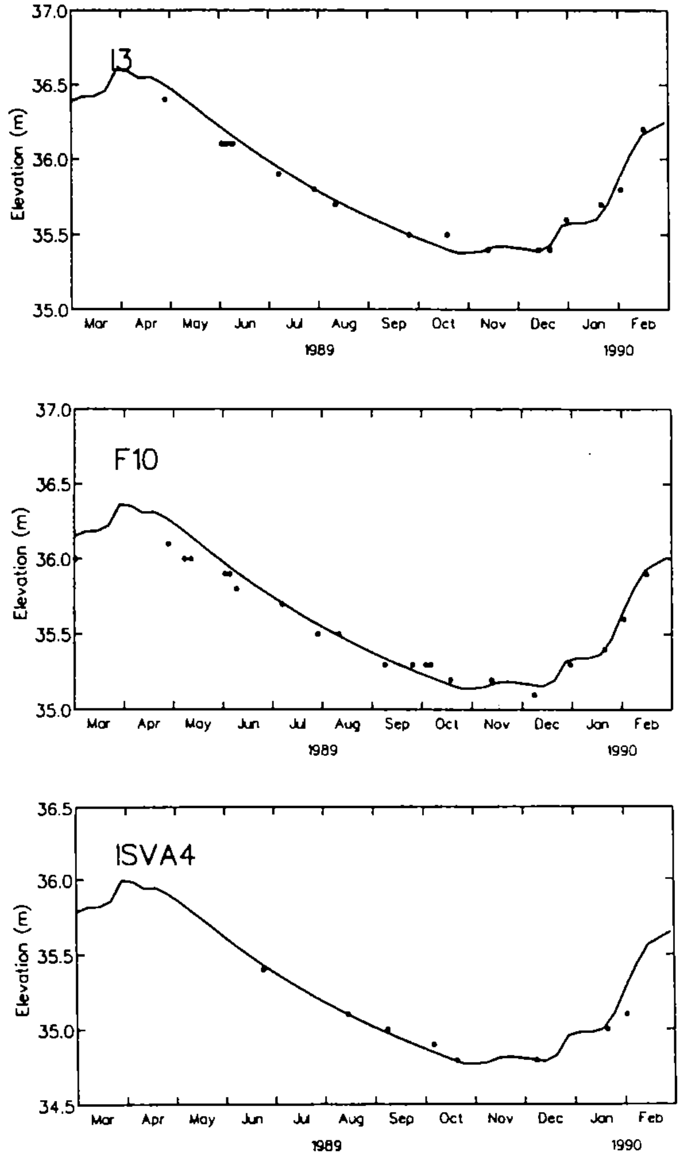

Figure 13. Observed and simulated water table fluctuations in selected piezometers.

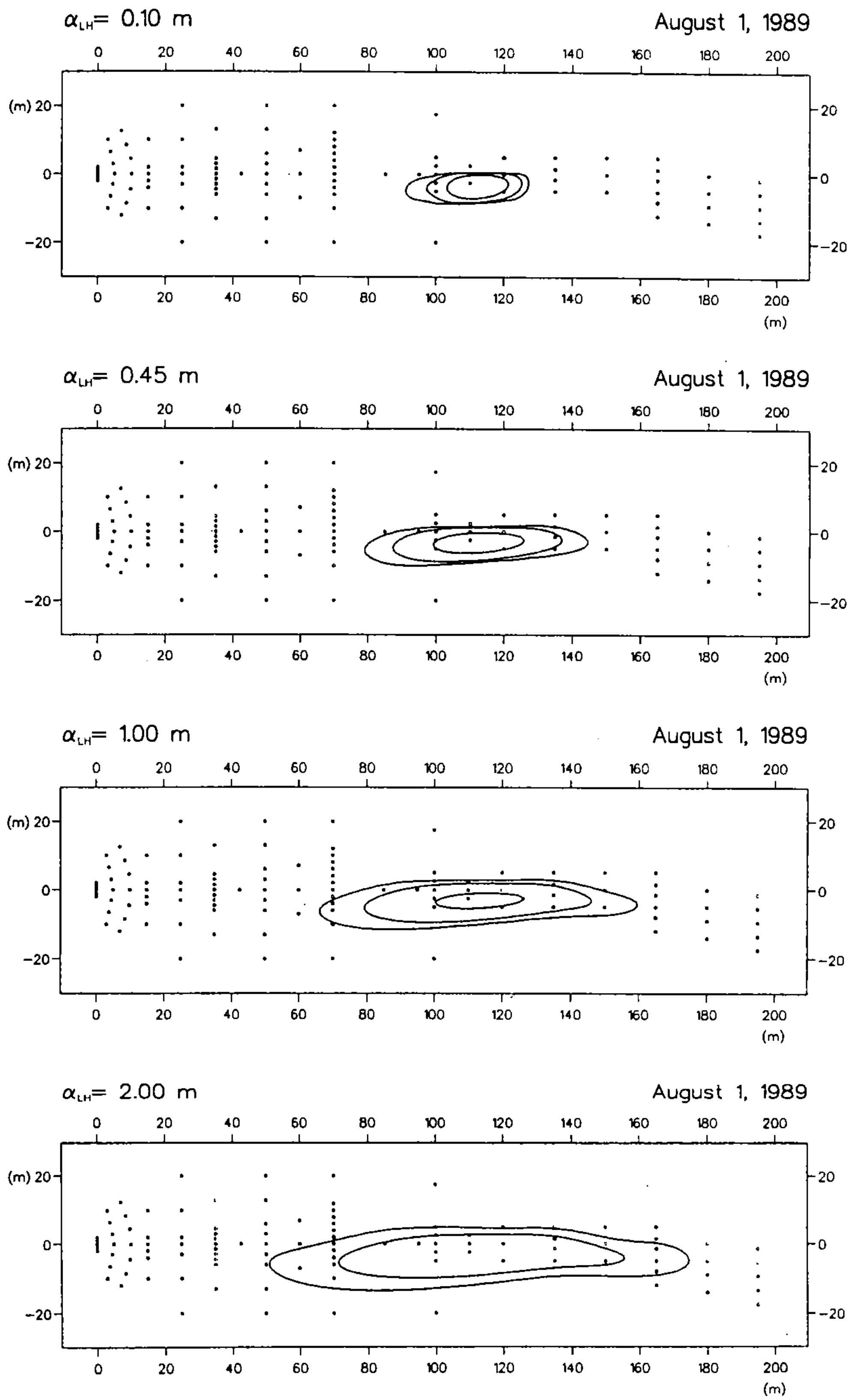

Figure 14. Sensitivity to horizontal longitudinal dispersivity (contour lines 1000, 10000, 100000 Bq/l).

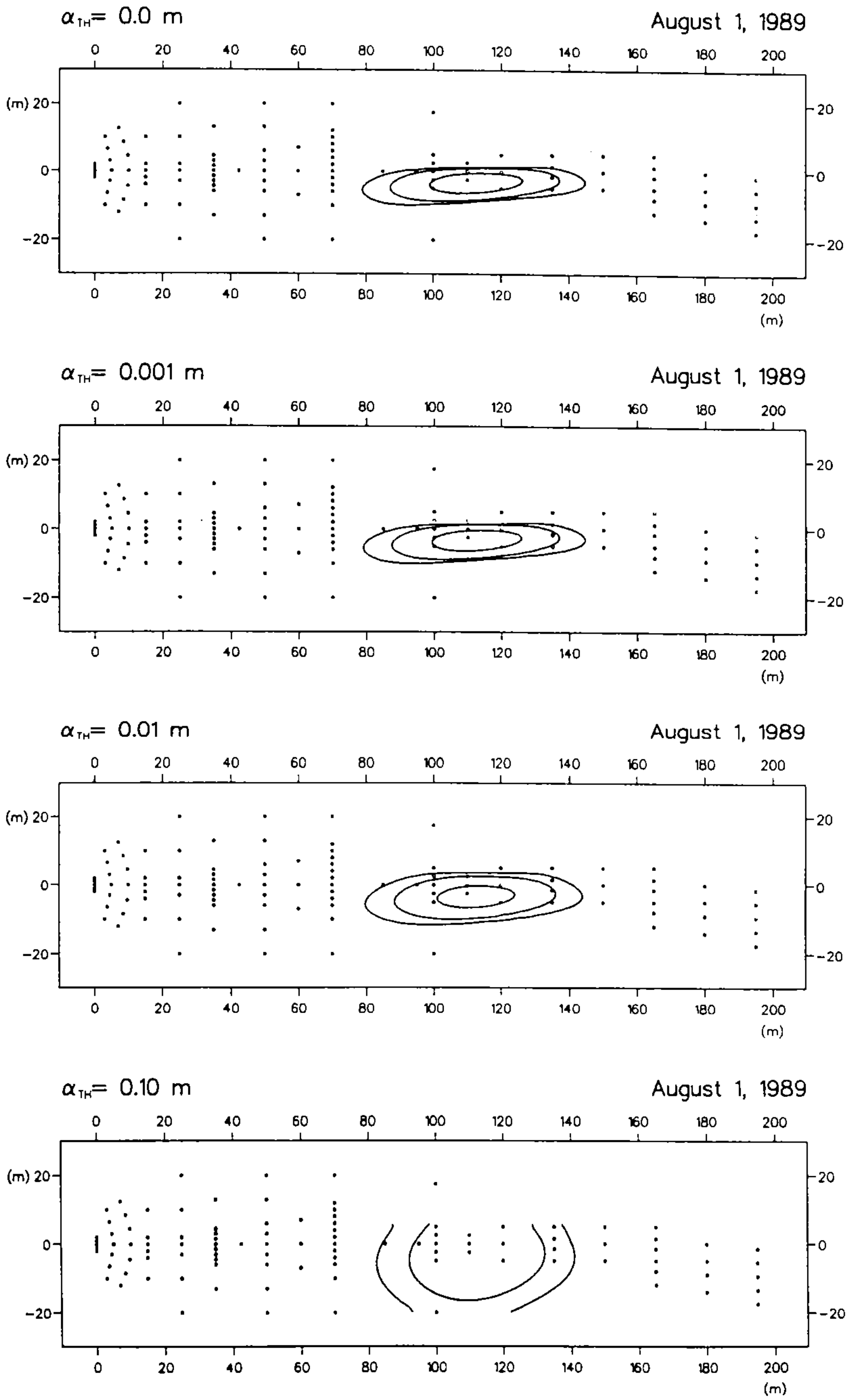

Figure 15. Sensitivity to horizontal transverse dispersivity (contour lines 1000, 10000, 100000 Bq/l).

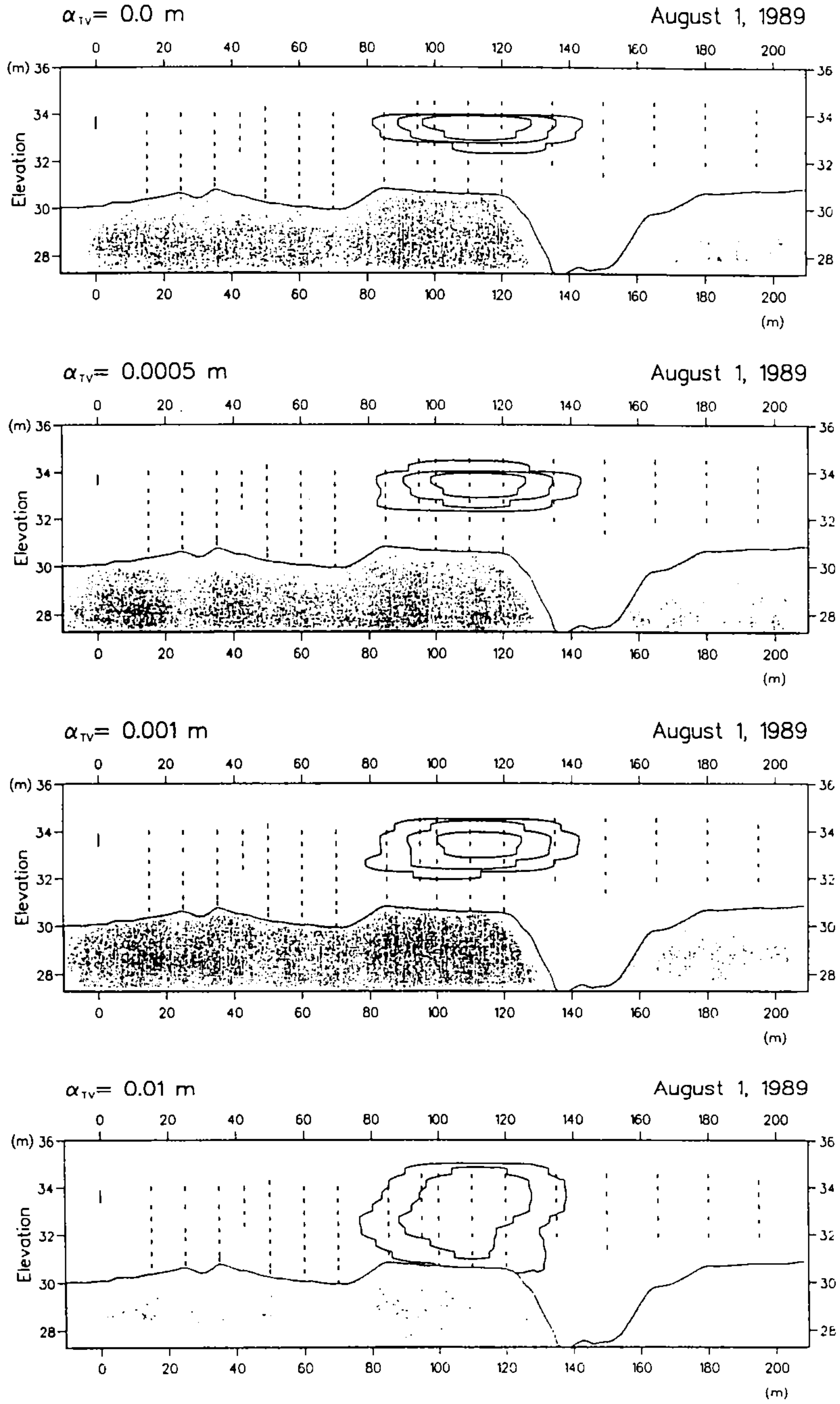

Figure 16. Sensitivity to vertical transverse dispersitivy (contour lines 1000, 10.000, 50000 Bq/l).

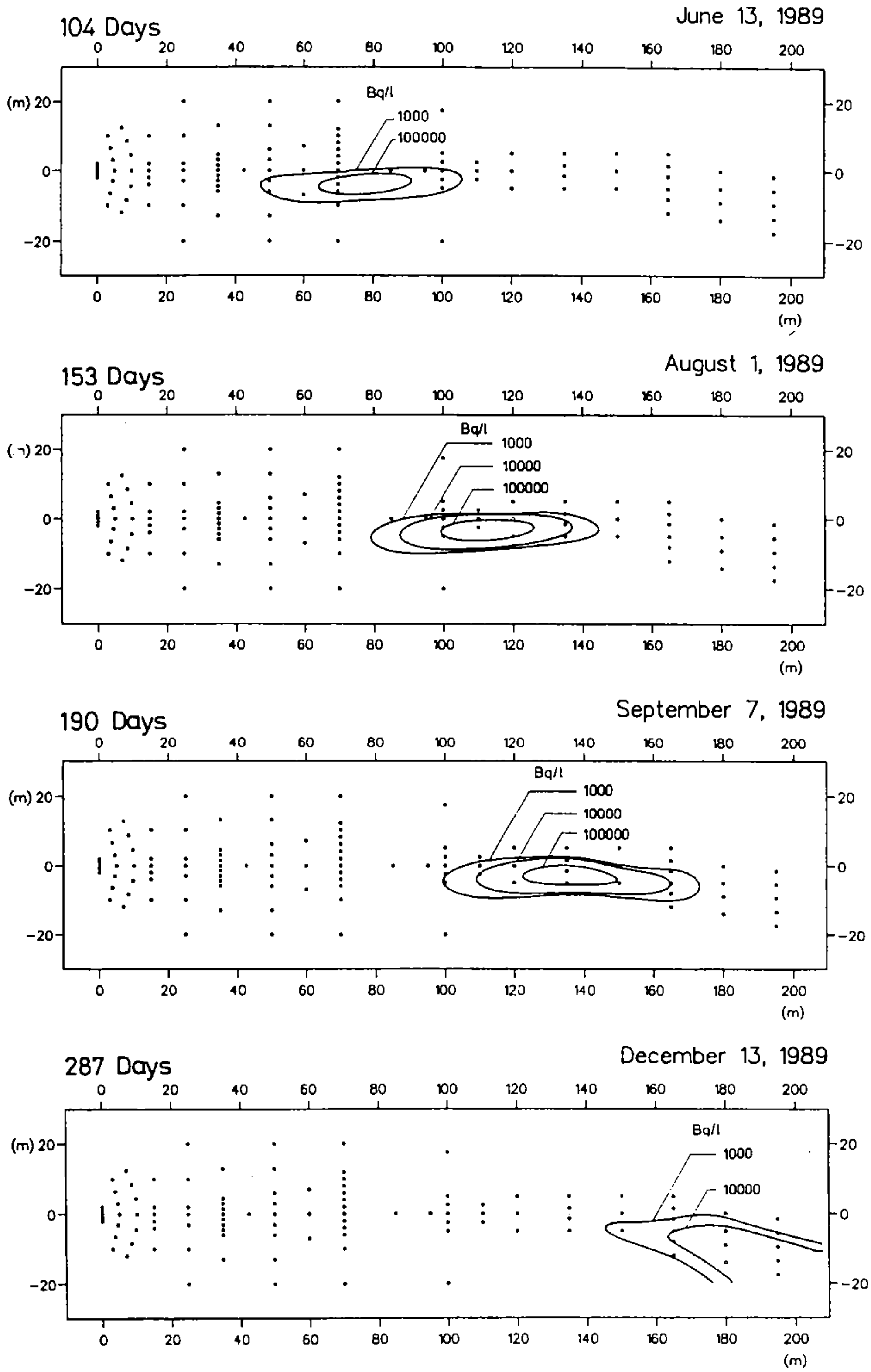

Figure 17. Simulated horizontal distribution of vertically integrated tritium concentrations (homogeneous 3-layer model).

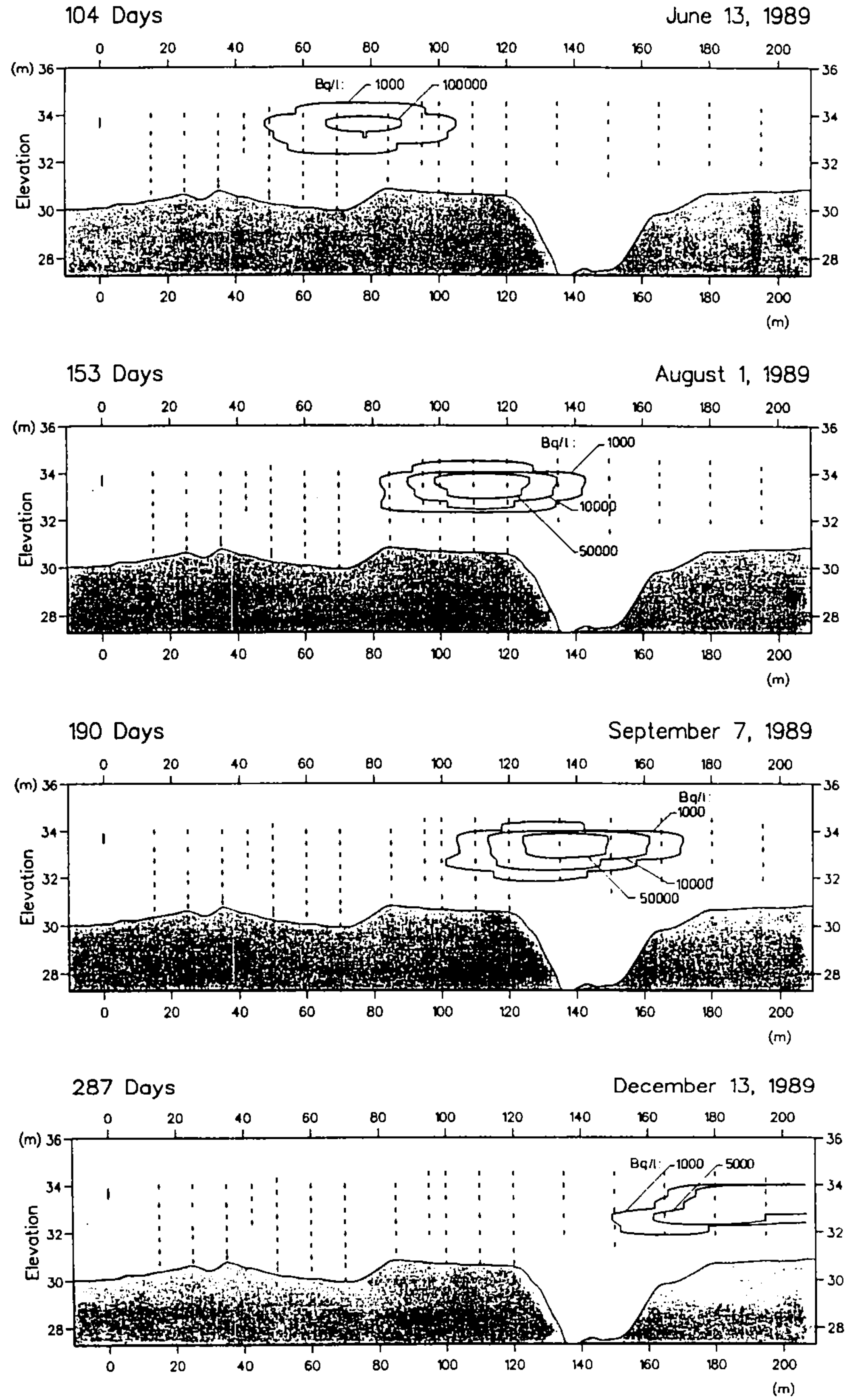

Figure 18. Simulated vertical distribution of tritium (homogeneous 3-layer model).

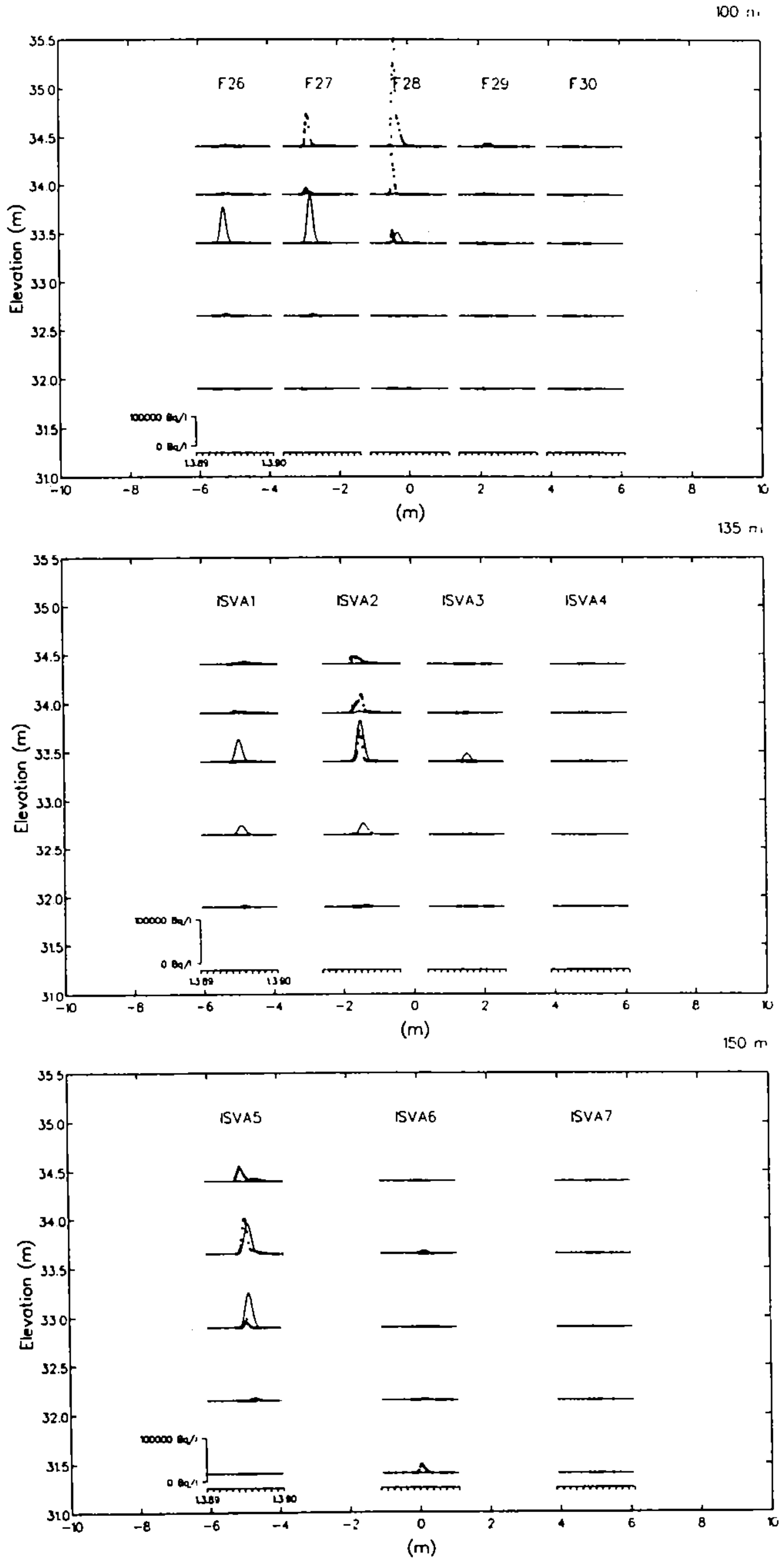

Figure 19. Observed and simulated breakthrough curves of tritium (homogeneous 3-layer model).

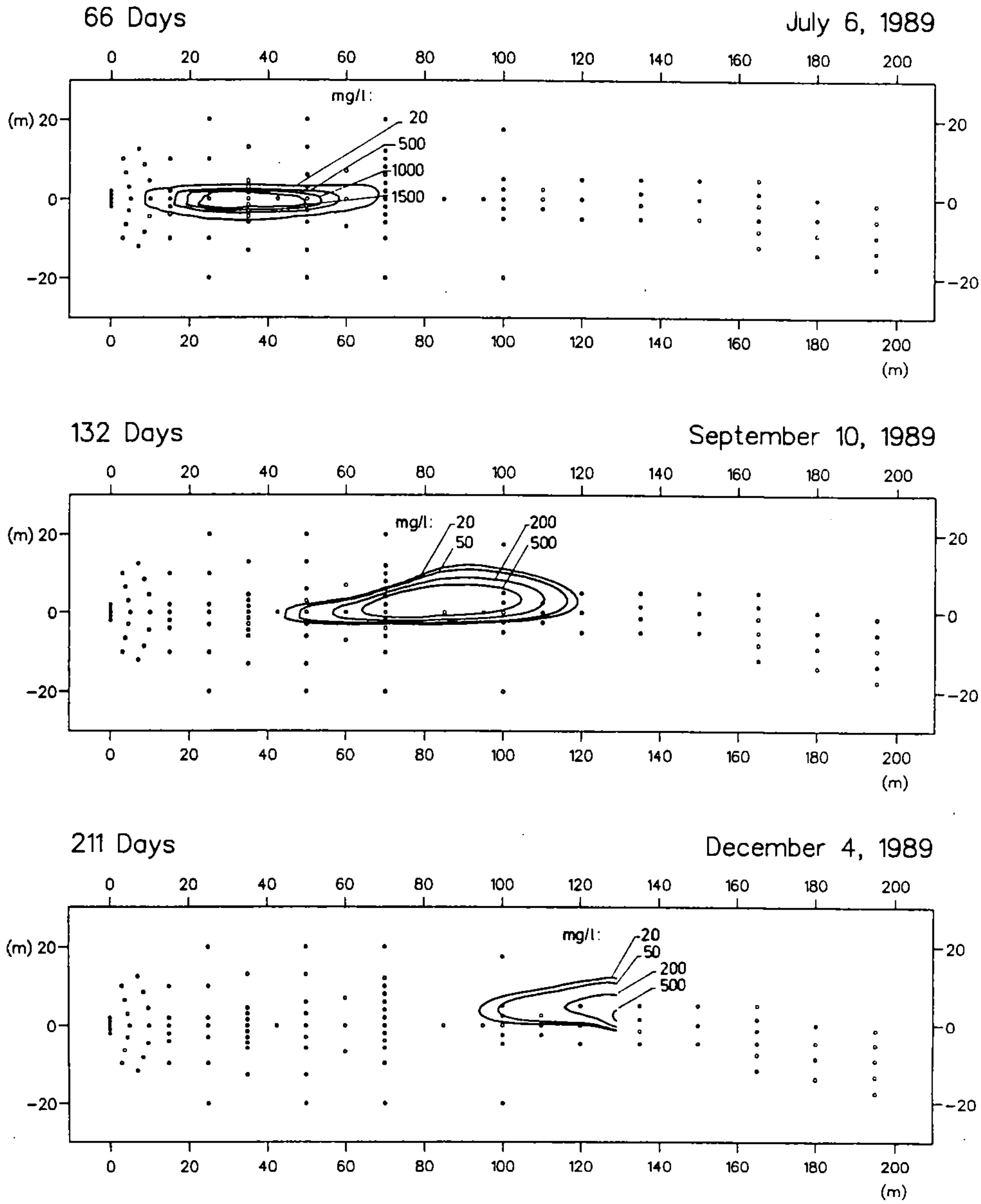

Figure 20 Simulated horizontal distribution of vertically integrated chloride concentrations (homogeneous 3-layer model).

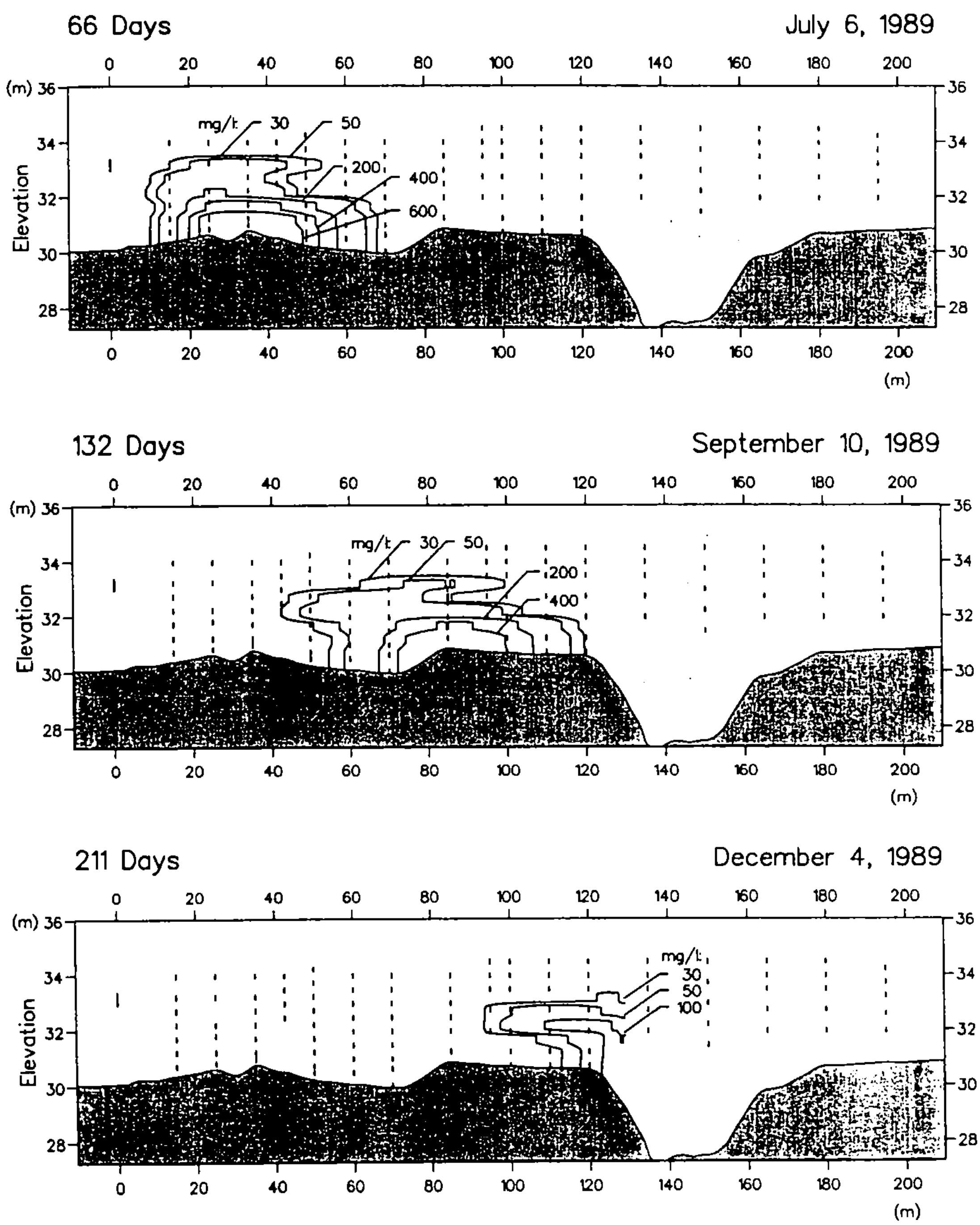

Figure 21 Simulated vertical distribution of chloride (homogeneous 3-layer model).

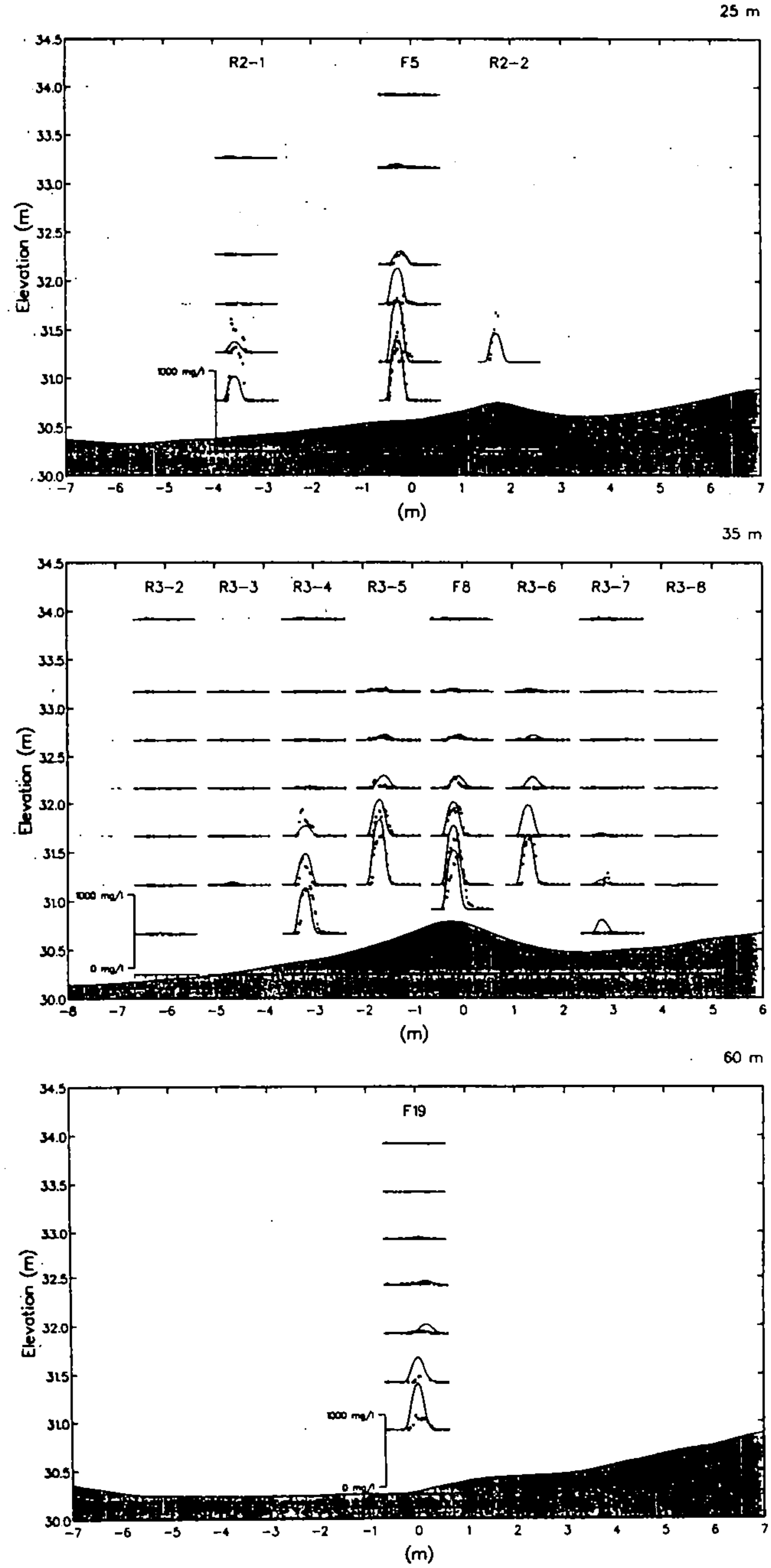

Figure 22 Observed and simulated breakthrough curves of chloride (homogenous 3-layer model).

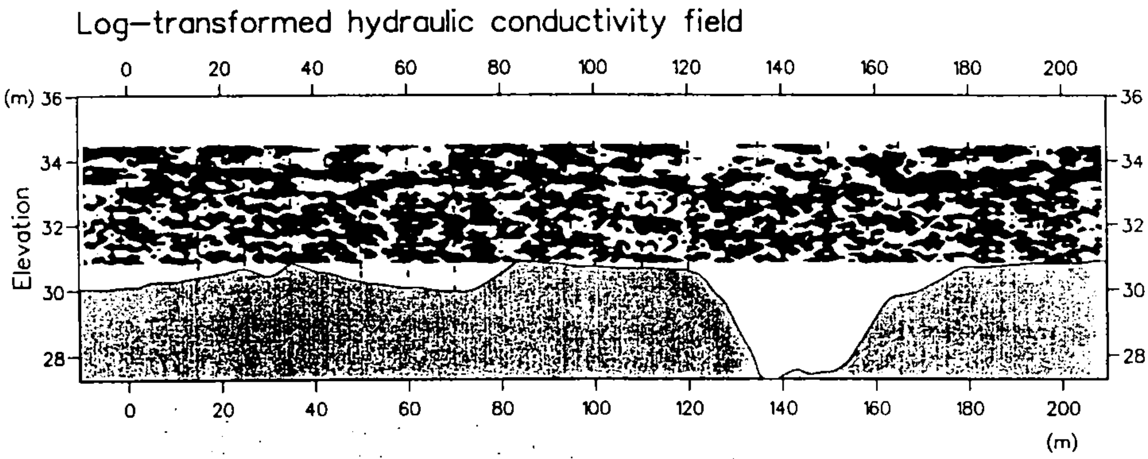

Figure 23 Generated hydraulic conductivity field (black: lnK above mean, white: lnK below mean).

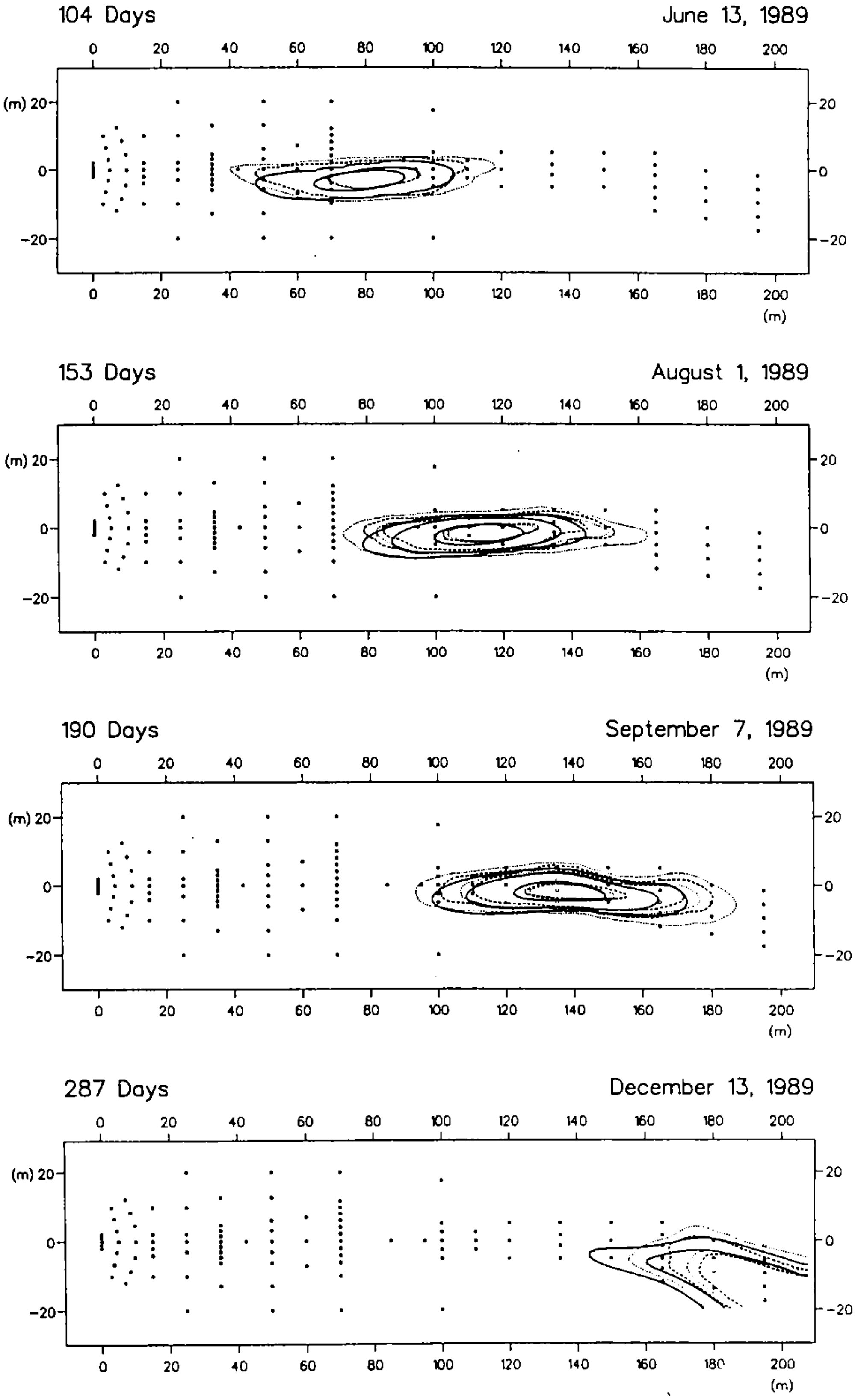

Figure 24 Simulated horizontal distribution of vertically integrated tritium concentrations.

———	Homogeneous 3-layer model	(α_{LH} = 0.45 m)
....	Heterogeneous 3-layer model	(α_{LH} = 0.45 m)
----	Heterogeneous 3-layer model	(α_{LH} = 0.10 m)

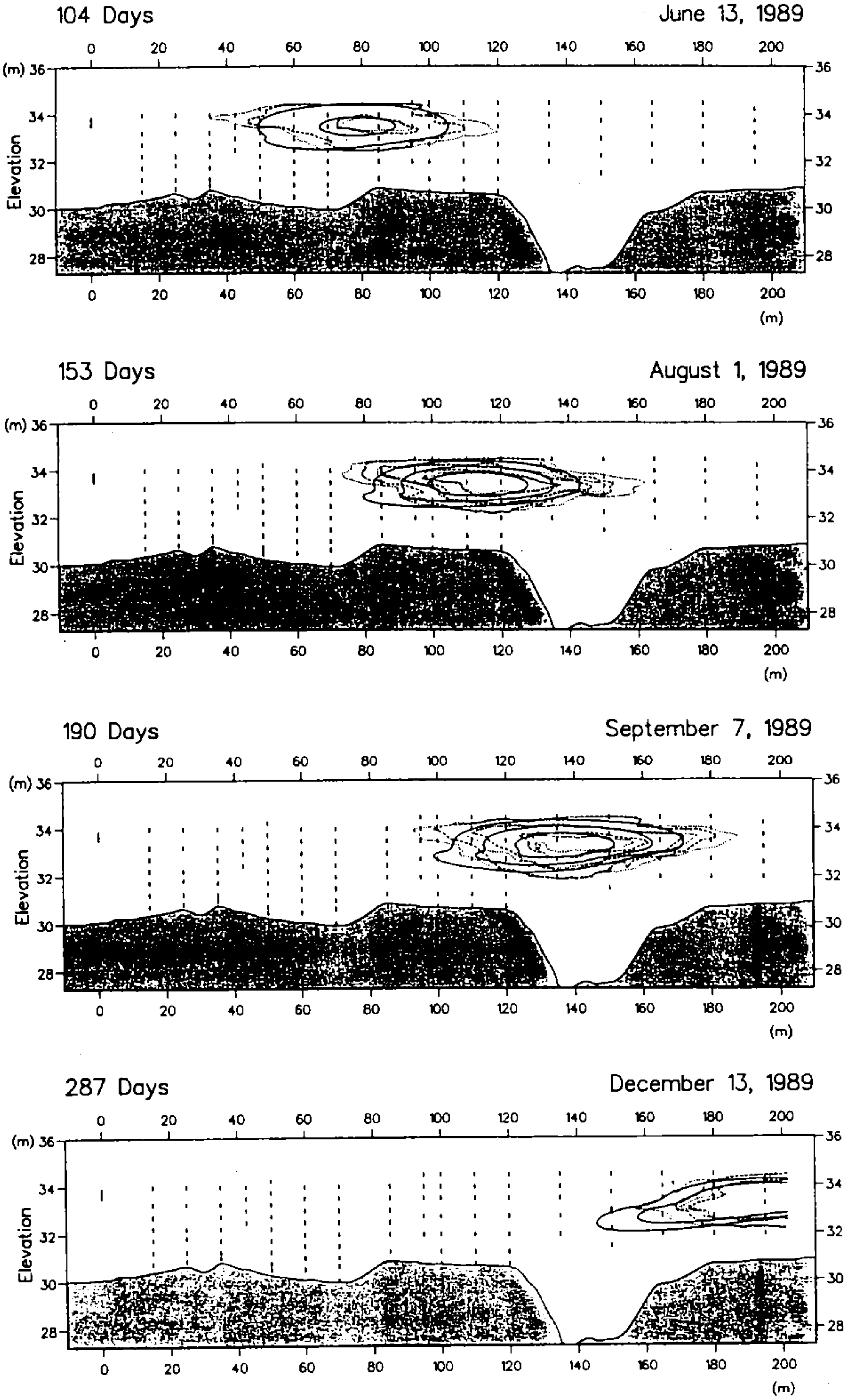

Figure 25 Simulated vertical distribution of tritium.

———	Homogeneous 3-layer model	(α_{LH} = 0.45 m)
....	Heterogeneous 3-layer model	(α_{LH} = 0.45 m)
----	Heterogeneous 3-layer model	(α_{LH} = 0.10 m)

UDGIVNE RAPPORTER

I forbindelse med LOSSEPLADSPROJEKTET er der med denne rapport ialt udgivet følgende rapporter:

HYDROGEOLOGI

EN REGIONAL GEOLOGISK MODEL FOR OMRÅDET VED VEJEN, Institut for Teknisk Geologi, DTH (Rapport HO-1, 20 sider), december 1987. ISBN 87-503-7079-0.

SEVA: PC-DATABASE FOR GEOLOGI, HYDROLOGI OG VANDKVALITET, Institut for Teknisk Geologi, DTH (Rapport HO-2, 46 sider), december 1990, ISBN 87-503-8915-7.

UNDERSØGELSER VED VEJEN LOSSEPLADS: GEOLOGISK, HYDROGEOLOGISK, GEOKEMISK INTEGRATION, Danmarks Geologiske Undersøgelse (Rapport HO-3, 110 sider), december 1991, ISBN 87-503-9547-5.

UNDERSØGELSER VED VEJEN LOSSEPLADS: LAGFØLGEBORINGER, Geoteknisk Institut (Rapport H1, 122 sider), juli 1990, ISBN 87-503-8183-0.

VEJEN INJEKTIONSFORSØG: HYDROGEOLOGI, Laboratoriet for teknisk Hygiejne, Danmarks Geologiske Undersøgelse m. fl. (Rapport H2, 168 sider), juni 1991, ISBN 87-503-9211-5.

UNDERSØGELSER VED VEJEN LOSSEPLADS: RESERVOIRFORHOLD OG FORURENINGSUDBREDELSE BESTEMT VED BOTESAM-METODEN, Danmarks Geologiske Undersøgelse (Rapport H5, 125 sider), oktober 1990, ISBN 87-503-8736-7.

UNDERSØGELSER VED VEJEN LOSSEPLADS: POTENTIALEFORHOLD, Geoteknisk Institut (Rapport H6, 121 sider), maj 1991, ISBN 87-503-9110-0.

BOTESAM OG SNEGLEBORING: SAMMENLIGNENDE UNDERSØGELSER, Laboratoriet for Geofysik (Århus Universitet), Danmarks Geologiske Undersøgelse og Lossepladsprojektets sekretariat (Rapport H7, 47 sider), oktober 1991, ISBN 87-503-9352-9.

EVALUERING OG UDVIKLING AF METODER TIL PRØVETAGNING OG FELTANALYSE AF ANOXISK GRUNDVAND, Institut for Teknisk Geologi, DTH (Rapport H8, 82 sider), oktober 1990, ISBN 87-503-8738-3.

HYDRAULIK OG STOFTRANSPORT I EN OPSPRÆKKET KALKBJERGART, Danmarks Geologiske Undersøgelse (Rapport H9, 70 sider), maj 1991, ISBN 87-503-9137-2.

UNDERSØGELSER VED VEJEN LOSSEPLADS: GEOLOGISKE FORHOLD,Danmarks Geologiske Undersøgelse (Rapport H10, 100 sider), december 1989, ISBN 87-503-8182-2.

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