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Floodplain Analysis by Two-Dimensional Model

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Floodplain Analysis by Two-Dimensional Model

by

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Synopsis :

By means of a two-dimensional unsteady flow model, different floodplain conditions are investigated. Some basic, simplified planes are simulated with different values of the Manning's roughness coefficient, of the slopes and with the presence of banks and channels. A case of real floodplain has been analysed accounting for the presence of roads, railways, highways and drainage channels. The results show the influence that each structure exerts on the flow pattern and are useful in term of planning and for civil protection purposes.

Key words : Hydraulic model, unsteady flow, levee break, river flood, floodplain analysis.

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ABSTRACT

Floodplain analysis constitutes a complex problem due to the interaction between flow and structures present in the plain. In this study, by means of a two-dimensional unsteady flow model that implements the complete De Saint Venant equations, different conditions of inundated plain are analysed. The effect of the Manning's roughness coefficient change, of mesh size, of the presence of banks, channels and culverts are studied in the case of a simple rectangular hypothetical plane. Numerical simulations for the case of an existing floodplain has also been done in order to achieve a better understanding of the dynamic of the flow in presence of more realistic conditions.

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FLOODPLAIN ANALYSIS BY TWO-DIMENSIONAL MODEL

1. INTRODUCTION

"Flooding of urban land is a frequent, natural or manmade disaster in large or small scale" (Yen, 1995). Floodplain analysis is needed in many practical situations, mainly because is in lowlands that human activities are concentrated. The study of the inundated plain requires at the same time quite of effort in terms of modelling, computational resources and data acquisition. The need for a two-dimensional model and the presence of a great number of different structures in the inundated zone make the problem complex. The effect of the plain topography, the presence of irrigation and/or natural channels, of roads, highways, railways, low dikes and culverts affect the pattern of the flooding flow and can change it considerably.

Aim of this work is the analysis of inundated plains for different conditions in very basic situations and further numerical simulations in case of a real floodplain.

The second chapter gives a brief overview about the used numerical model. The third chapter describes numerical simulations carried out to account for different value of the parameters involved in the simulation with different type of structures present in the inundated plane. Finally, in the fourth chapter, an existent floodplain will be analysed, trying to decompose the real situation in many elementary ones in order to achieve a better understanding about the effect that each single structure has on the flooding flow pattern.

2. DESCRIPTION OF THE MODEL

The model used for the simulation has been developed at the Public Works Research Institute (Yoshimoto et Al. 1992).

In order to simulate the flow in the floodplain, the model uses the fully dynamic two-dimensional unsteady flow equations consisting of:

continuity equation,

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \quad \dots\dots\dots(2.1)$$

dynamic equation in the x-direction, .

$$\frac{\partial M}{\partial t} + \frac{\partial(uM)}{\partial x} + \frac{\partial(vM)}{\partial y} + gh \frac{\partial H}{\partial x} + \frac{1}{\rho} \tau_x = 0 \quad \dots\dots\dots(2.2)$$

and a dynamic equation in the y-direction,

$$\frac{\partial N}{\partial t} + \frac{\partial(uN)}{\partial x} + \frac{\partial(vN)}{\partial y} + gh \frac{\partial H}{\partial y} + \frac{1}{\rho} \tau_y = 0 \quad \dots\dots\dots(2.3)$$

with:

$$\tau_x = \frac{\rho g n^2 u \sqrt{u^2 + v^2}}{h^{1/3}} \quad \dots\dots\dots(2.4)$$

$$\tau_y = \frac{\rho g n^2 v \sqrt{u^2 + v^2}}{h^{1/3}} \quad \dots\dots\dots(2.5)$$

where,

g = gravitational acceleration;

ρ = density of water;

$M = u \cdot h$ = flux (flow rate per unit width) in the x-direction;

$N = v \cdot h$ = flux in the y-direction;

h = water depth;

H = water surface elevation;

x, y = spatial coordinates;

t = temporal coordinate;

τ_x = shear stress at the bottom in the x-direction

τ_y = shear stress at the bottom in the y-direction

The numerical method used to solve the system of partial differential equations 2.1-2.3 uses an explicit staggered finite difference scheme (Iwasa et. Al. 1980).

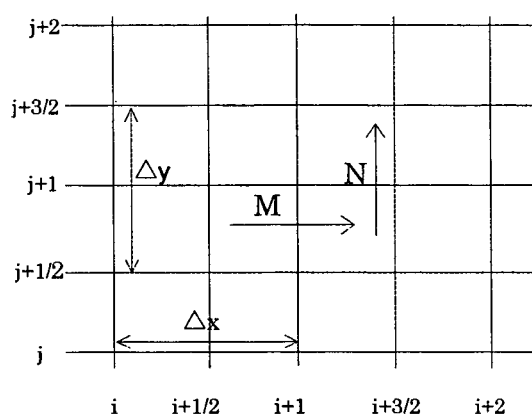


Fig.2.1 Discretization scheme (arrows indicate the positive versus of the fluxes N and M)

With reference to Fig.2.1, equation 2.1 is discretized as follows

$$\frac{h_{i+1/2,j+1/2}^{n+3} - h_{i+1/2,j+1/2}^{n+1}}{2\Delta t} + \frac{M_{i+1,j+1/2}^{n+2} - M_{i,j+1/2}^{n+2}}{\Delta x} + \frac{N_{i+1/2,j+1}^{n+2} - N_{i+1/2,j}^{n+2}}{\Delta y} = 0 \quad \dots\dots\dots(2.6)$$

terms in eq. 2.2 are:

$$a) \quad \frac{\partial M}{\partial t} = \frac{M_{i,j+1/2}^{n+2} - M_{i,j+1/2}^n}{2\Delta t} \quad \dots\dots\dots(2.7)$$

$$b) \quad \frac{\partial(uM)}{\partial x} = \frac{1}{\Delta x} \left(\frac{1}{h_{i+1/2,j+1/2}^{n+1}} \left(\frac{M_{i+1,j+1/2}^n + M_{i,j+1/2}^n}{2} \right)^2 - \frac{1}{h_{i-1/2,j+1/2}^{n+1}} \left(\frac{M_{i,j+1/2}^n + M_{i-1,j+1/2}^n}{2} \right)^2 \right) \dots\dots\dots(2.8)$$

$$c) \quad \frac{\partial(vM)}{\partial y} = \frac{1}{\Delta y} \left[\frac{(M_{i,j+1/2}^n + M_{i,j+3/2}^n)(N_{i+1/2,j+1}^n + N_{i-1/2,j+1}^n)}{h_{i-1/2,j+1/2}^{n+1} + h_{i+1/2,j+1/2}^{n+1} + h_{i=1/2,j+3/2}^{n+1} + h_{i-1/2,j+3/2}^{n+1}} - \frac{(M_{i,j+1/2}^n + M_{i,j-1/2}^n)(N_{i+1/2,j}^n + N_{i-1/2,j}^n)}{h_{i-1/2,j-1/2}^{n+1} + h_{i+1/2,j-1/2}^{n+1} + h_{i+1/2,j+1/2}^{n+1} + h_{i-1/2,j+1/2}^{n+1}} \right] \dots\dots\dots(2.9)$$

$$d) \quad gh \frac{\partial H}{\partial x} = g \cdot \left(\frac{h_{i+1/2,j+1/2}^{n+1} + h_{i-1/2,j+1/2}^{n+1}}{2} \right) \cdot \left(\frac{H_{i+1/2,j+1/2}^{n+1} - H_{i-1/2,j+1/2}^{n+1}}{\Delta x} \right) \dots\dots\dots(2.10)$$

$$e) \quad \frac{1}{\rho} \tau_x = \frac{gn_{i,j+1/2}^2 (\bar{u}_{i,j+1/2}) \sqrt{(u_{i,j+1/2}^n)^2 + (v_{i,j+1/2}^n)^2}}{\left((h_{i+1/2,j+1/2}^{n+1} + h_{i-1/2,j+1/2}^{n+1}) / 2 \right)^{1/3}} \dots\dots\dots(2.11)$$

For eq.2.3:

$$a') \quad \frac{\partial N}{\partial t} = \frac{N_{i+1/2,j}^{n+2} - N_{i+1/2,j}^n}{2\Delta t} \dots\dots\dots(2.12)$$

$$b') \quad \frac{\partial(uN)}{\partial x} = \frac{1}{\Delta x} \left[\frac{(M_{i+1,j+1/2}^n + M_{i+1,j-1/2}^n)(N_{i+1/2,j}^n + N_{i+3/2,j}^n)}{h_{i+1/2,j+1/2}^{n+1} + h_{i+1/2,j-1/2}^{n+1} + h_{i+3/2,j-1/2}^{n+1} + h_{i+3/2,j+1/2}^{n+1}} - \frac{(M_{i,j+1/2}^n + M_{i,j-1/2}^n)(N_{i-1/2,j}^n + N_{i+1/2,j}^n)}{h_{i-1/2,j+1/2}^{n+1} + h_{i-1/2,j-1/2}^{n+1} + h_{i+1/2,j-1/2}^{n+1} + h_{i+1/2,j+1/2}^{n+1}} \right] \dots\dots\dots(2.13)$$

$$c') \quad \frac{\partial(vN)}{\partial y} = \frac{1}{\Delta y} \left(\frac{1}{h_{i+1/2,j+1/2}^{n+1}} \left(\frac{N_{i+1/2,j}^n + N_{i+1/2,j+1}^n}{2} \right)^2 - \frac{1}{h_{i+1/2,j-1/2}^{n+1}} \left(\frac{N_{i+1/2,j-1}^n + N_{i+1/2,j}^n}{2} \right)^2 \right) \dots\dots\dots(2.14)$$

$$d') \quad gh \frac{\partial H}{\partial y} = g \cdot \left(\frac{h_{i+1/2,j+1/2}^{n+1} + h_{i+1/2,j-1/2}^{n+1}}{2} \right) \cdot \left(\frac{H_{i+1/2,j+1/2}^{n+1} - H_{i+1/2,j-1/2}^{n+1}}{\Delta y} \right) \dots\dots\dots(2.15)$$

$$e') \quad \frac{1}{\rho} \tau_y = \frac{gn_{i+1/2,j}^2 (\bar{v}_{i+1/2,j}) \sqrt{(u_{i+1/2,j}^n)^2 + (v_{i+1/2,j}^n)^2}}{\left((h_{i+1/2,j+1/2}^{n+1} + h_{i+1/2,j-1/2}^{n+1}) / 2 \right)^{1/3}} \dots\dots\dots(2.16)$$

where:

$$\bar{u}_{i,j+1/2} = \frac{(M_{i,j+1/2}^{n+2} + M_{i,j+1/2}^n) / 2}{(h_{i+1/2,j+1/2}^{n+1} + h_{i-1/2,j+1/2}^{n+1}) / 2}$$

$$\bar{v}_{i+1/2,j} = \frac{(N_{i+1/2,j}^{n+2} + N_{i+1/2,j}^n) / 2}{(h_{i+1/2,j+1/2}^{n+1} + h_{i+1/2,j-1/2}^{n+1}) / 2}$$

The calculation proceeds solving the equations 2.2 and 2.3 for the unknown M^{n+2} and N^{n+2} since the values M^n , N^n and h^{n+1} are given by the initial condition or are known from the previous time step. The values M^{n+2} and N^{n+2} are substituted in the continuity equations to find h^{n+3} . A new version of the model, changes the nonlinear terms in order to obtain a better stability of the scheme.

Two different types of boundary conditions are present in the model. The first one is that of a closed boundary in which is $M=N=0$; the second one is the case of an open boundary condition that can be a critical depth condition in case of sluice gate insertion in the boundary, or a relation that extract from the floodplain the arriving discharge like in the case of the presence of a pump station.

The front of the flow is treated such that if a water depth less than a prefixed value (e.g. 0.001m) occur, the fluxes are assumed to be zero.

Particular equations are used in case of a fall or step between two adjacent cells (Fig. 2.2).

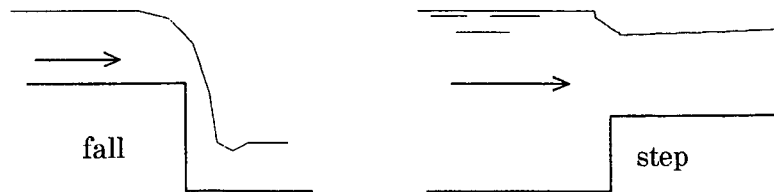


Fig.2.2 Fall or step between two adjacent cells

The flood routing in the river is achieved by using the complete De Saint-Venant equations:

$$\frac{1}{gA} \cdot \frac{\partial Q}{\partial t} + \frac{2Q}{gA^2} \frac{\partial Q}{\partial x} - \frac{Q^2}{gA^3} \frac{\partial A}{\partial x} + \frac{\partial H}{\partial x} + \frac{n^2 |Q| Q}{A^2 R^{4/3}} = 0$$

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q$$

where:

Q = discharge;

A = cross sectional area;

R = hydraulics radius;

H = water level.

q = lateral flow

The equations are solved numerically by means of an explicit finite difference scheme. The two necessary boundary conditions are supplied as a discharge hydrograph for the upstream end and a stage hydrograph for the downstream one.

The break in the river levee can be described by fixing the final width of the break, the velocity of breaking and the final level of the broken levee. The equation for the water over the break are the ones valid for a broad crested weir.

3. SIMULATION OF HYPOTHETICAL SIMPLIFIED FLOODPLAINS

In this chapter, a simple, hypothetical floodplain is considered. Many numerical simulations have been run in order to analyse this simple situation by changing in each series a particular variable. Different values of the roughness coefficient and of the longitudinal and transversal slope have been simulated; the presence of banks and channels has also been considered. Some simulations have been carried out to test the response of the model to different cells dimension.

3.1 EFFECT OF ROUGHNESS COEFFICIENT

Roughness coefficient is the only parameter that must be estimated in order to solve the equations for the hydraulic routing. The roughness value in a floodplain is determined by the microtopography and the presence of obstacles like buildings and vegetation. The program uses the Manning equation for the estimation of the friction slope.

Values for the Manning coefficient n in case of floodplain are given, for example, by Chow (1959); Chow, in the case of flood plain, divides the land in pasture, cultivated, brush and trees. The value of the roughness coefficient varies from 0.02 as minimum value for flood plain with pasture, no brush and short grass up to 0.20 for land with trees, dense willows. No values are given for the case of urbanized areas.

To account for the presence of building in urbanized areas, experiments have been carried out at PWRI (Kuriki et Al. 1996). The elaboration of the collected data are condensed in an equation in which the total roughness coefficient is function of the base roughness coefficient, the percent of building in the urbanized area and the water depth:

$$n^2 = n_0^2 + 0.02 \frac{\theta}{100 - \theta} h^{4/3} \dots\dots\dots(3.1.1)$$

where:

n = equivalent roughness coefficient;

θ = percent of building area ;

h = water depth;

n_0 = base roughness coefficient.

and where the coefficient 0.02 accounts for the drag coefficient relative to the buildings and represents a rough mean value that can be used for practical estimation.

The base roughness coefficient can be expressed, for each cell as:

$$n_o^2 = \frac{\sum_i n_i^2 A_i}{\sum_i A_i} \dots\dots\dots (3.1.2)$$

in which A_i and n_i are the different areas and roughness values present in the cell.

Fig. 3.1.1 and 3.1.2 show the behaviour of equation 3.1.1. In Fig. 3.1.1 is reported the value of n as a function of the urbanization value taking the depth of water h as parameter, while Fig.3.1.2 reports the value of n as a function of h with the percent of urbanization as parameter. The total roughness coefficient assumes the same value of the base roughness in case of no urbanization ($n_o=0.05$ in the specific case) and increase with the increase of both the urbanization ratio and the water depth. The experiments were carried out in the range $0<\theta<59\%$.

Numerical simulations have been carried out considering a single horizontal plane divided in a mesh of 90×100 cells in which each cell has a dimension of 25×25 m. A sketch of the plane is shown in Fig.3.1.3. The cells are numbered for rows starting from the top left side and ending on the bottom right corner.

The border cells of the mesh represent points of boundary conditions for the model; in those cells the general condition is that the flux must be zero except in particular case in which a pump or a sluice gate is present.

TABLE 3.1.1 Numerical simulations for series N

Run	n_o	θ (%)	S_y	S_x	Input hydrograph
N1	0.05	0	0.0	0.0	U
N2	0.10	0	0.0	0.0	U
N3	0.20	0	0.0	0.0	U
N4	0.05	25	0.0	0.0	U
N5	0.05	50	0.0	0.0	U
NT1	0.05	0	0.0	0.0	T
NT2	0.10	0	0.0	0.0	T
NT3	0.20	0	0.0	0.0	T
NT4	0.05	25	0.0	0.0	T
NT5	0.05	50	0.0	0.0	T

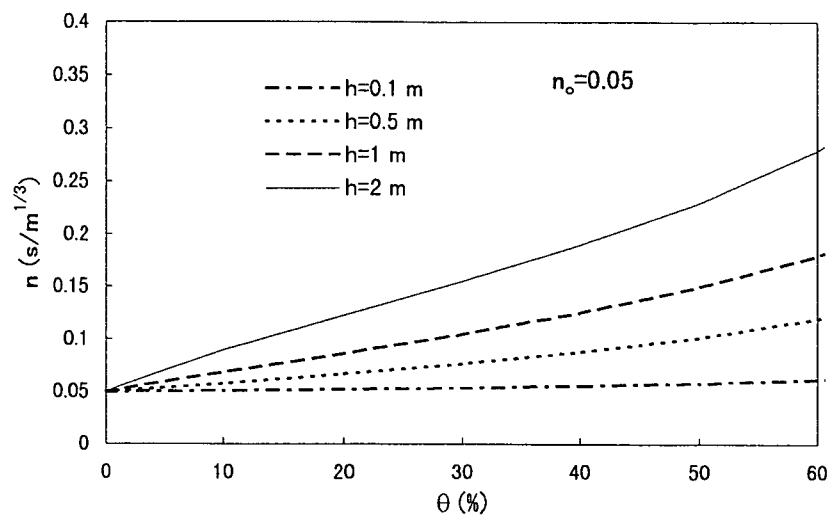


Fig. 3.1.1 Total roughness coefficient as a function of urbanization

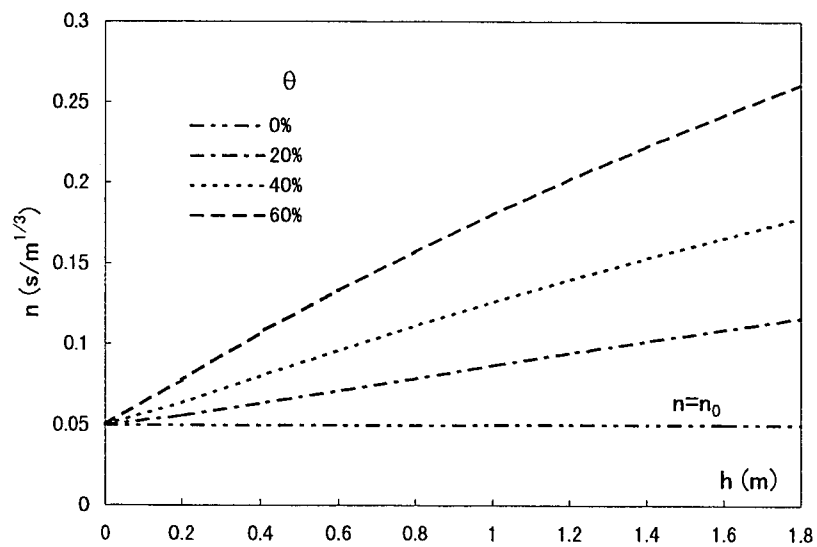


Fig. 3.1.2 Total roughness coefficient as a function of water depth

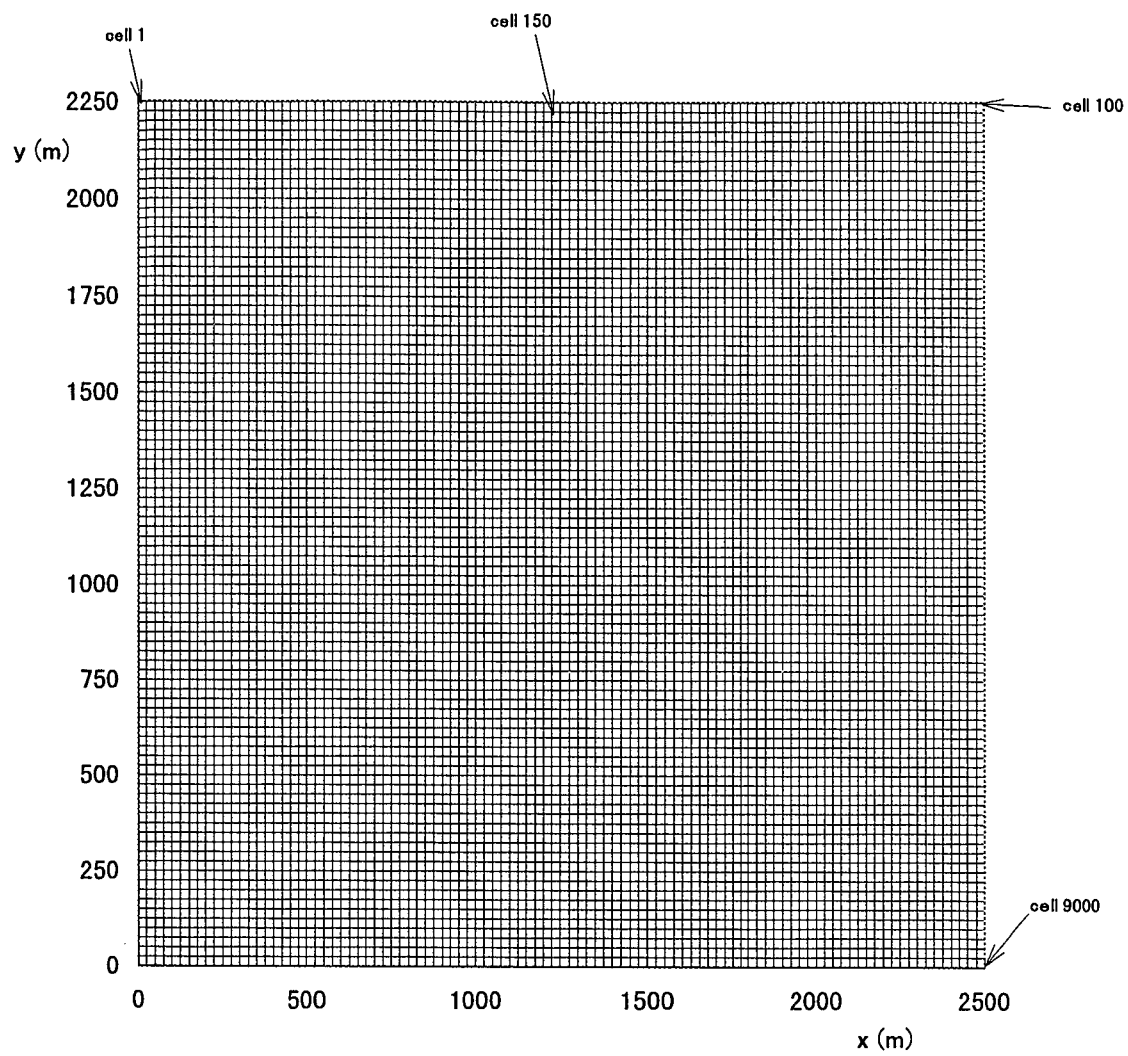


Fig.3.1.3 Mesh used in the numerical simulations

Ten runs have been simulated in order to highlight the differences due to the change of the base roughness coefficient and the presence of urbanization. The series of simulations is shown in Table 3.1.1

There are two sub-series of five runs that differ only for the input hydrograph that in the first case is a uniform (U) one while in the second case is of triangular (T) shape (Fig.3.1.4).

The uniform hydrograph has a constant discharge of $100 \text{ m}^3/\text{s}$ while the triangular one is symmetric with a peak flow value of $400 \text{ m}^3/\text{s}$ and a total duration of 40 minutes.

The hydrograph is inserted in the cell n.150 of the mesh, that is in a symmetrical position with respect to the x-axis.

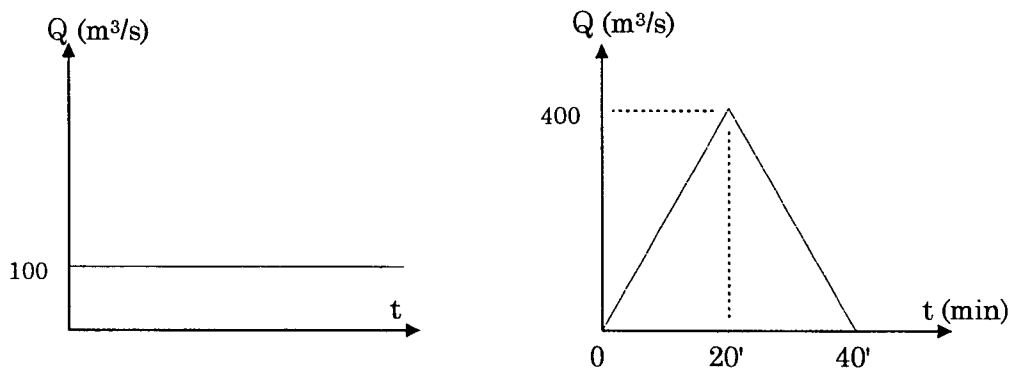


Fig.3.1.4 Uniform and triangular Input hydrograph

The time step for the calculation was set equal to 2 seconds, necessary for the stability of the explicit scheme used. The results are printed out with time step of 20 minutes.

The plots relative to the simulations N1 to N5 are shown in Figg. 3.1.5-3.1.19. For each simulation are reported contour plots, surface plots in which is shown the water depth in a tridimensional view and vector plots that show the flux (m^2/s) from each cell of the mesh. All the graphs of this series are relative to time value equal to $t = 20'$, 1 hour, $1^{\text{h}}40'$ and 2 hours. For all the calculations, the error in the continuity was in the order of 5%.

Fig.3.1.20 shows, selected points for which a graph of depth as a function of time is reported. In the figure, points I and I' are immission cells and the point with an apex are relative to the runs for which the immission cell was the cell number 130. Tab. 3.1.2 describes the location of the points.

Tab.3.1.2 Selected points of the mesh

Point	Cell No.	Point	Cell No.
A	350 (immission point)	E'	4010
A'	330 (immission point)	F	4050
B	2030	F'	4030
B'	2010	G	4070
C	2050	G'	4050
C'	2030	H	7050
D	2070	H'	7030
E	4030		

Fig. 3.1.21 shows the water depth as a function of time for the points reported in Fig. 3.1.20. In this case, the graphs tend to an horizontal limit, due to the fact that the input hydrograph is uniform. The depth is higher for lower values of the roughness coefficient due to the lower velocity connected with the increase of the roughness in the floodplain.

Some graphs of comparison are reported in Fig.3.1.22; the figure shows, for $t=1$ hour and $t=2$ hours, the front of the flow relative to the different simulations. The front is, of course, advanced when the roughness coefficient is low (run N1) and retarded when it is high (run N3). In case of presence of urbanized area, the total roughness coefficient varies according to the depth of water and the degree of urbanization.

Fig. 3.1.23 to 3.1.37 show the results in the case of triangular input hydrograph by means of the same type of graphs described for the case of uniform input hydrograph. Fig.3.1.38 reports the behaviour of the water depth as a function of time in selected cells. It can be distinguished a rising part and a decreasing one connected with the shape of the input hydrograph.

In Fig.3.1.39 is reported the variation of the roughness coefficient (according to eq. 3.1.1) for the point A of the run number N5T (in which the value of urbanization is equal to 50 %); during the flood, the total roughness coefficient increases from the base value of 0.05 to a peak value of about 0.25 connected with a water depth of about 2 meter and than decreases again with the decreasing of the water level.

Finally Fig.3.1.40 shows a comparison for time values equal to $t=1$ and 2 hours. The behaviour is, in this case, similar to the one shown for the case of uniform hydrograph.

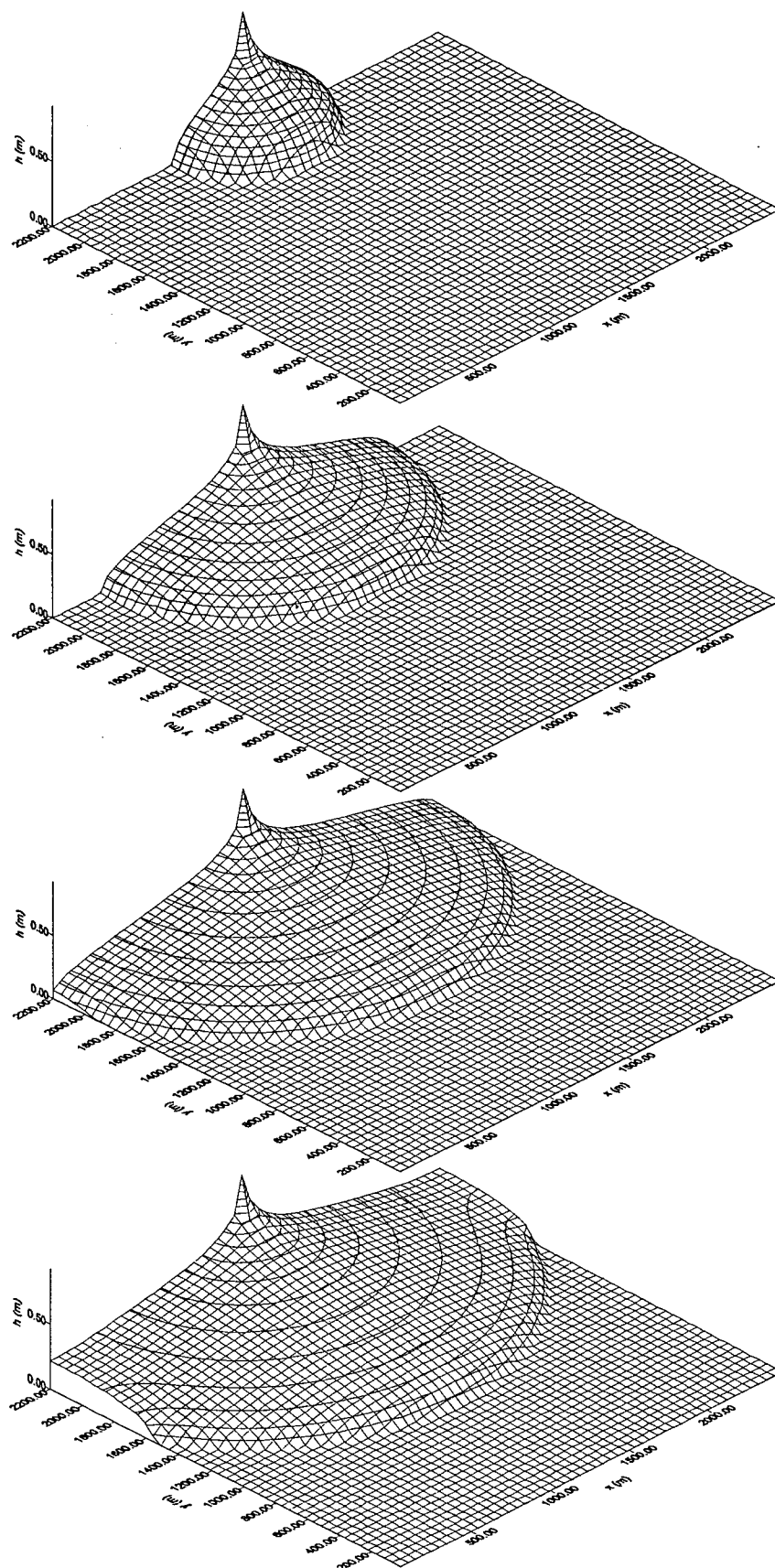


Fig.3.1.5 Surface plot for run N1. From top to bottom: $t=20'$, $t=1$ hour, $t=1\text{h}40'$ and $t=2$ hours (x , y and z scale in meters).

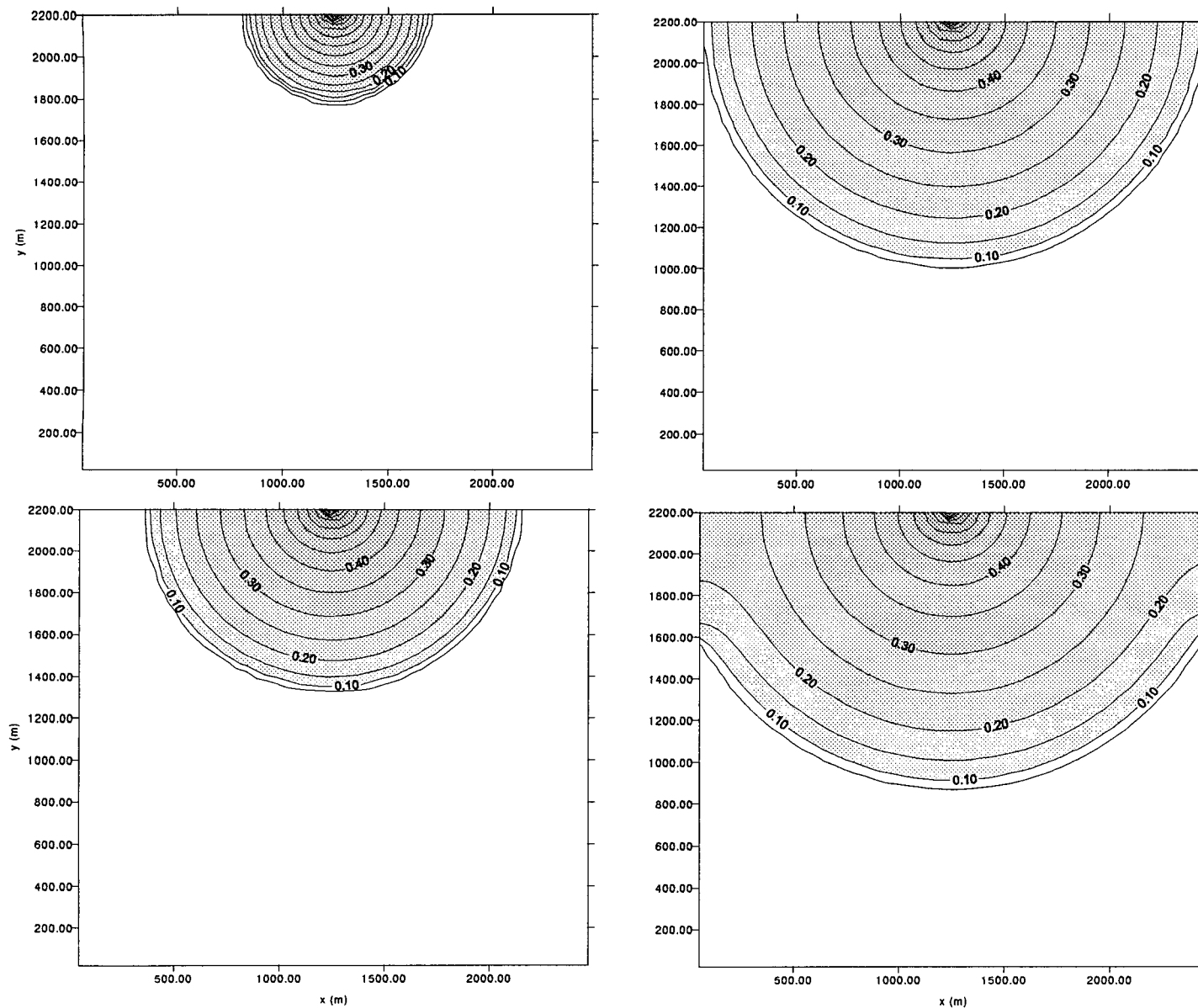


Fig.3.1.6 Contour plot for run N1. On the left: top $t=20'$, bottom $t=1$ hour; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

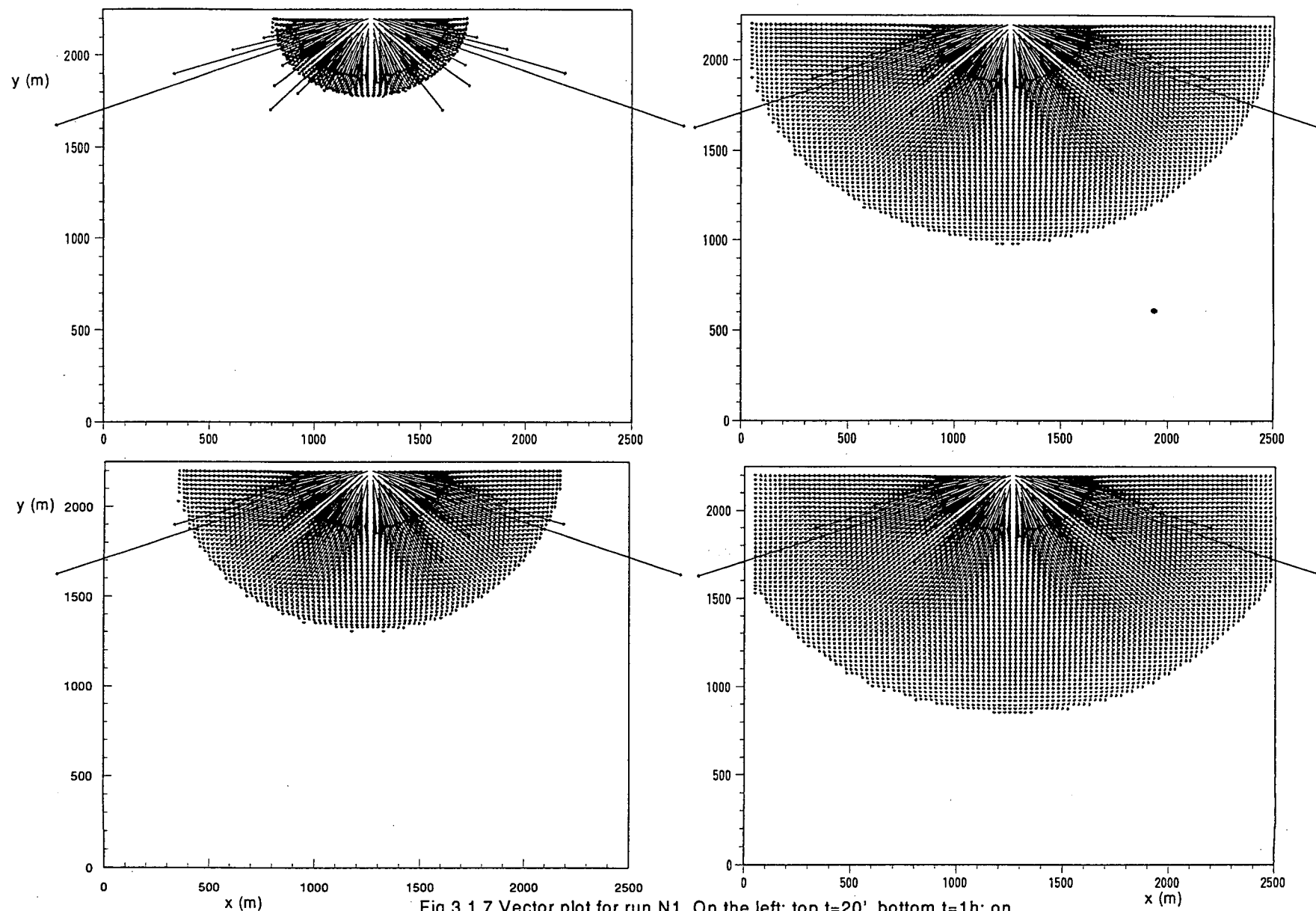


Fig.3.1.7 Vector plot for run N1. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 1000 times the plot unit.

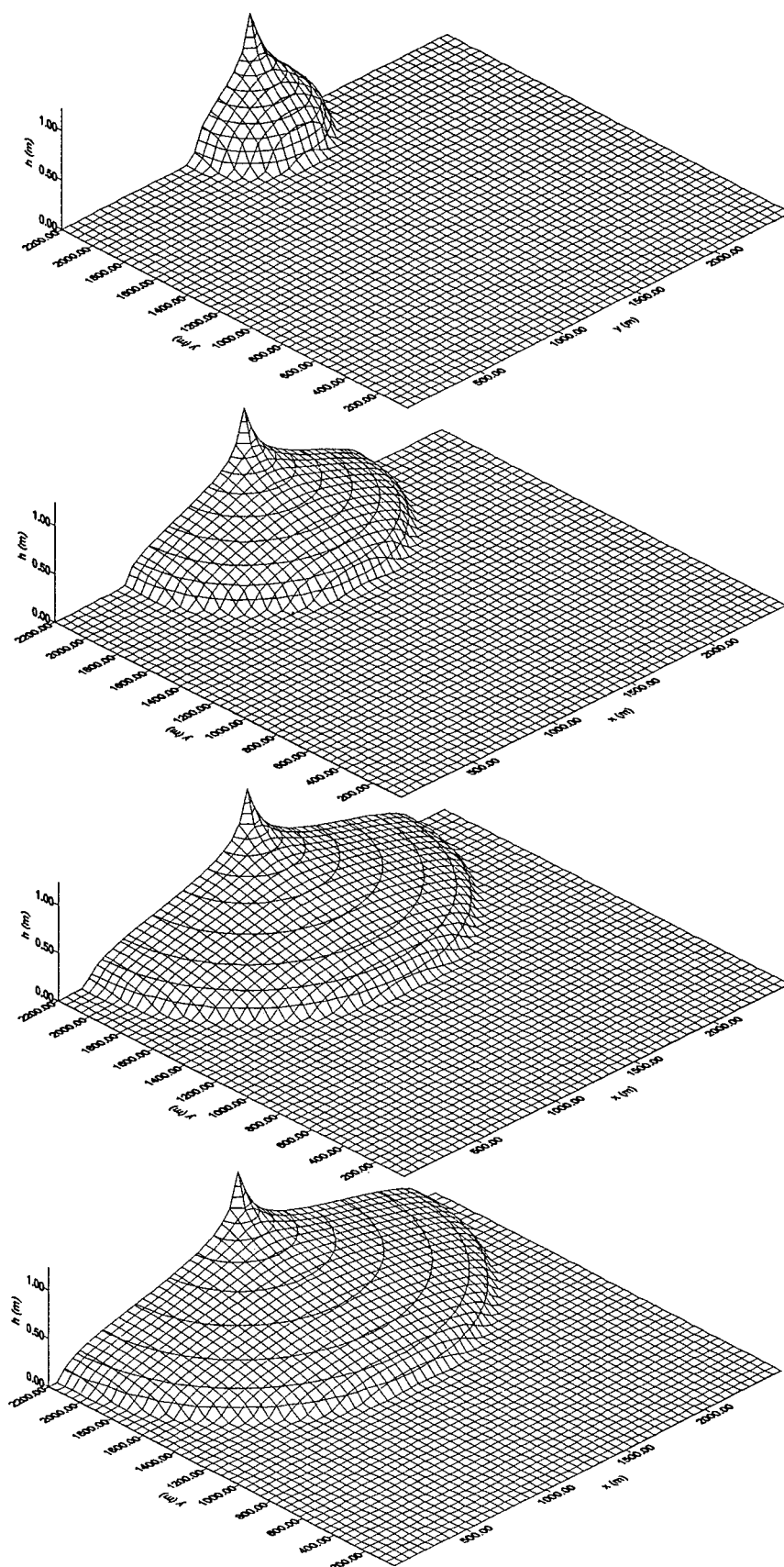


Fig.3.1.8 Surface plot for run N2. From top to bottom: $t=20'$, $t=1$ hour, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

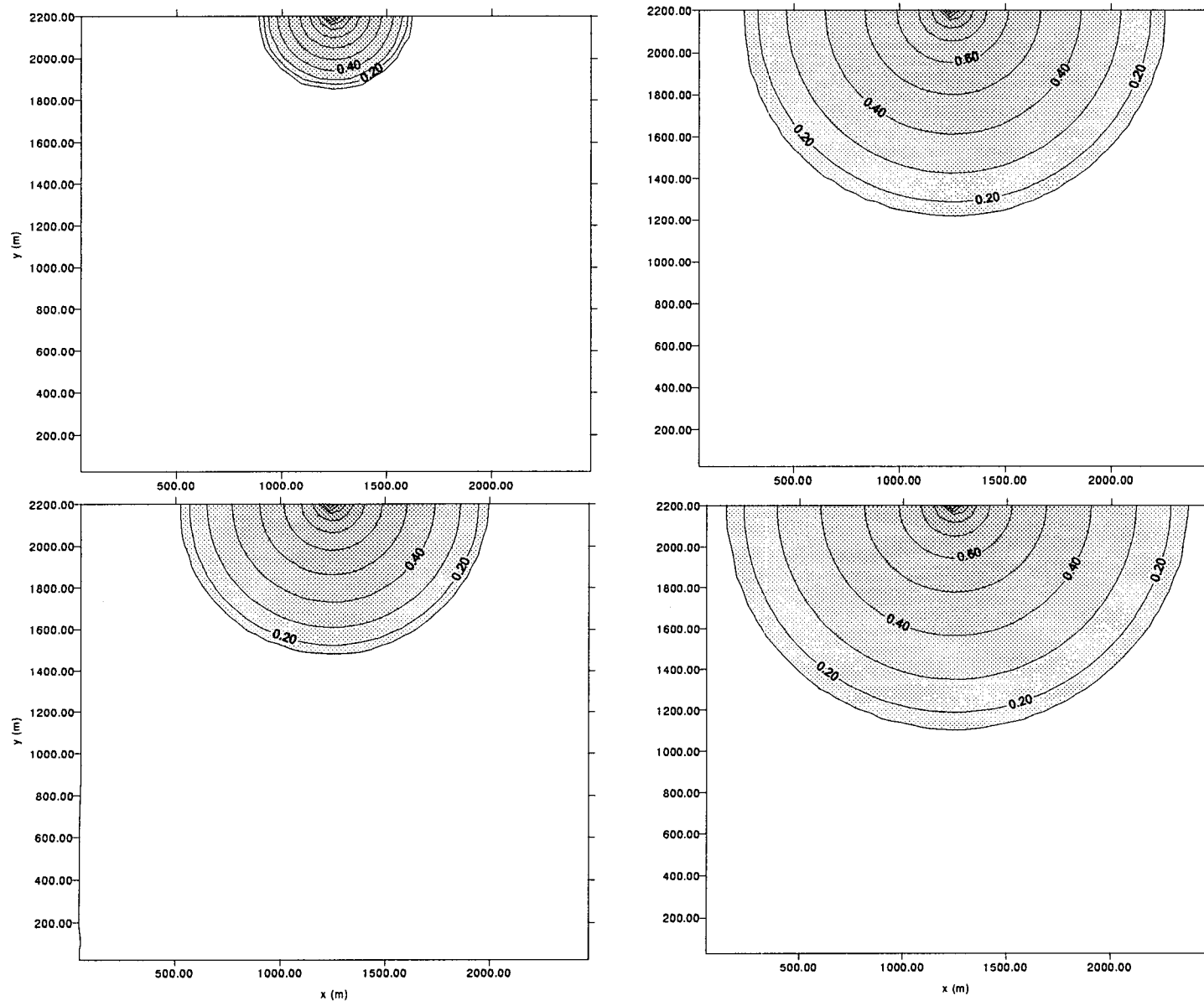


Fig.3.1.9 Contour plot for run N2. On the left: top $t=20'$, bottom $t=1$ hour; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

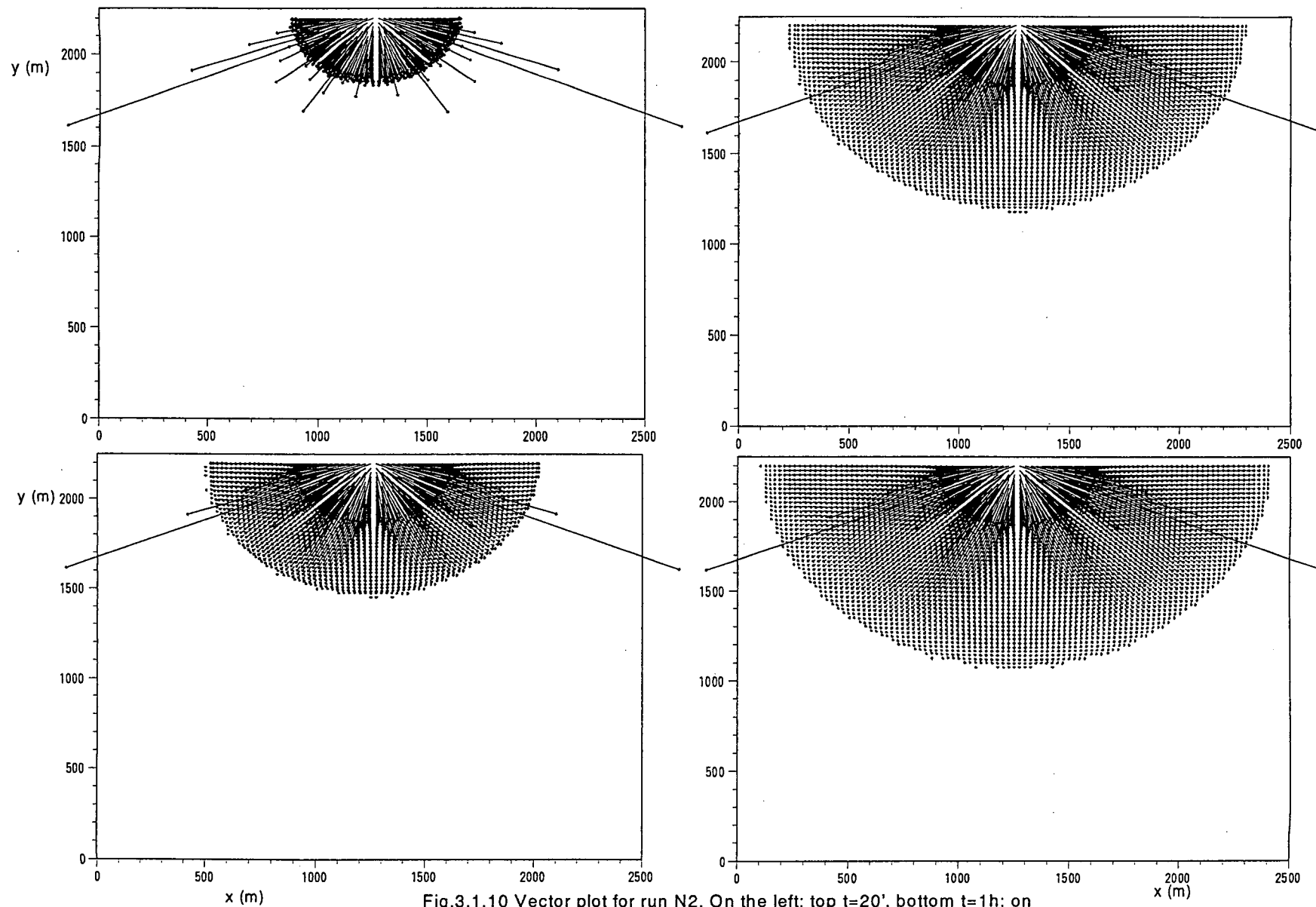


Fig.3.1.10 Vector plot for run N2. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 1000 times the plot unit.

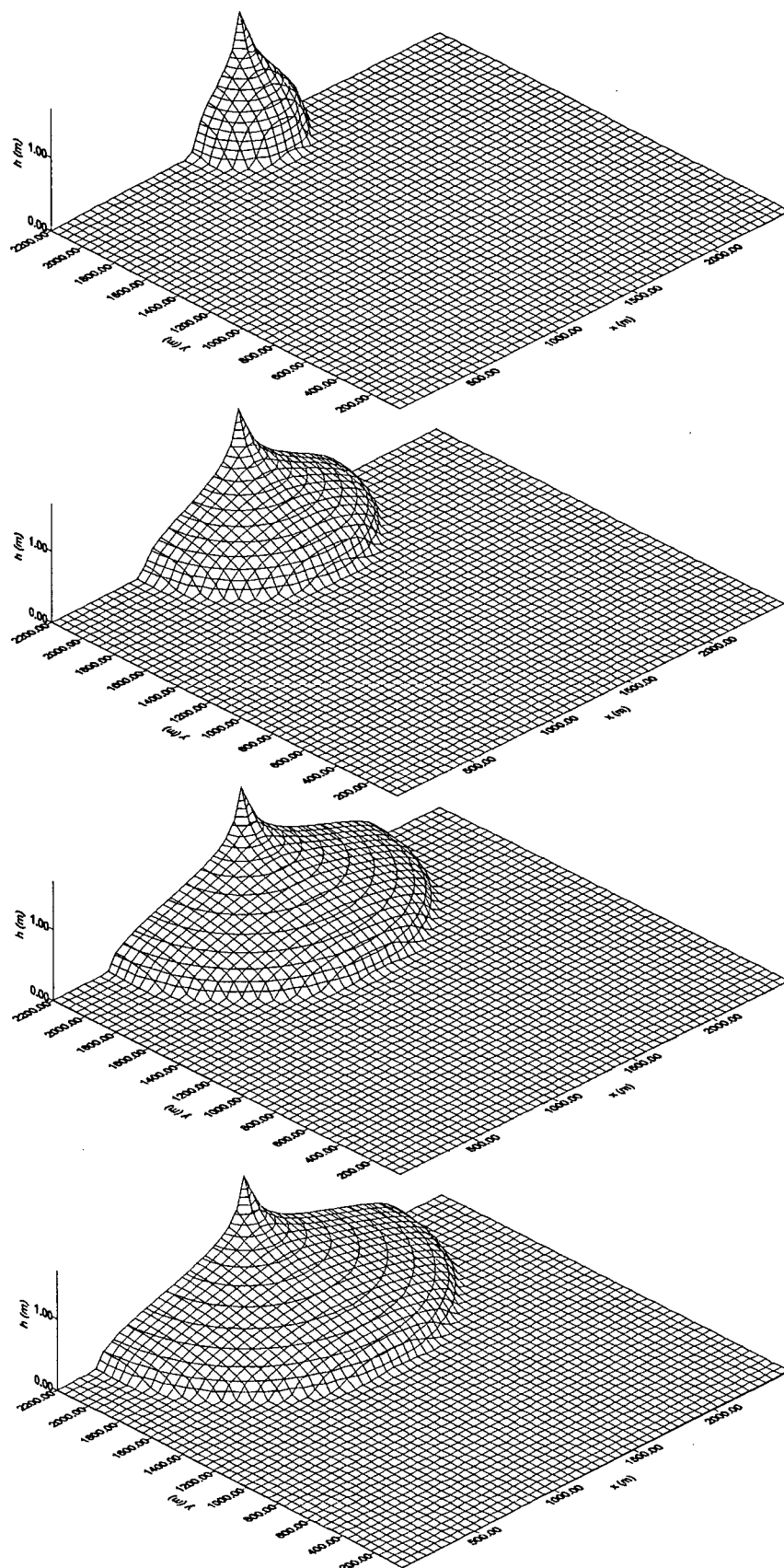


Fig.3.1.11 Surface plot for run N3. From top to bottom: $t=20'$, $t=1 \text{ hour}$, $t=1\text{h}40'$ and $t=2 \text{ hours}$ (x , y and z scale in meters).

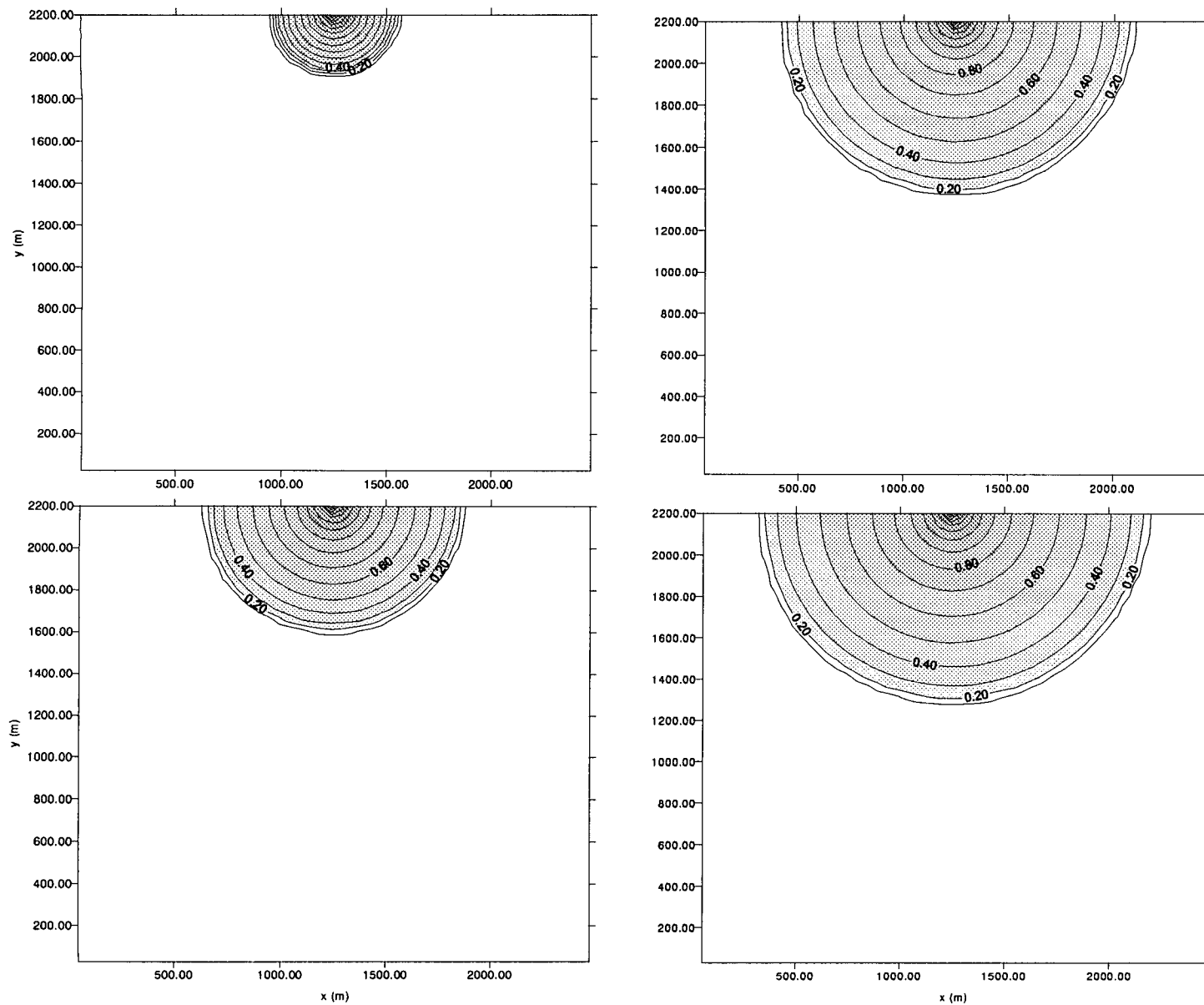


Fig.3.1.12 Contour plot for run N3. On the left: top $t=20'$, bottom $t=1\text{ hour}$; on the right: top $t=1\text{h}40'$, bottom $t=2\text{ hours}$ (scale in meter).

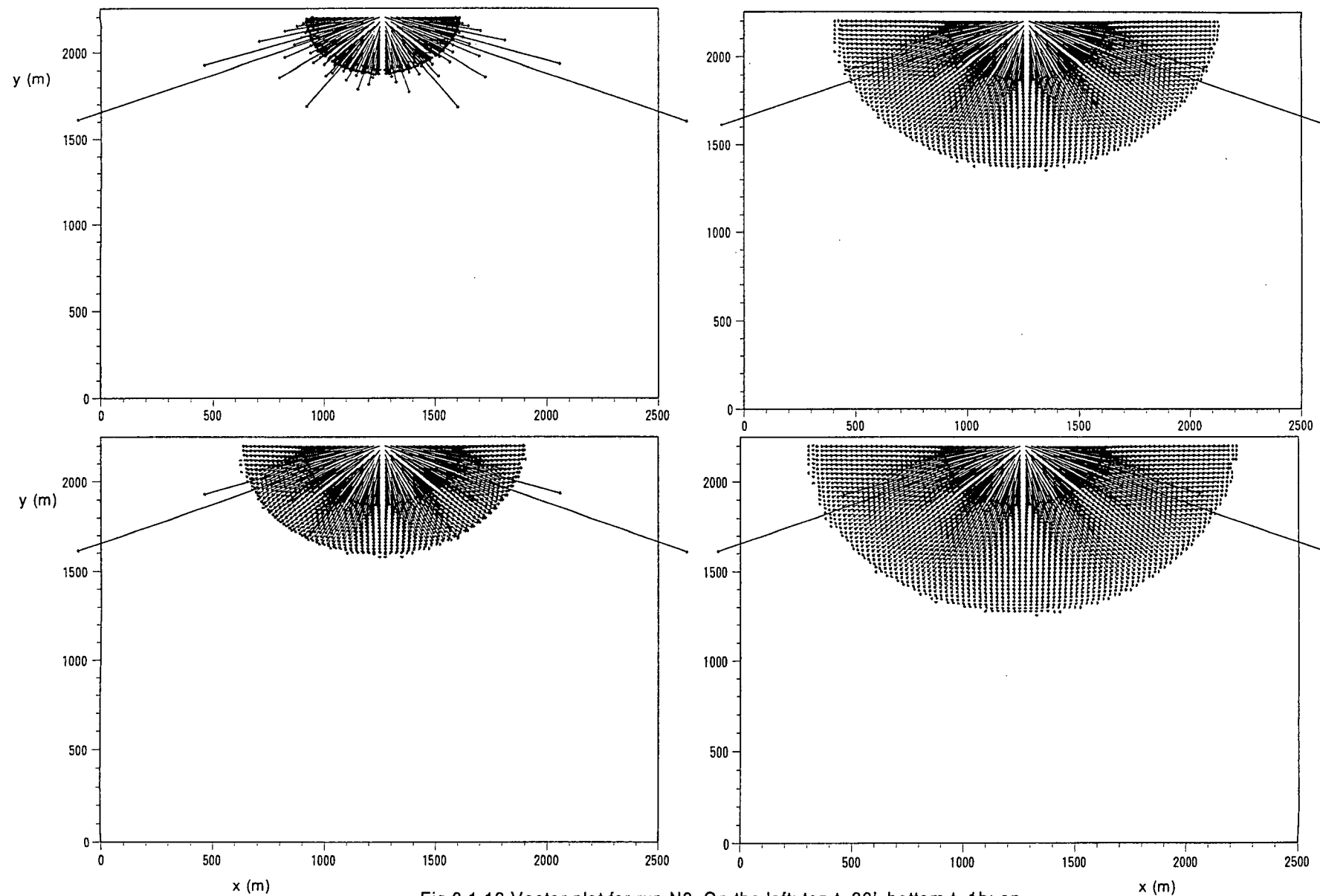


Fig.3.1.13 Vector plot for run N3. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 1000 times the plot unit.

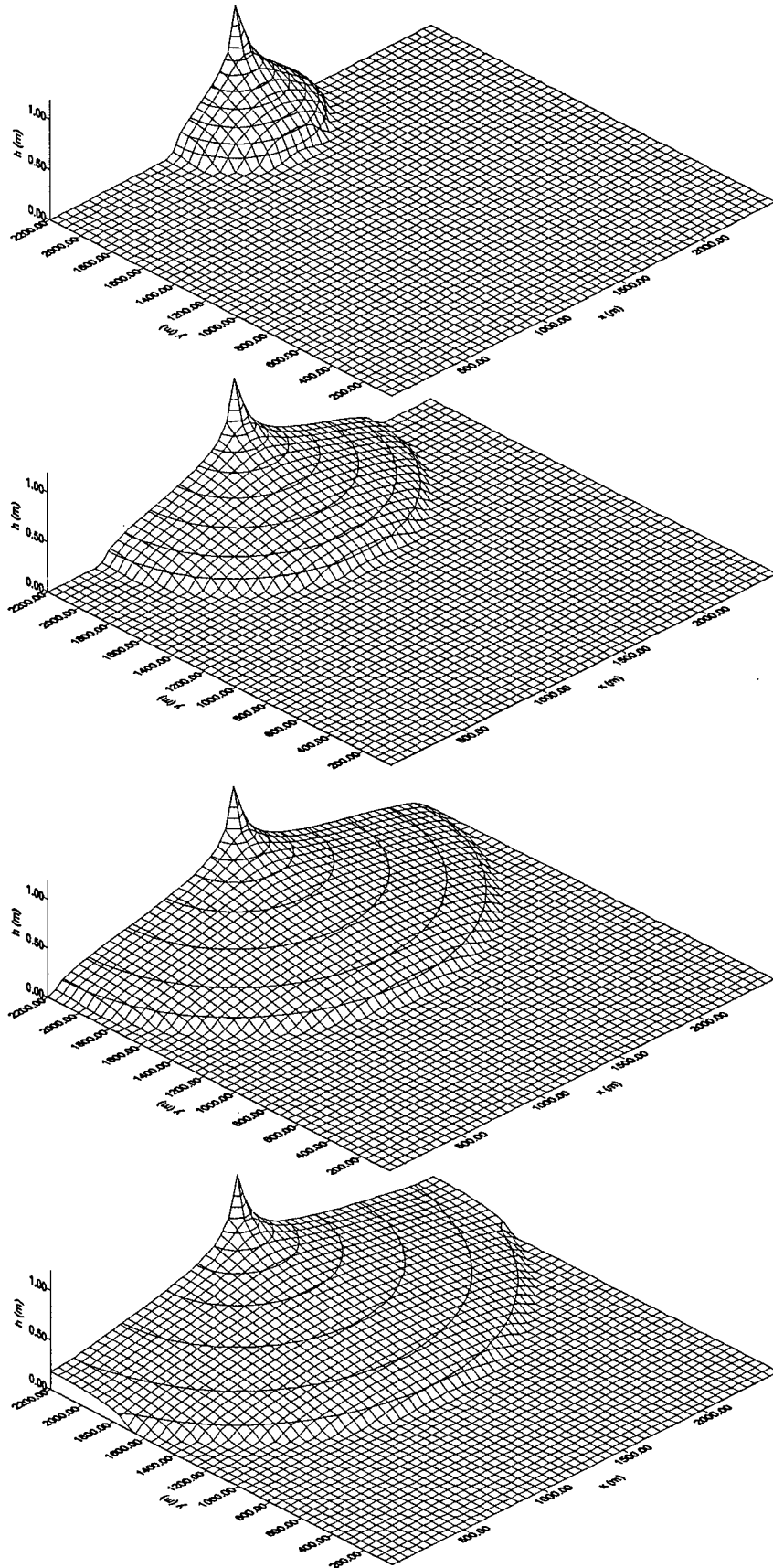


Fig.3.1.14 Surface plot for run N4. From top to bottom: $t=20'$, $t=1$ hour, $t=1\text{h}40'$ and $t=2$ hours (x , y and z scale in meters).

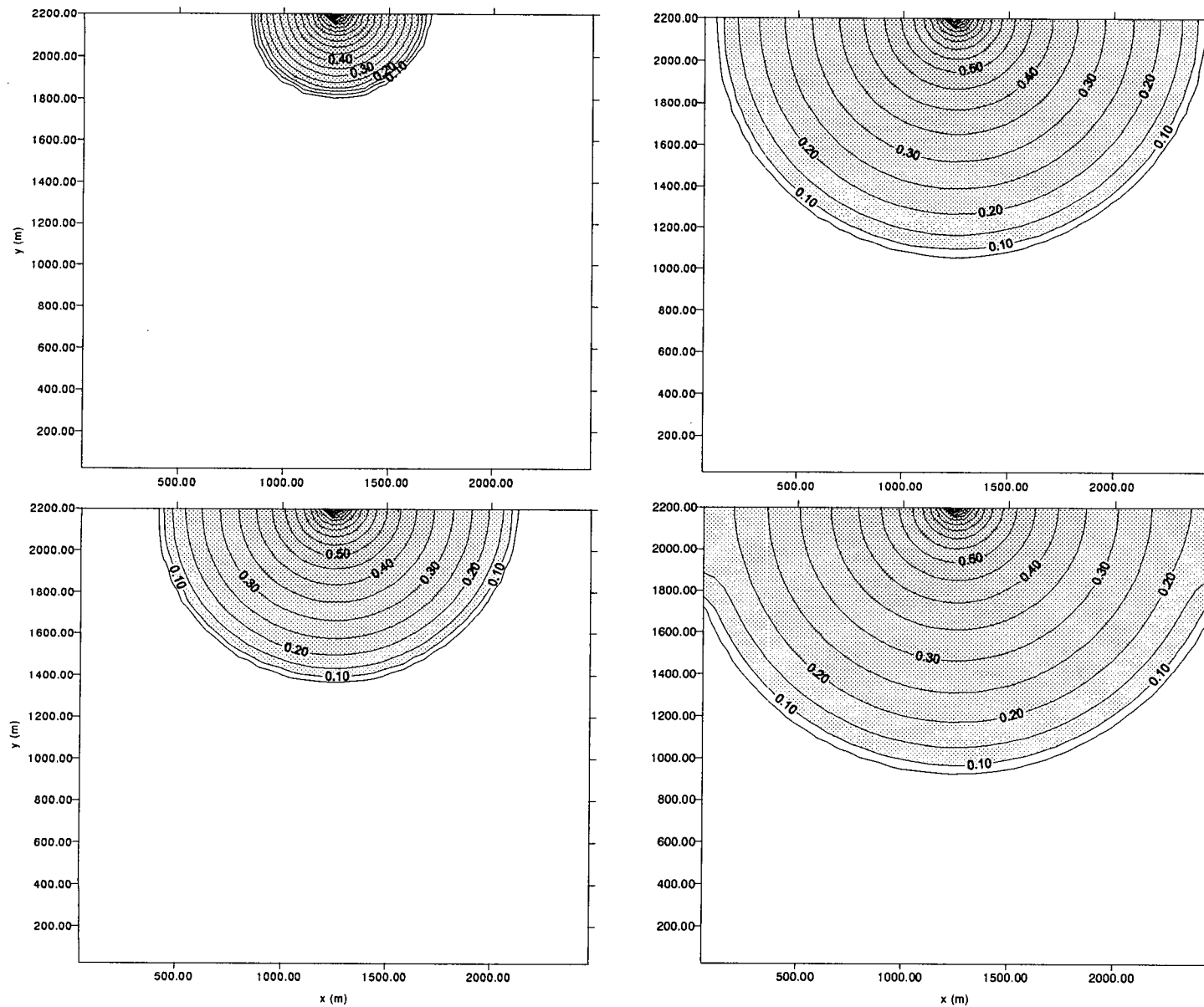


Fig.3.1.15 Contour plot for run N4. On the left: top $t=20'$, bottom $t=1$ hour; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

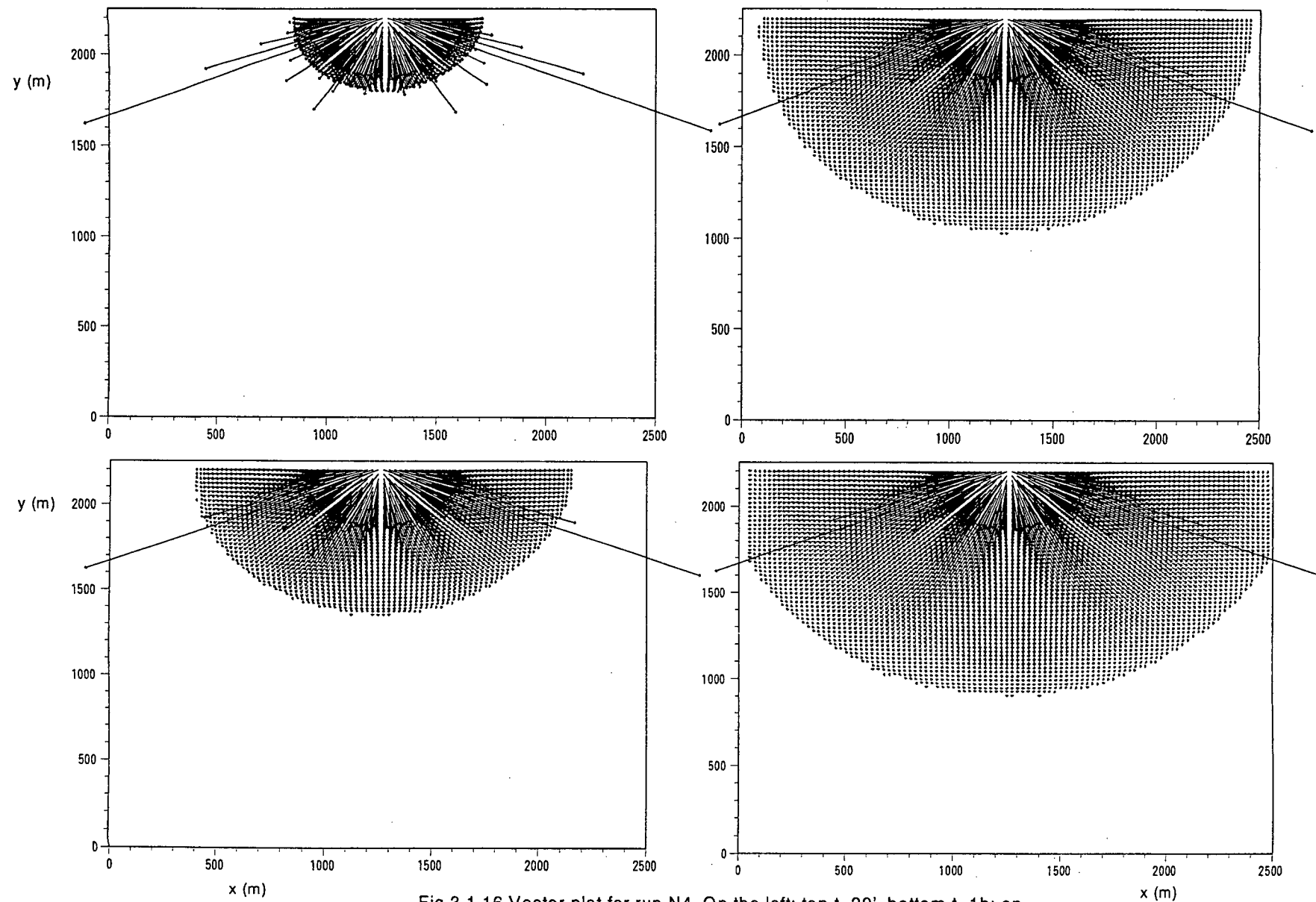


Fig.3.1.16 Vector plot for run N4. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 1000 times the plot unit.

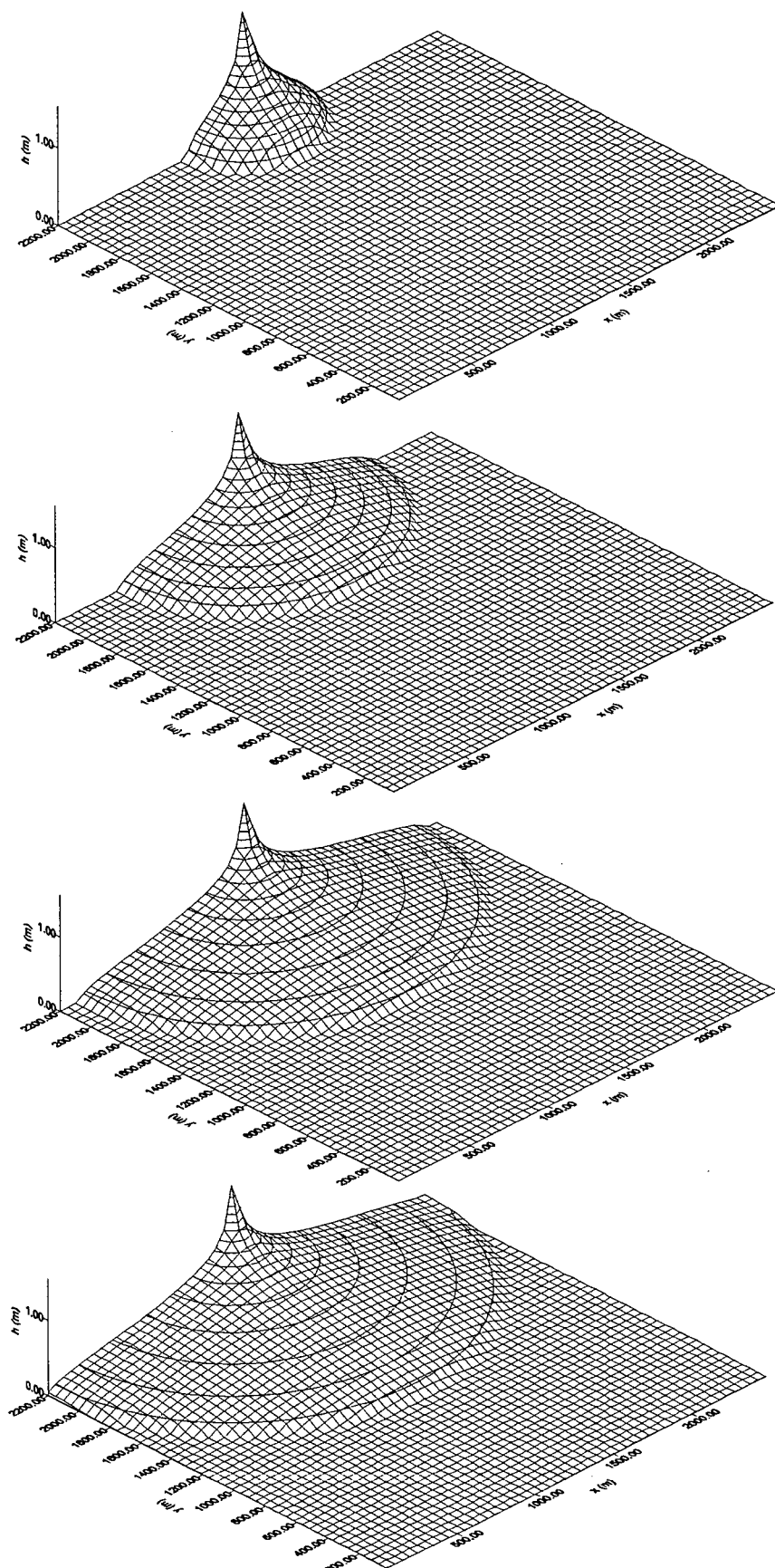


Fig.3.1.17 Surface plot for run N5. From top to bottom: $t=20'$, $t=1$ hour, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

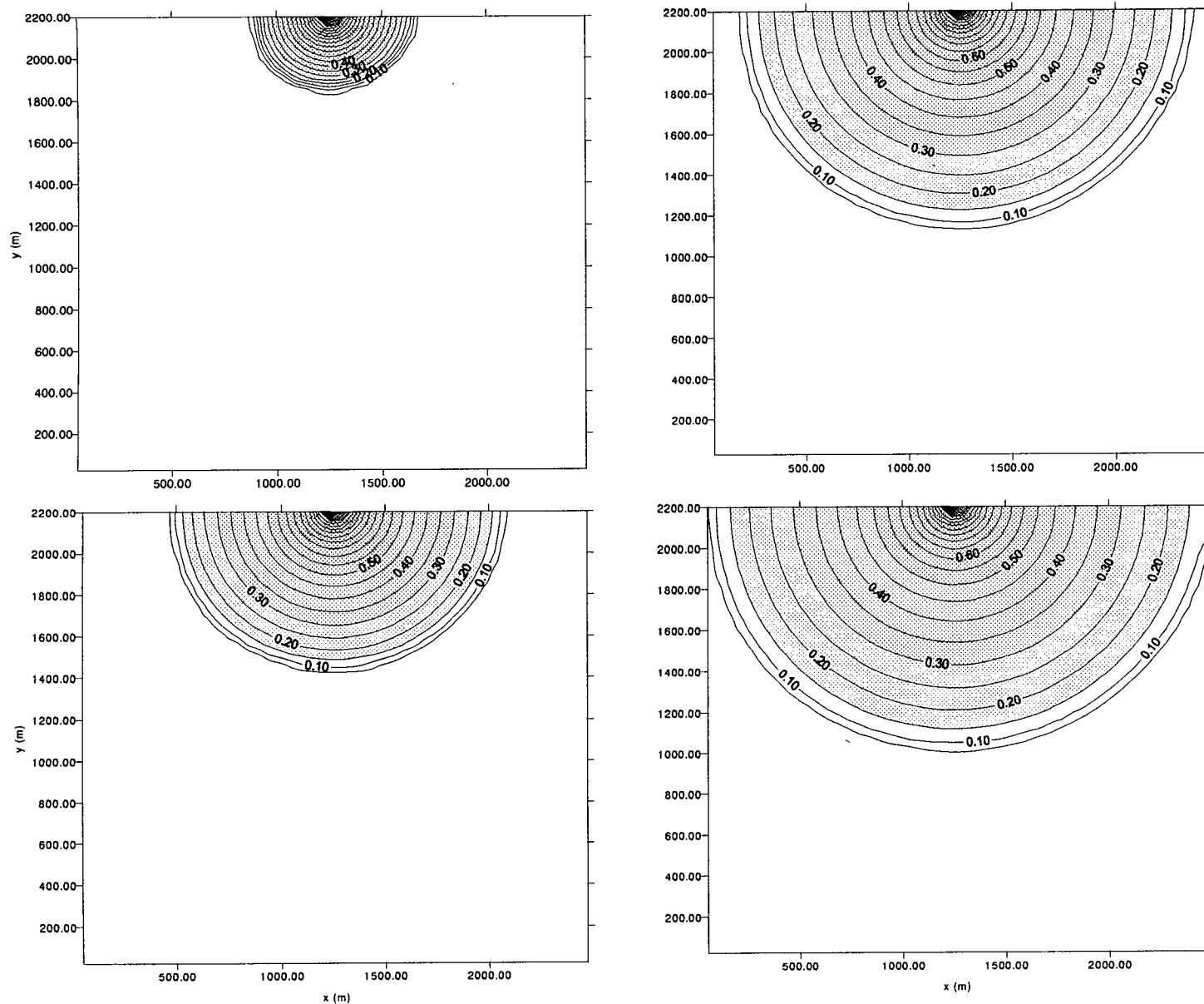


Fig.3.1.18 Contour plot for run N5. On the left: top $t=20'$, bottom $t=1$ hour; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

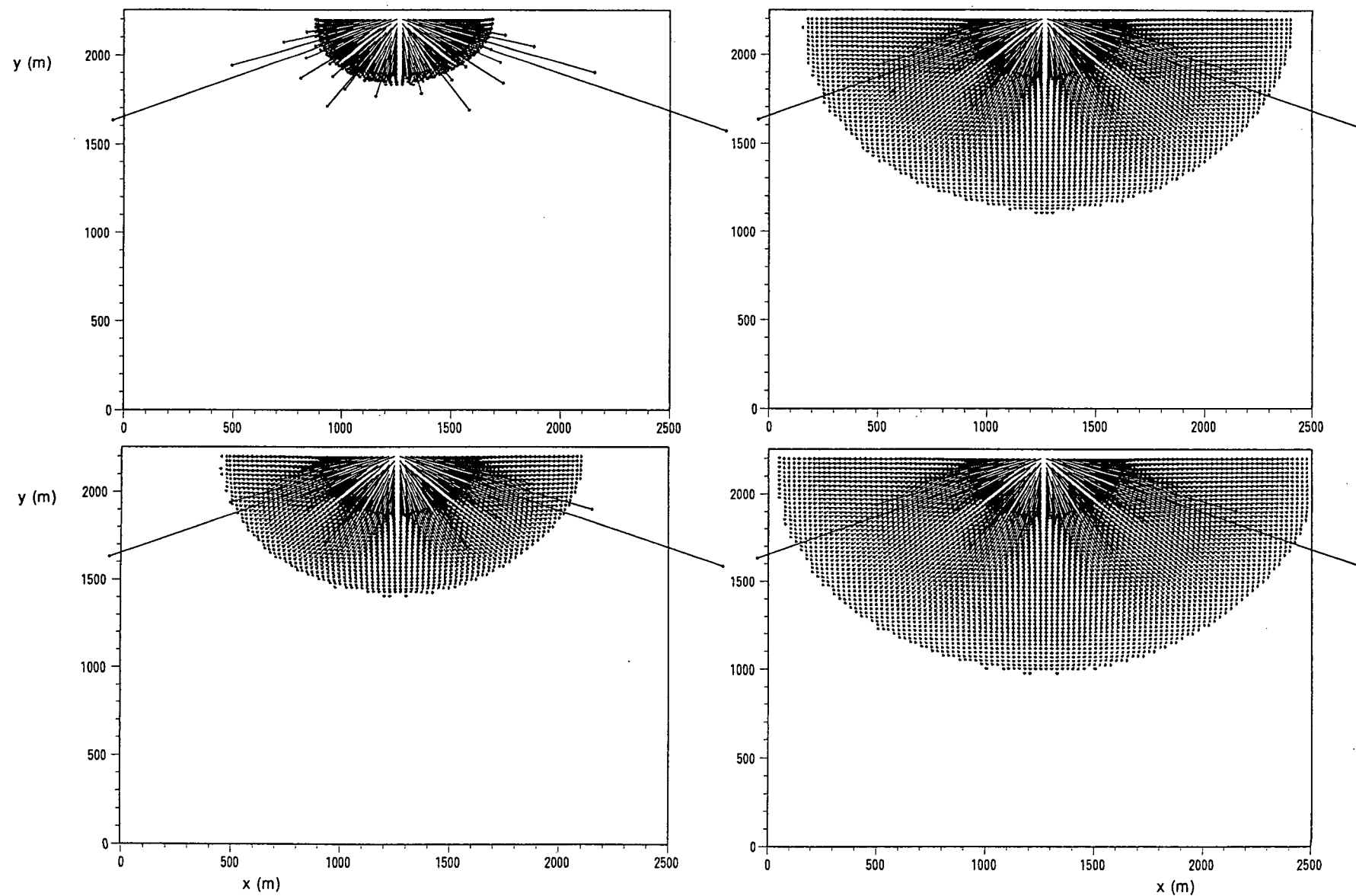


Fig.3.1.19 Vector plot for run N5. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 1000 times the plot unit.

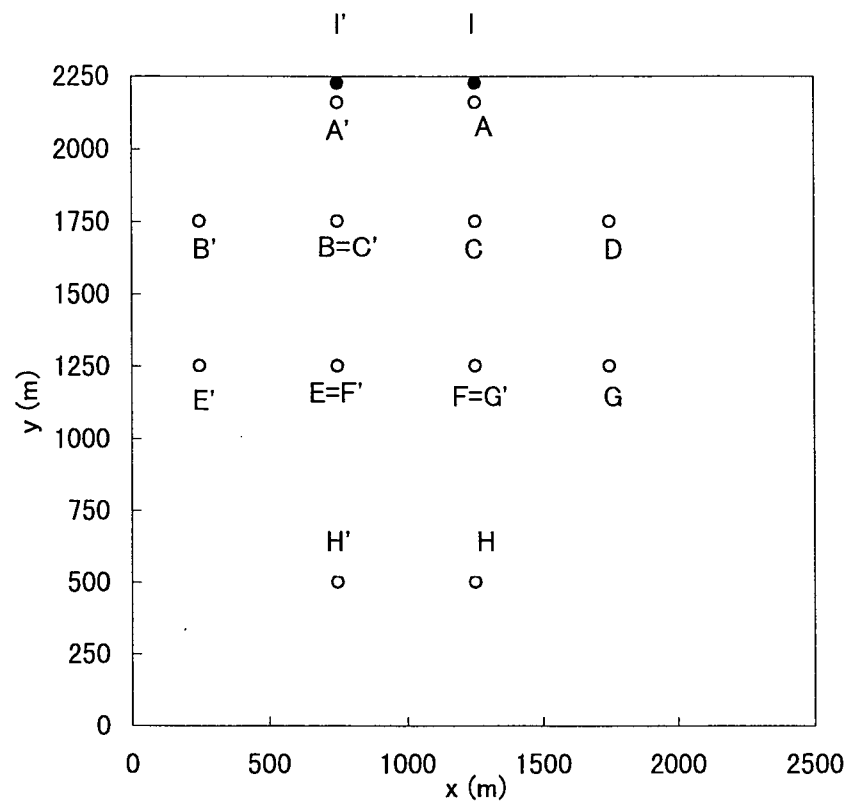


Fig. 3.1.20 Selected points of the mesh

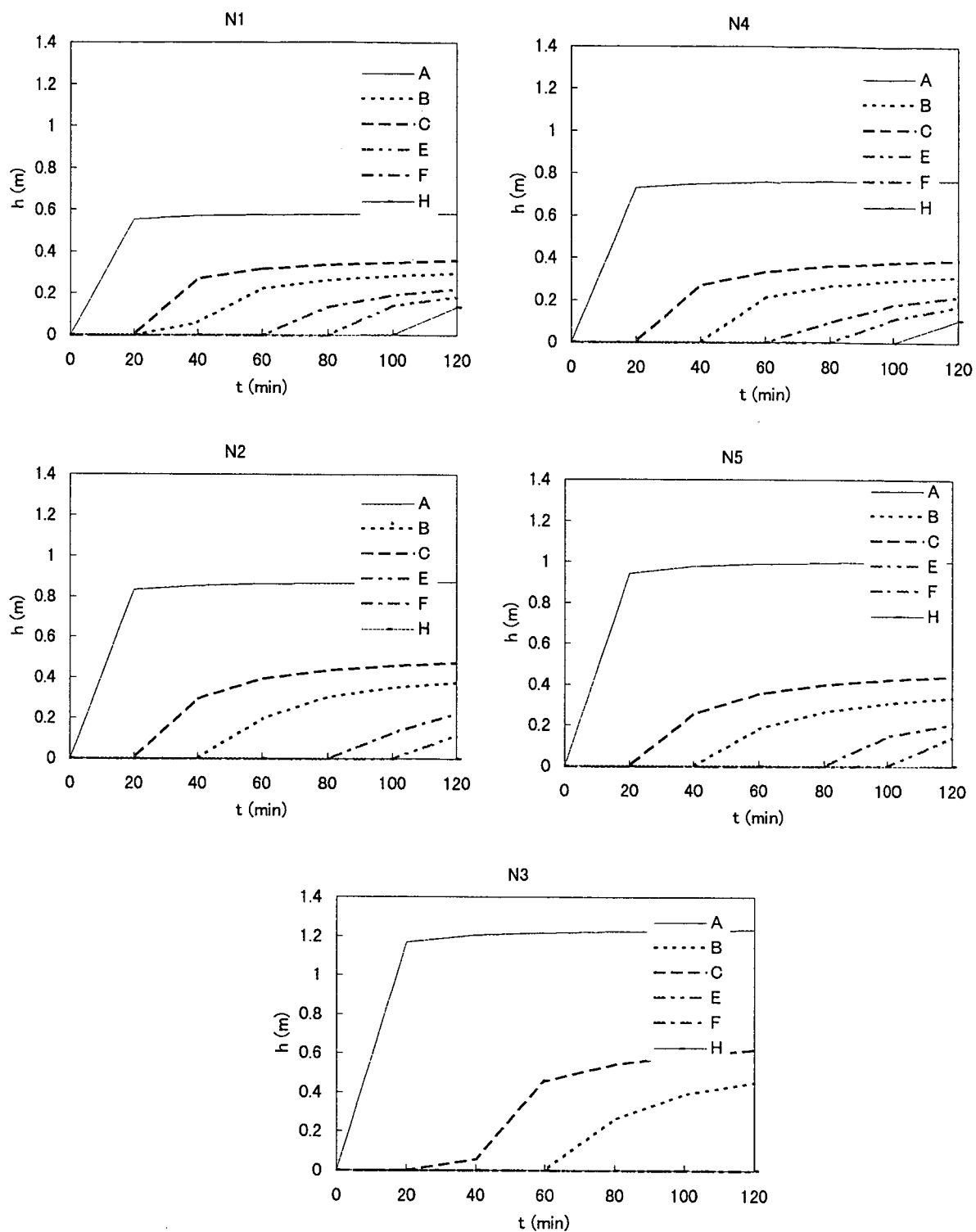


Fig.3.1.21 Water depth as a function of time for selected points

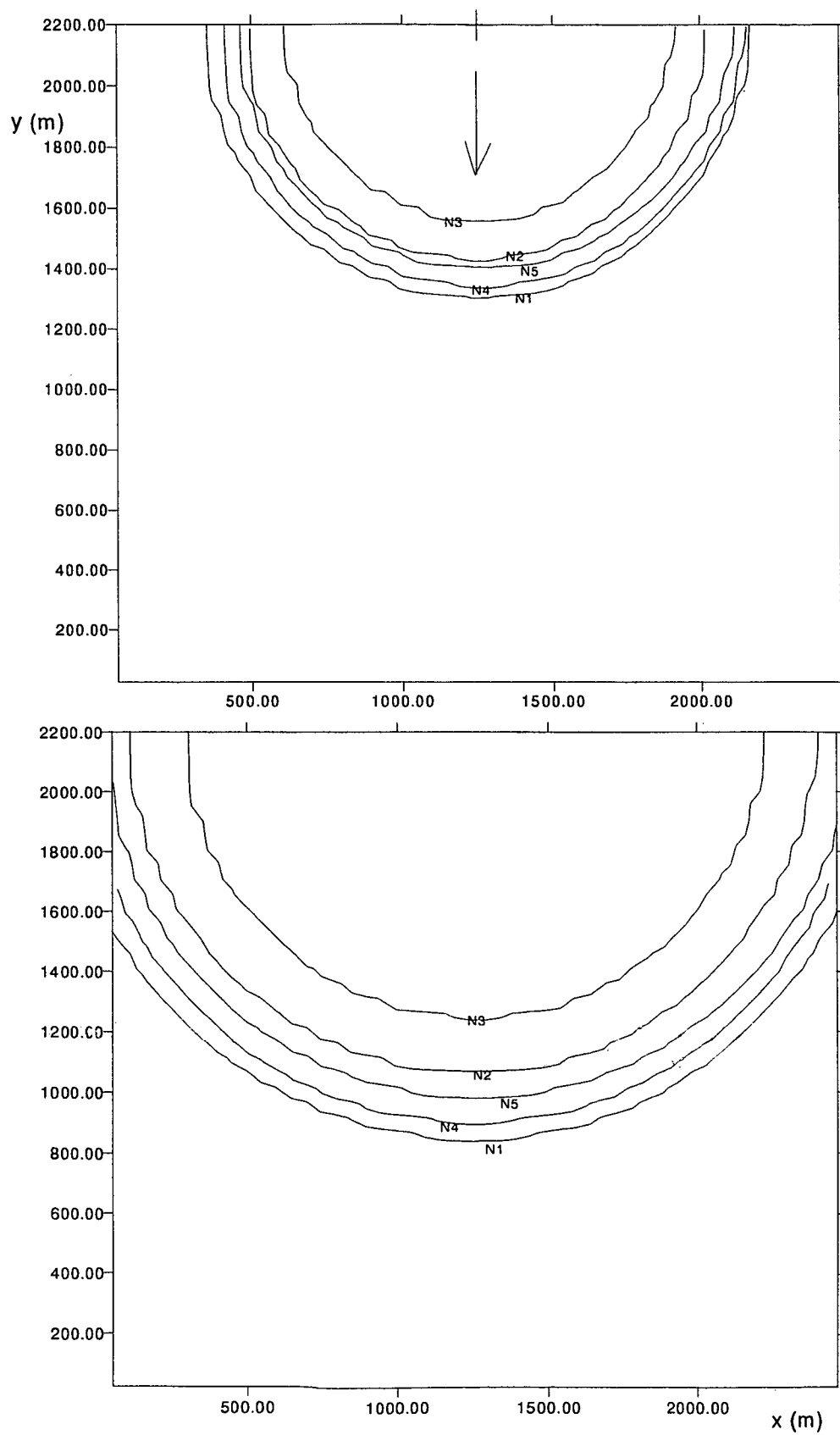


Fig.3.1.22 Comparison between water fronts for runs N1 to N5. Plot for $t=1h$ (top) and $t=2h$ (bottom)

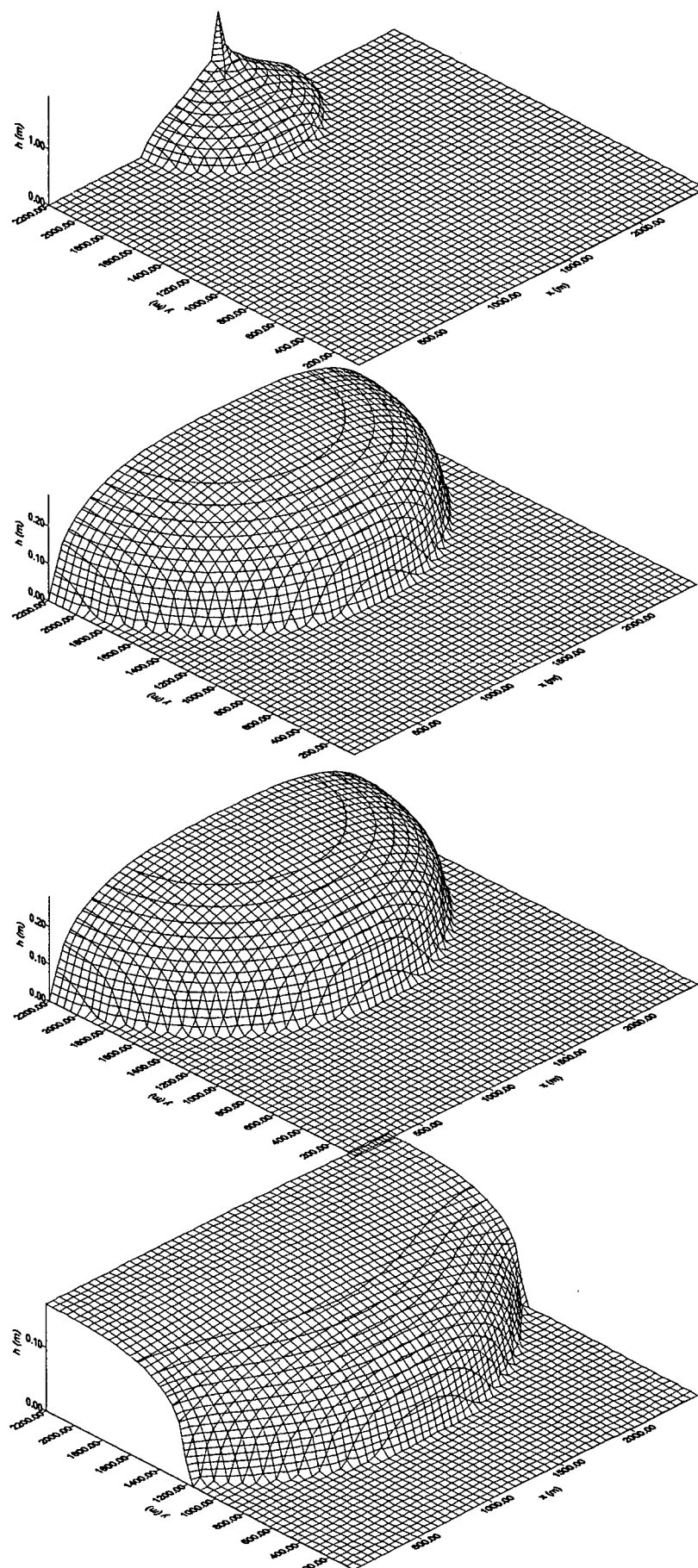


Fig.3.1.23 Surface plot for run N1T. From top to bottom: $t=20'$, $t=1$ hour, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

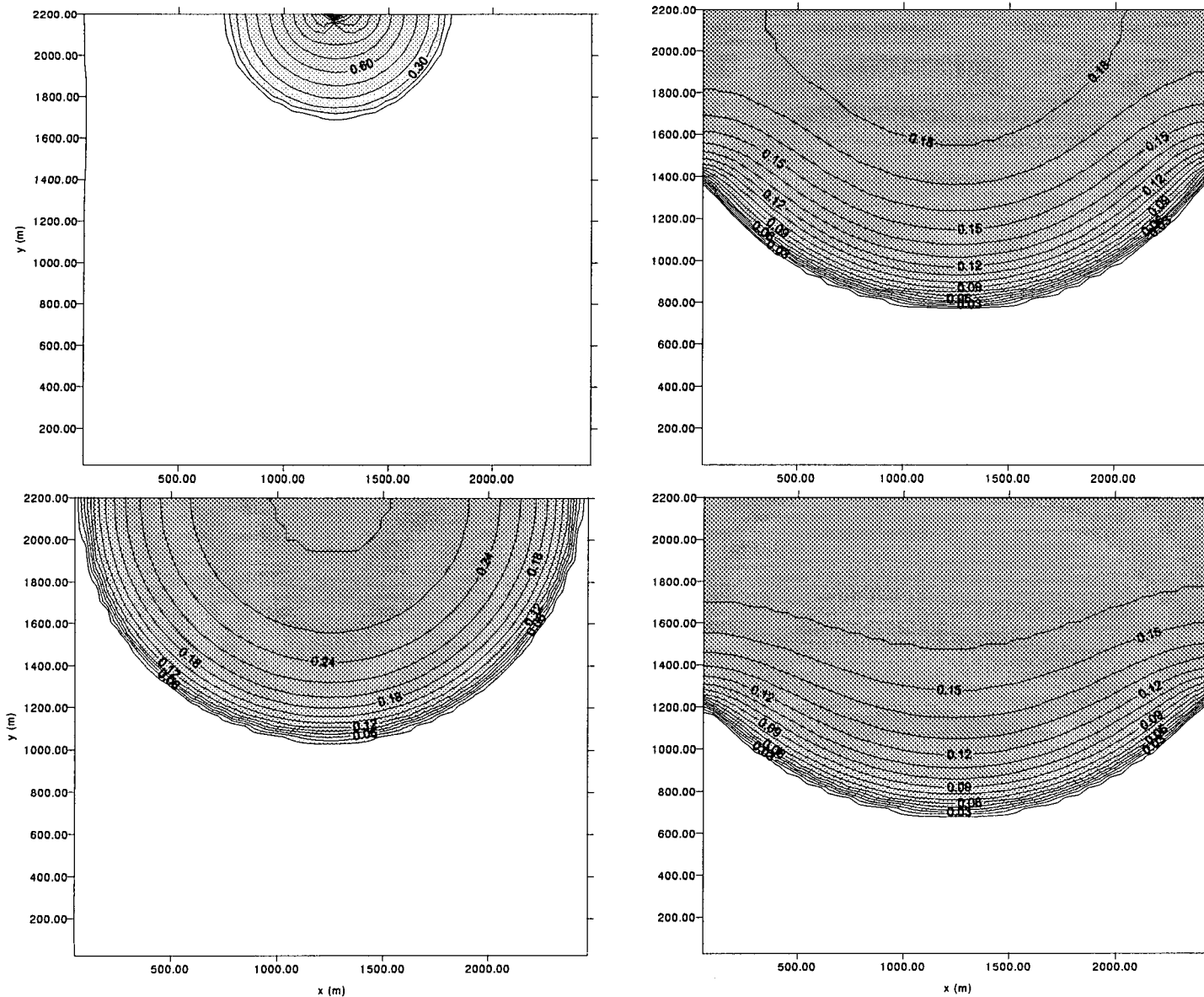


Fig.3.1.24 Contour plot for run N1T. On the left: top t=20', bottom t=1 hour; on the right: top t=1h40', bottom t= 2 hours (scale in meter).

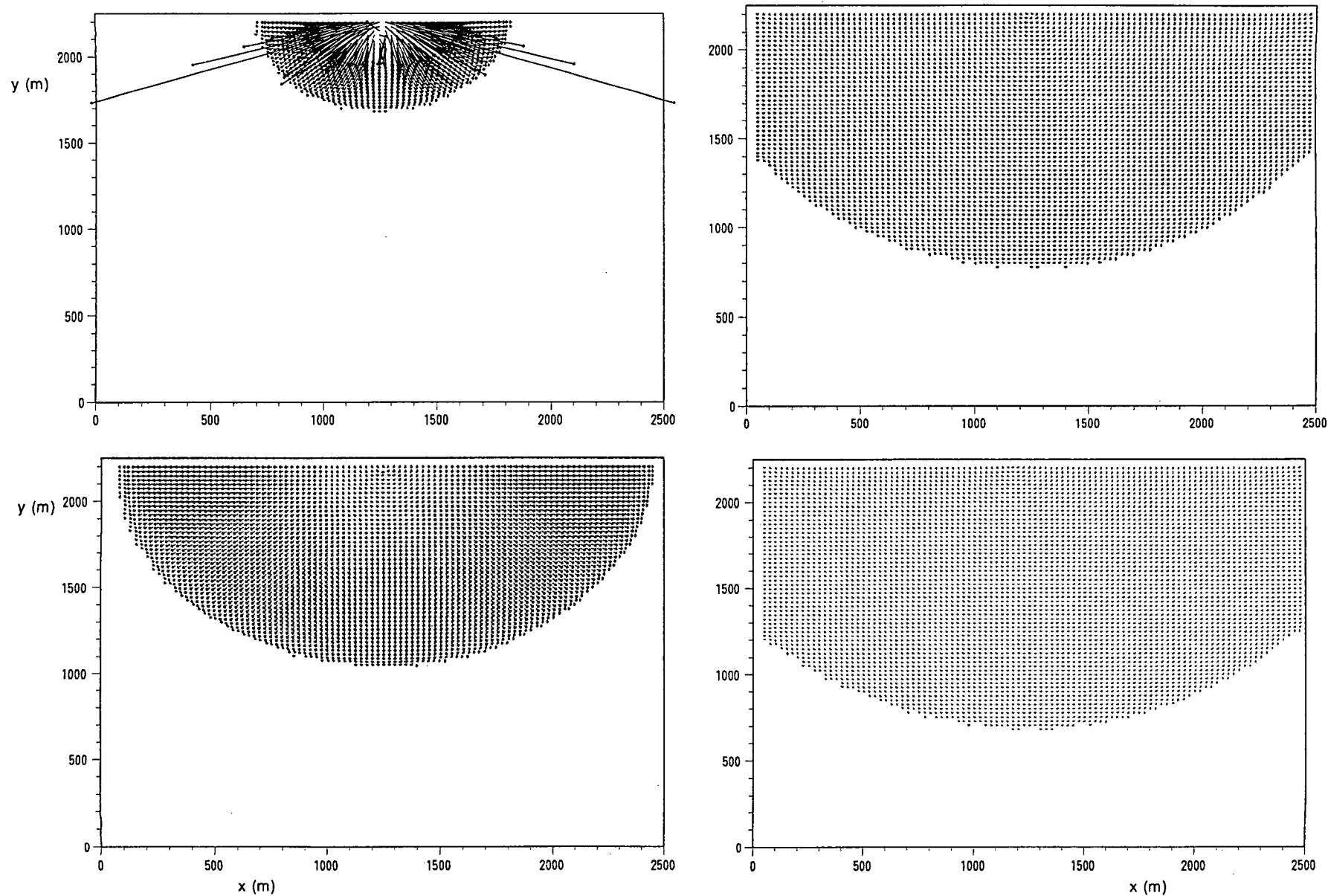


Fig.3.1.25 Vector plot for run N1T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 200 times the plot unit for $t=20'$ and 1000 for $t=1h, 1h40', 2h..$

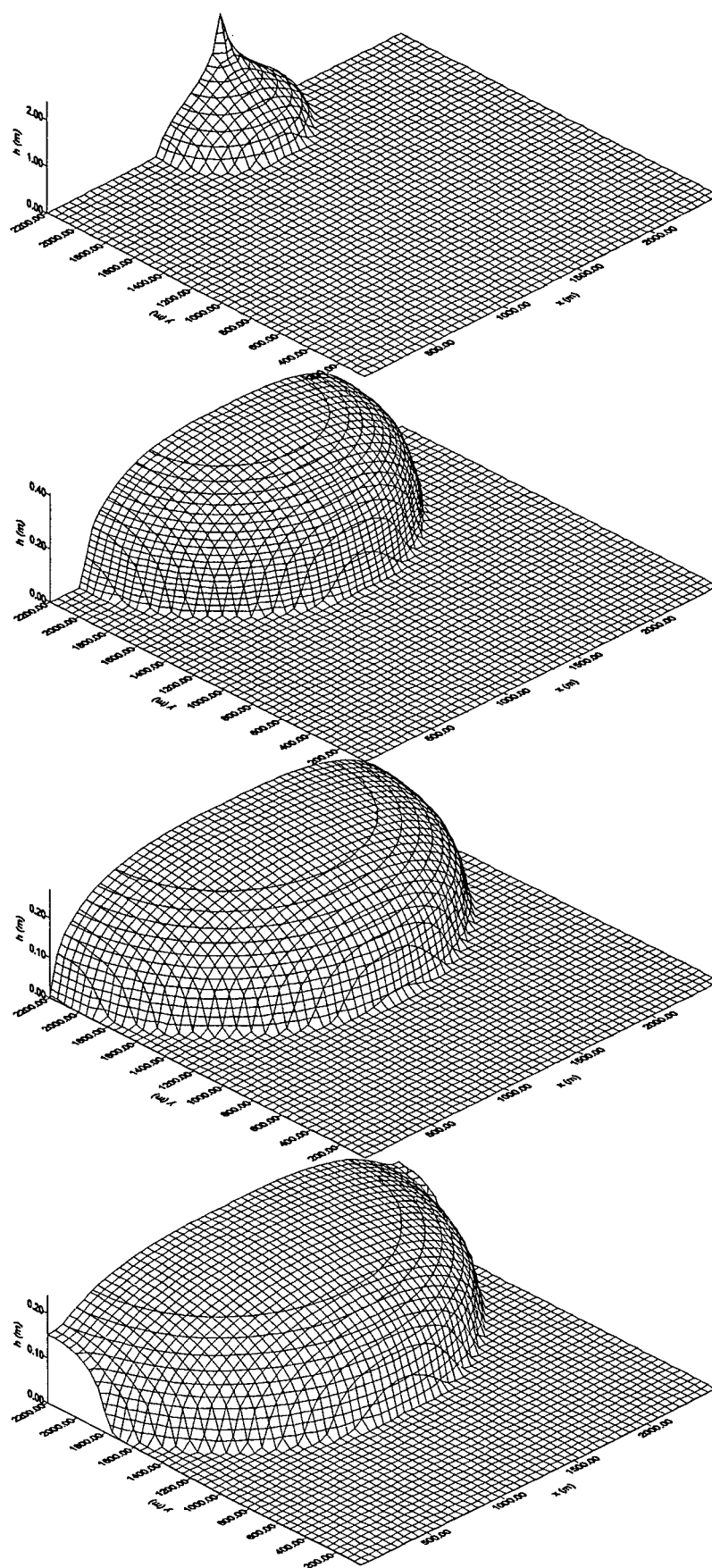


Fig.3.1.26 Surface plot for run N2T. From top to bottom: $t=20'$, $t=1$ hour, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

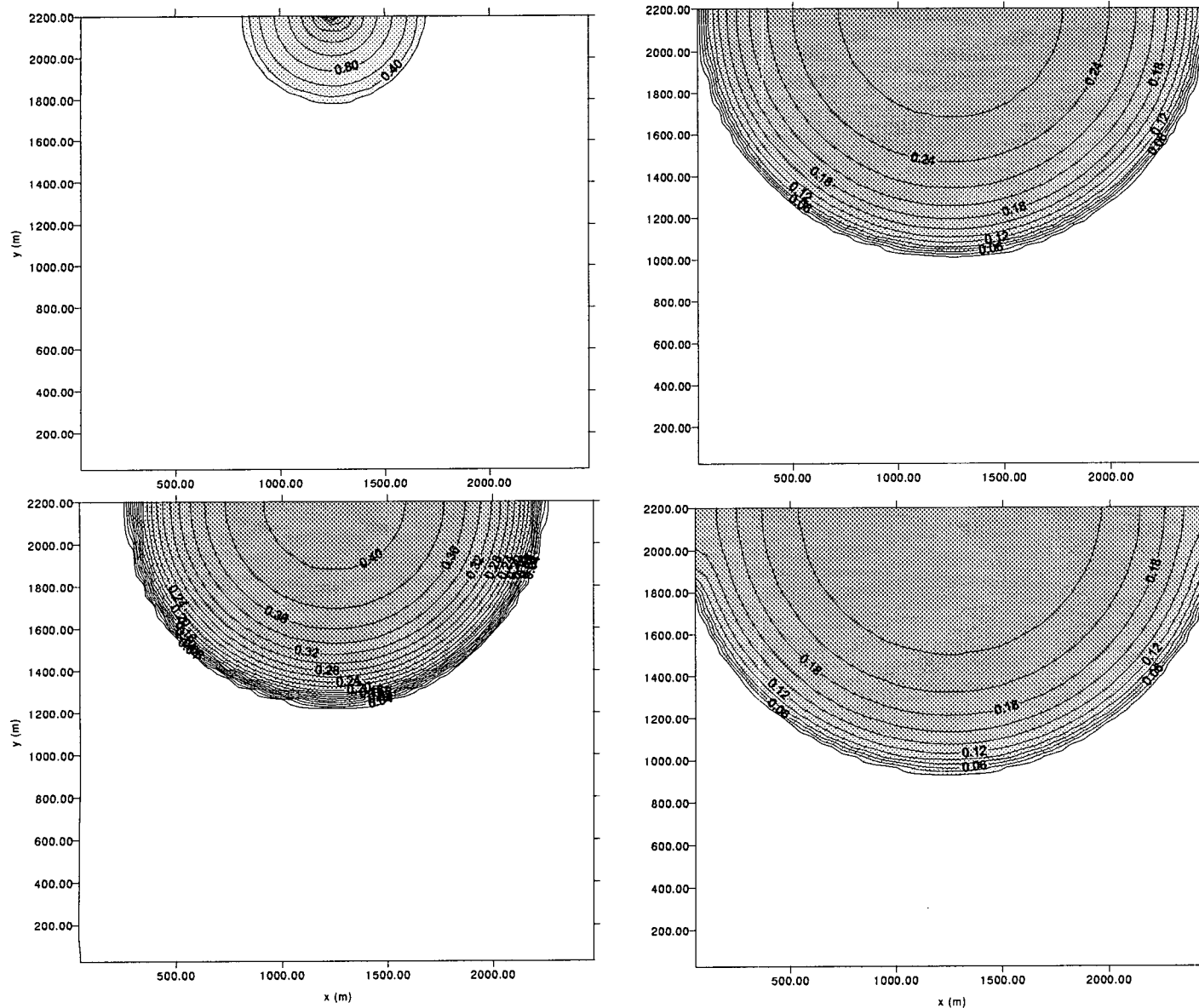


Fig.3.1.27 Contour plot for run N2T. On the left: top t=20', bottom t=1 hour; on the right: top t=1h40', bottom t= 2 hours (scale in meter).

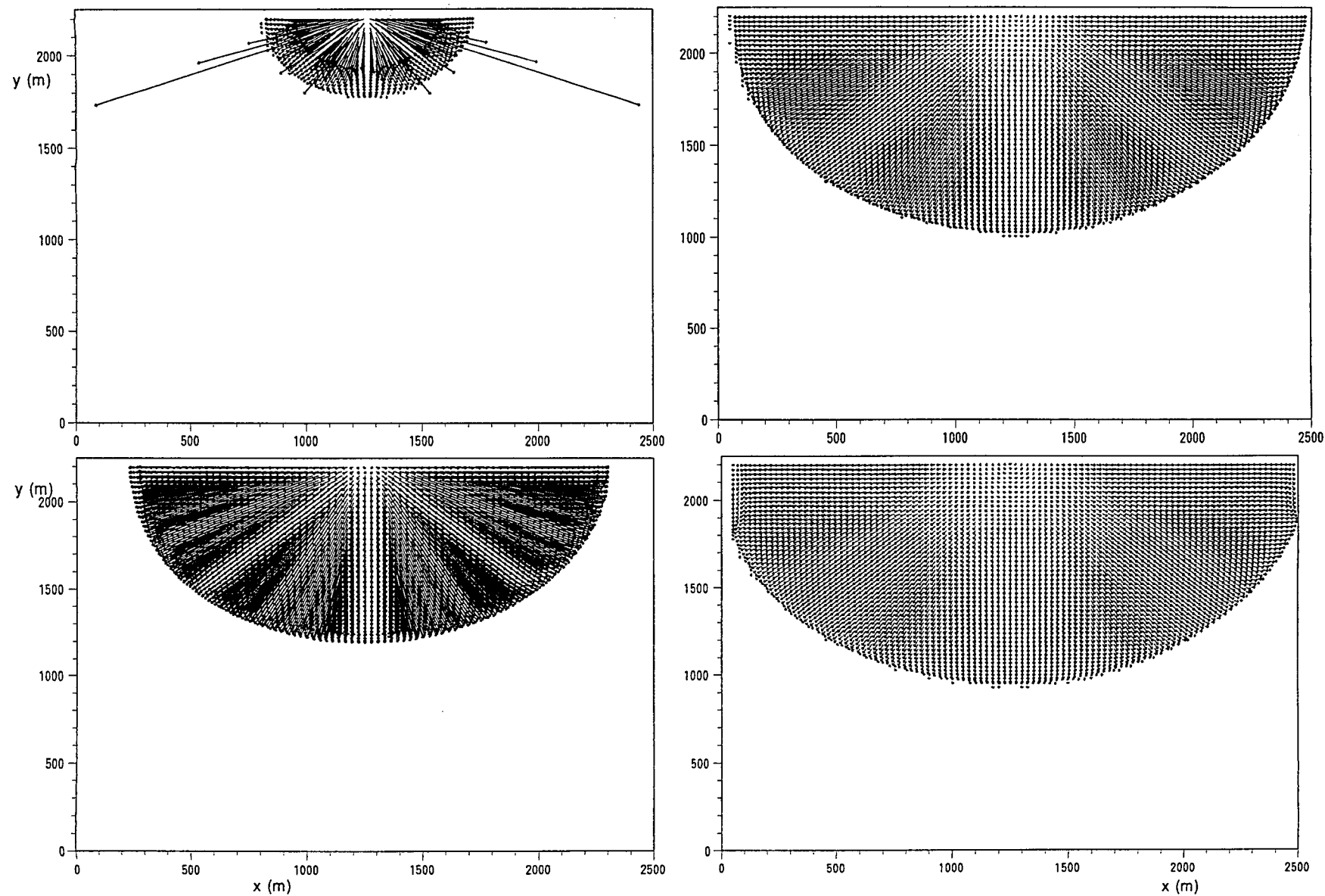


Fig.3.1.28 Vector plot for run N2T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 200 times the plot unit for $t=20'$ and 5000 for $t=1h, 1h40', 2h$.

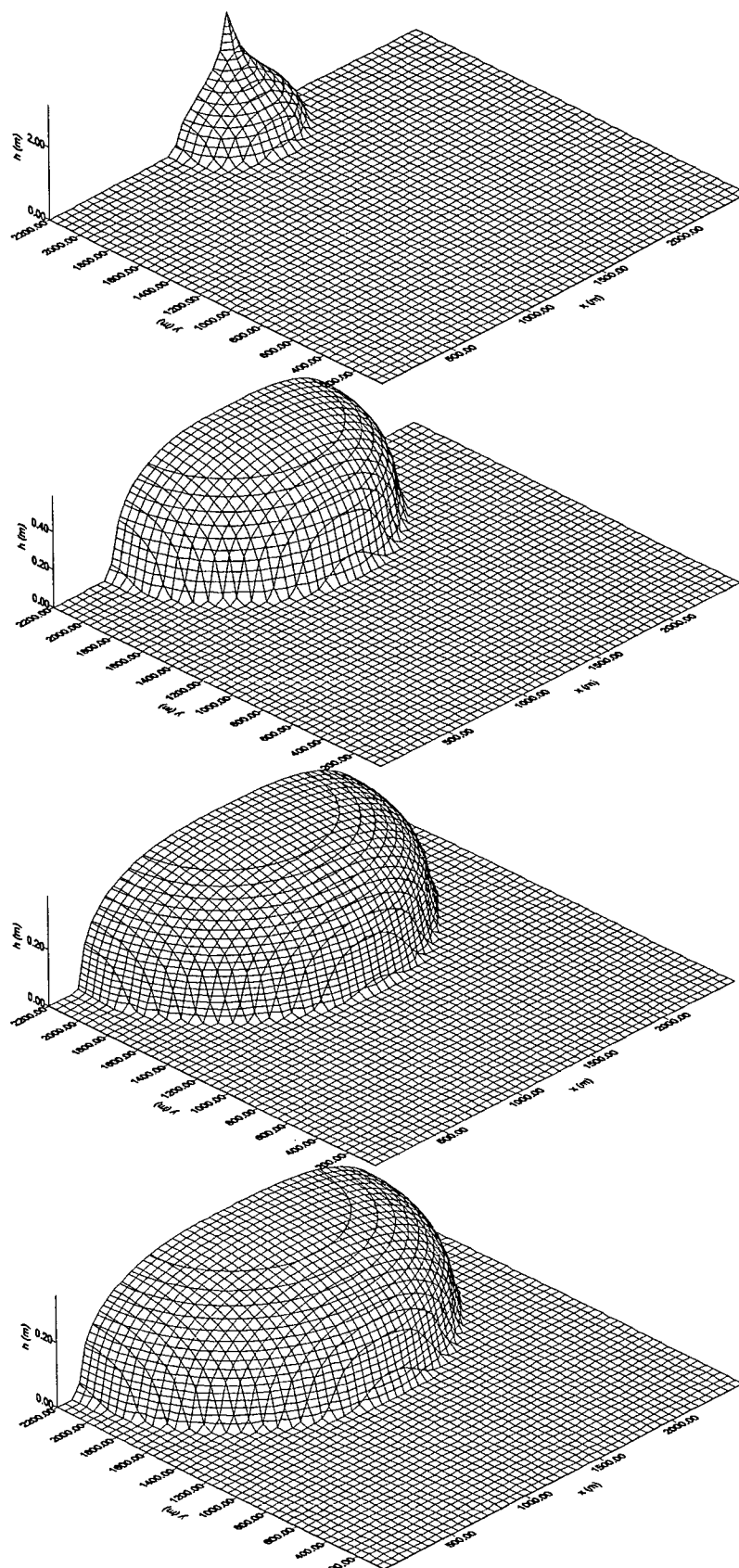


Fig.3.1.29 Surface plot for run N3T. From top to bottom: $t=20'$, $t=1 \text{ hour}$, $t=1\text{h}40'$ and $t=2 \text{ hours}$ (x , y and z scale in meters).

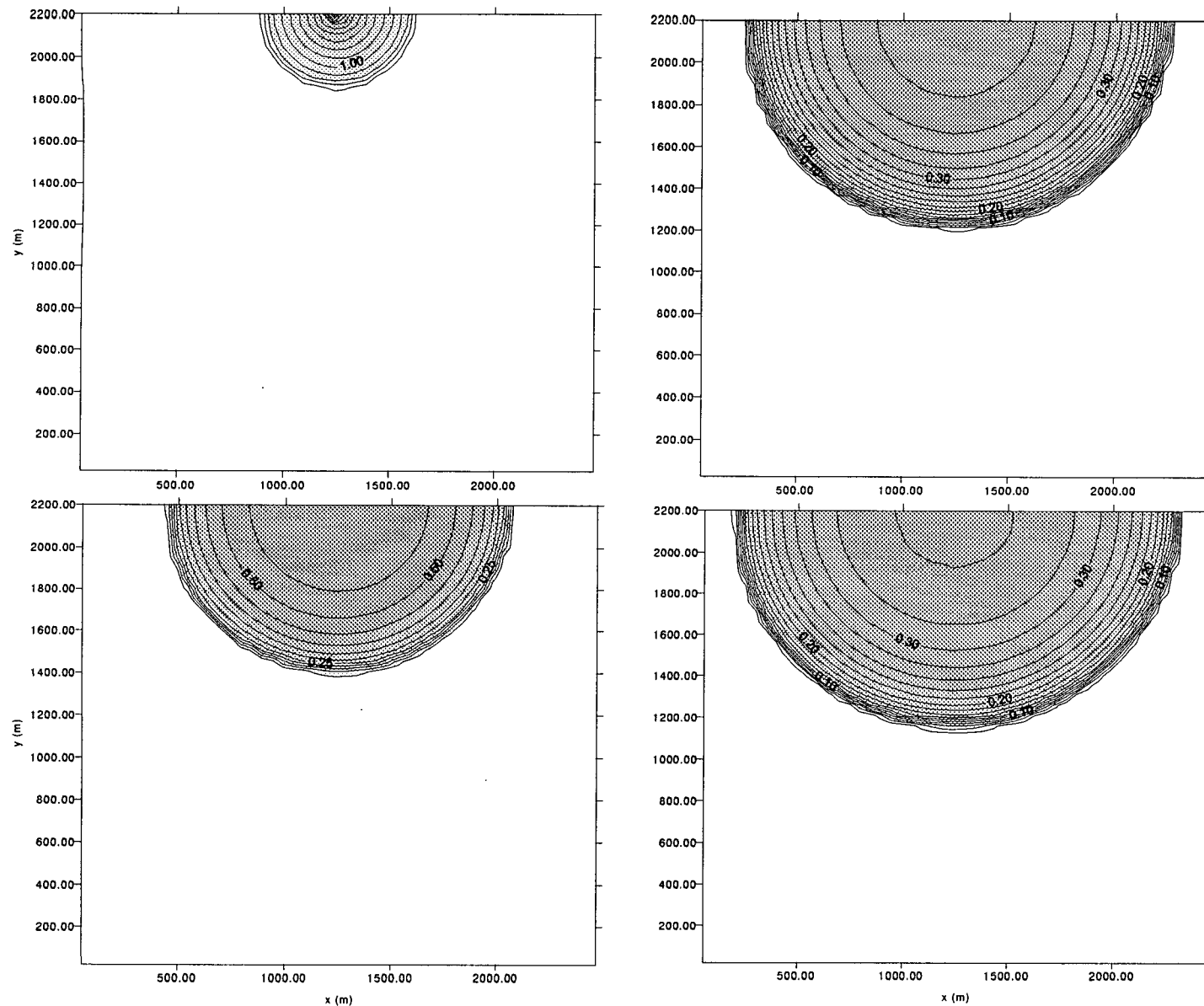


Fig.3.1.30 Contour plot for run N3T. On the left: top $t=20'$, bottom $t=1$ hour; on the right: top $t=1\text{h}40'$, bottom $t=2$ hours (scale in meter).

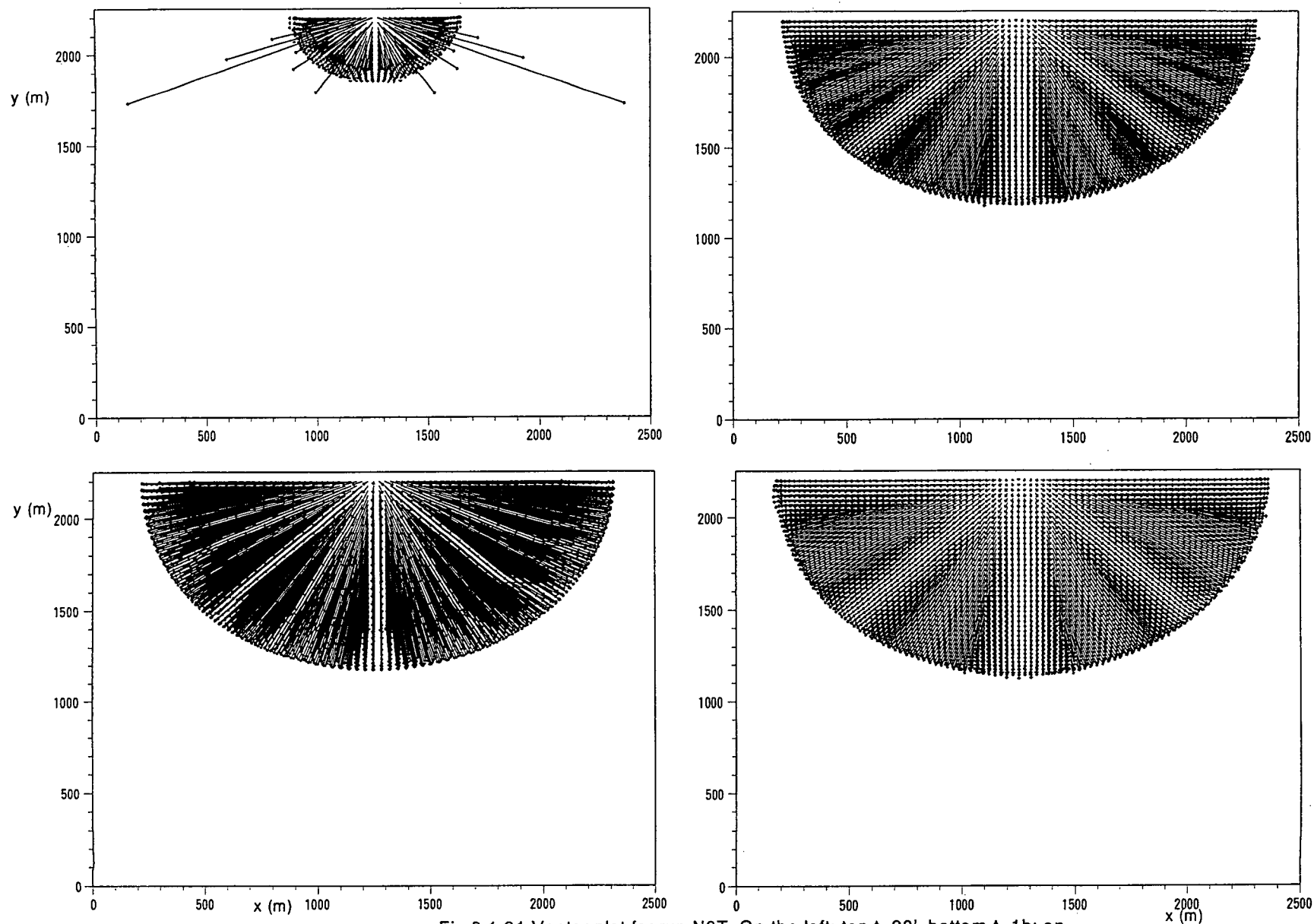


Fig.3.1.31 Vector plot for run N3T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 200 times the plot unit for $t=20'$ and 10000 for $t=1h, 1h40', 2h..$

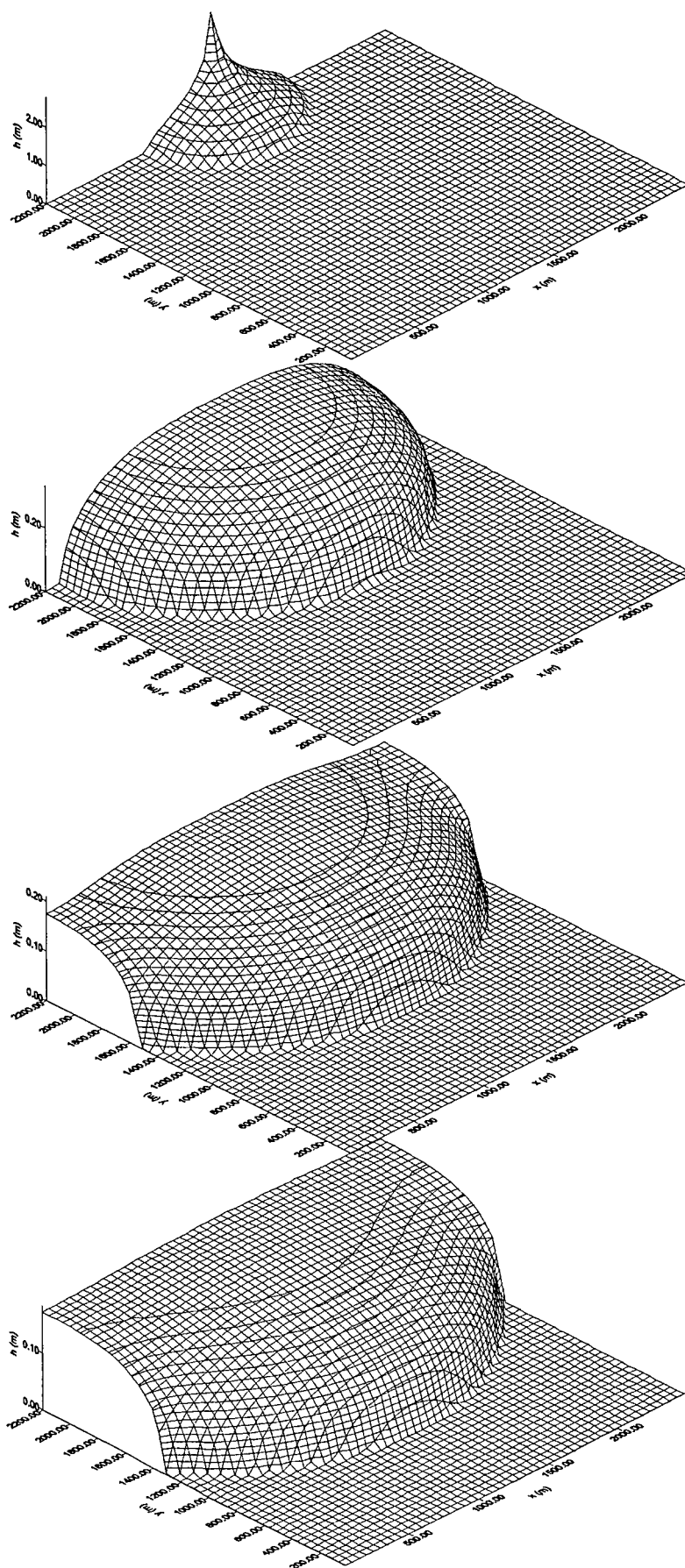


Fig.3.1.32 Surface plot for run N4T. From top to bottom: $t=20'$, $t=1$ hour, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

Fig.3.1.33 Contour plot for run N4T. On the left: top $t=20'$, bottom $t=1$ hour; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

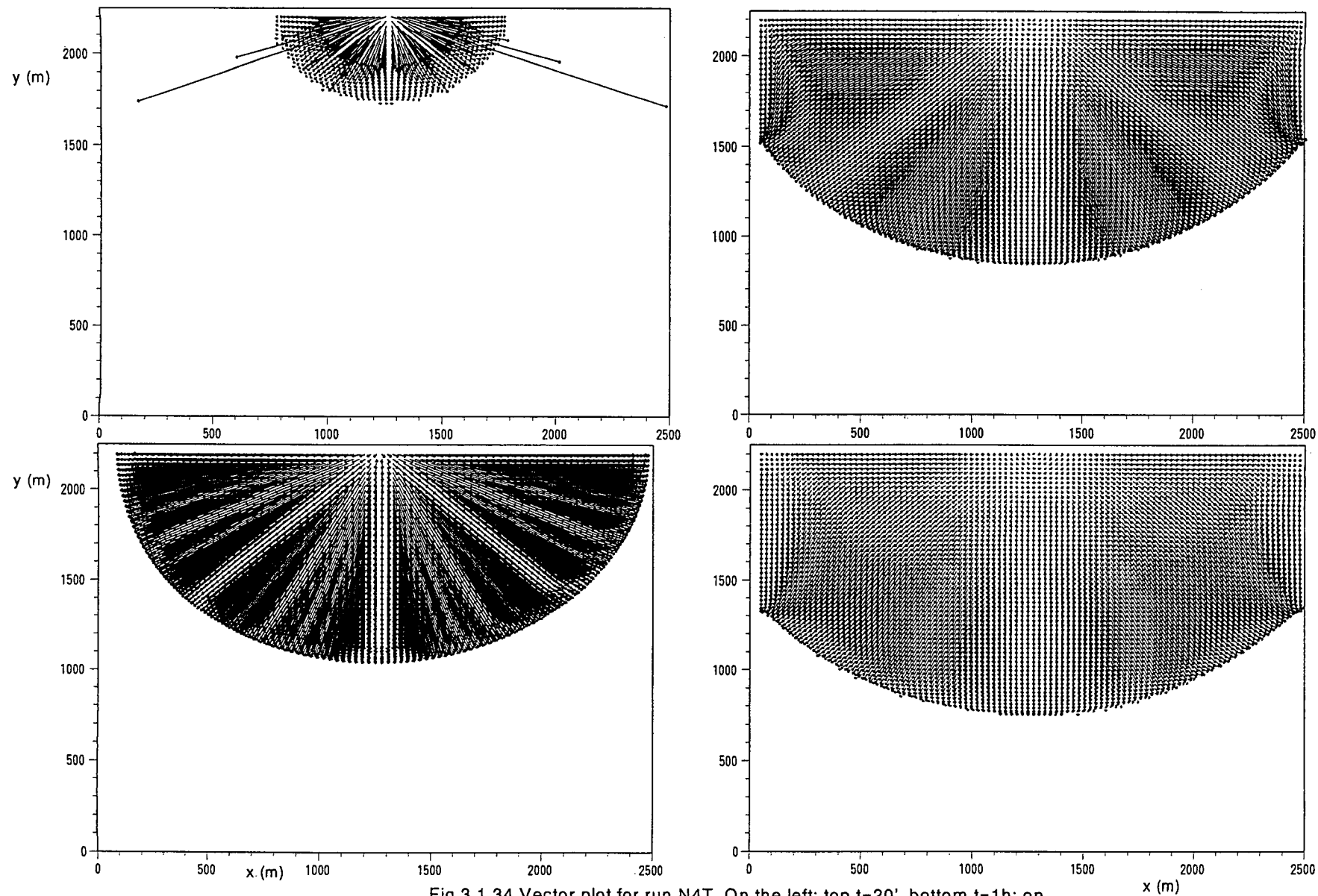


Fig.3.1.34 Vector plot for run N4T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 200 times the plot unit for $t=20'$ and 7500 for $t=1h, 1h40', 2h..$

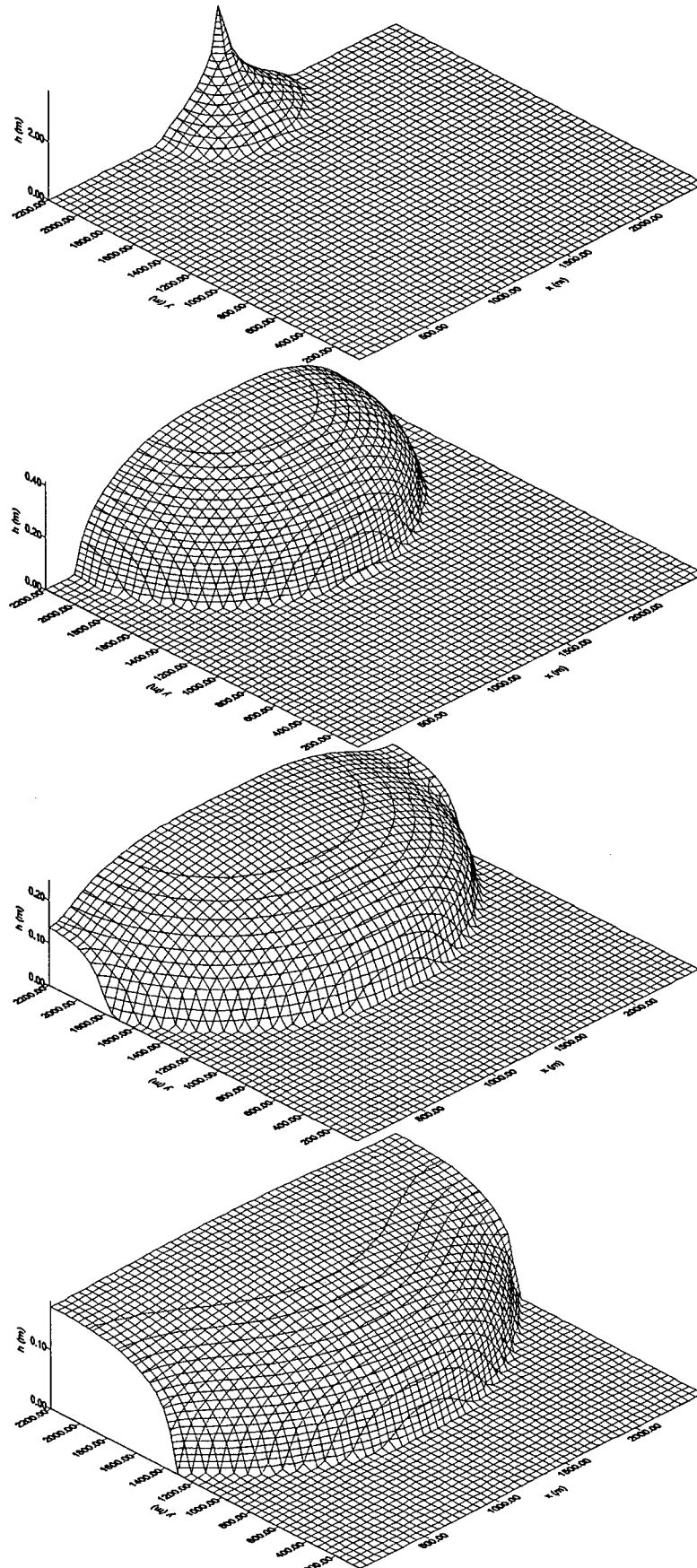


Fig.3.1.35 Surface plot for run N5T. From top to bottom: $t=20'$, $t=1$ hour, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

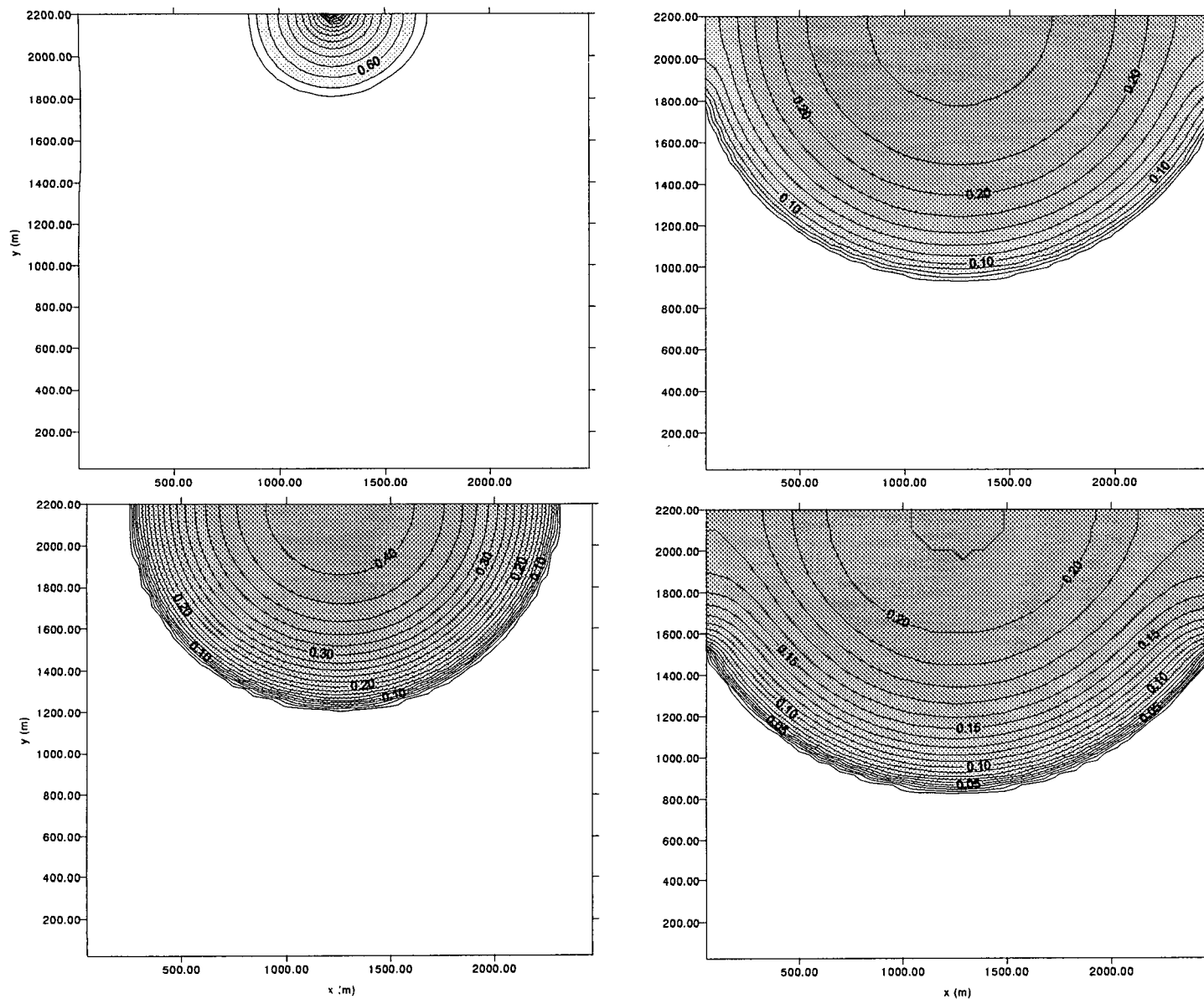


Fig.3.1.36 Contour plot for run N5T. On the left: top $t=20'$, bottom $t=1$ hour; on the right: top $t=1\text{h}40'$, bottom $t=2$ hours (scale in meter).

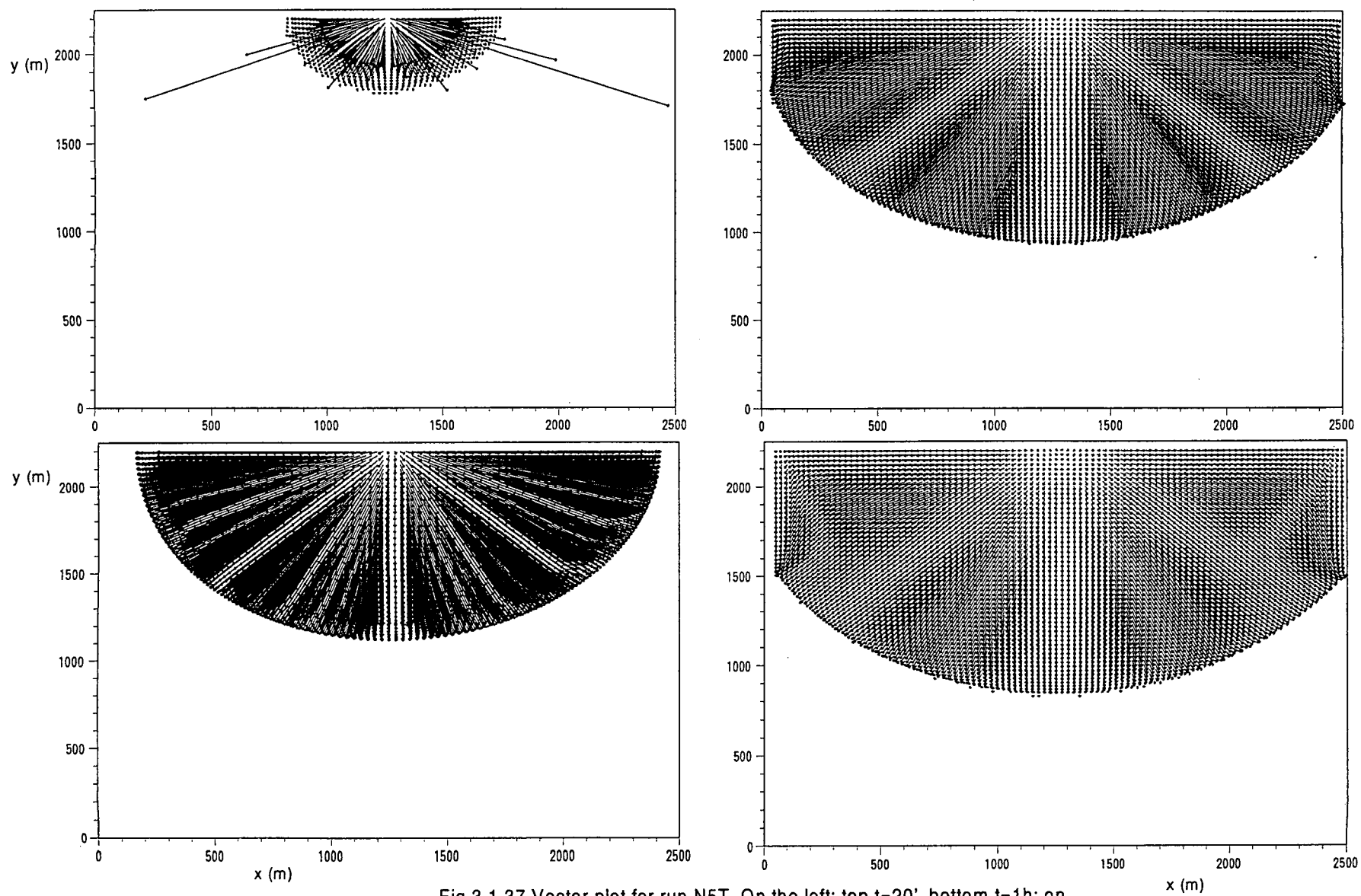


Fig.3.1.37 Vector plot for run N5T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 200 times the plot unit for $t=20'$ and 7500 for $t=1h, 1h40', 2h$.

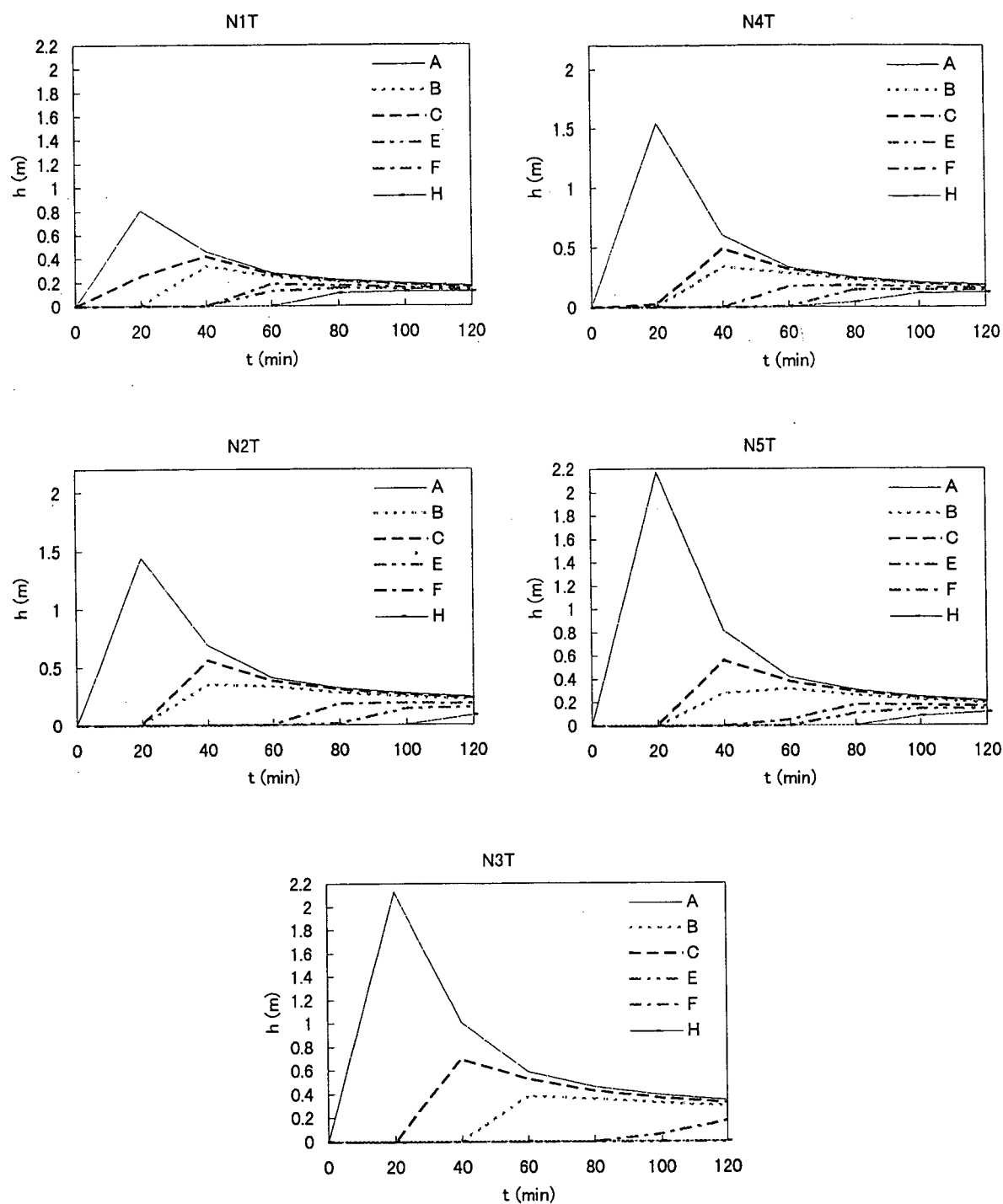


Fig.3.1.38 Water depth as a function of time for selected point for runs N1T to N5T

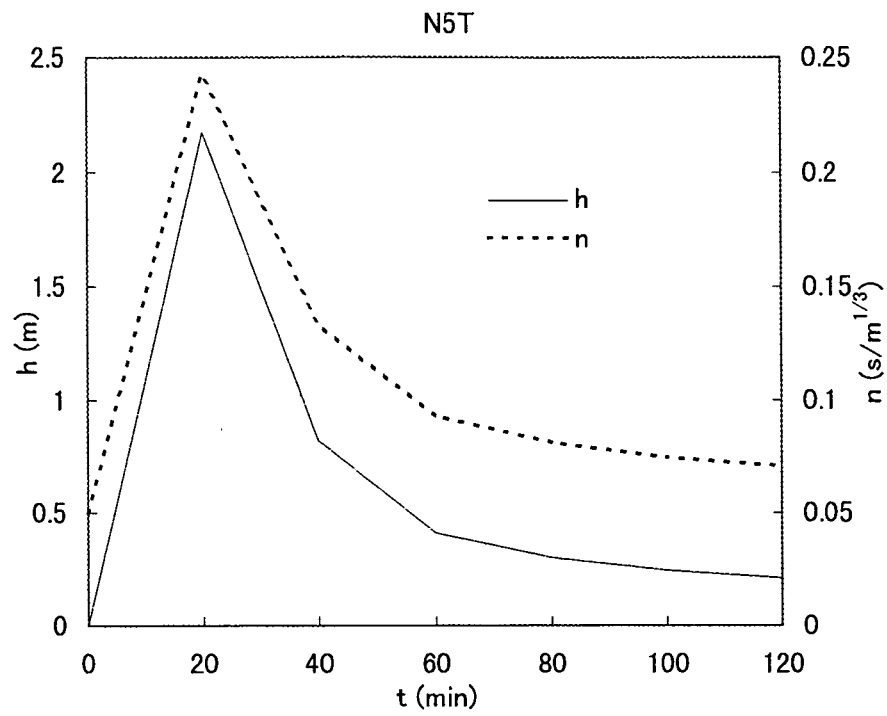


Fig.3.1.39 Variation of the water depth and the total roughness coefficient for the run N5T (urbanization=50%) for the point A (cell 350).

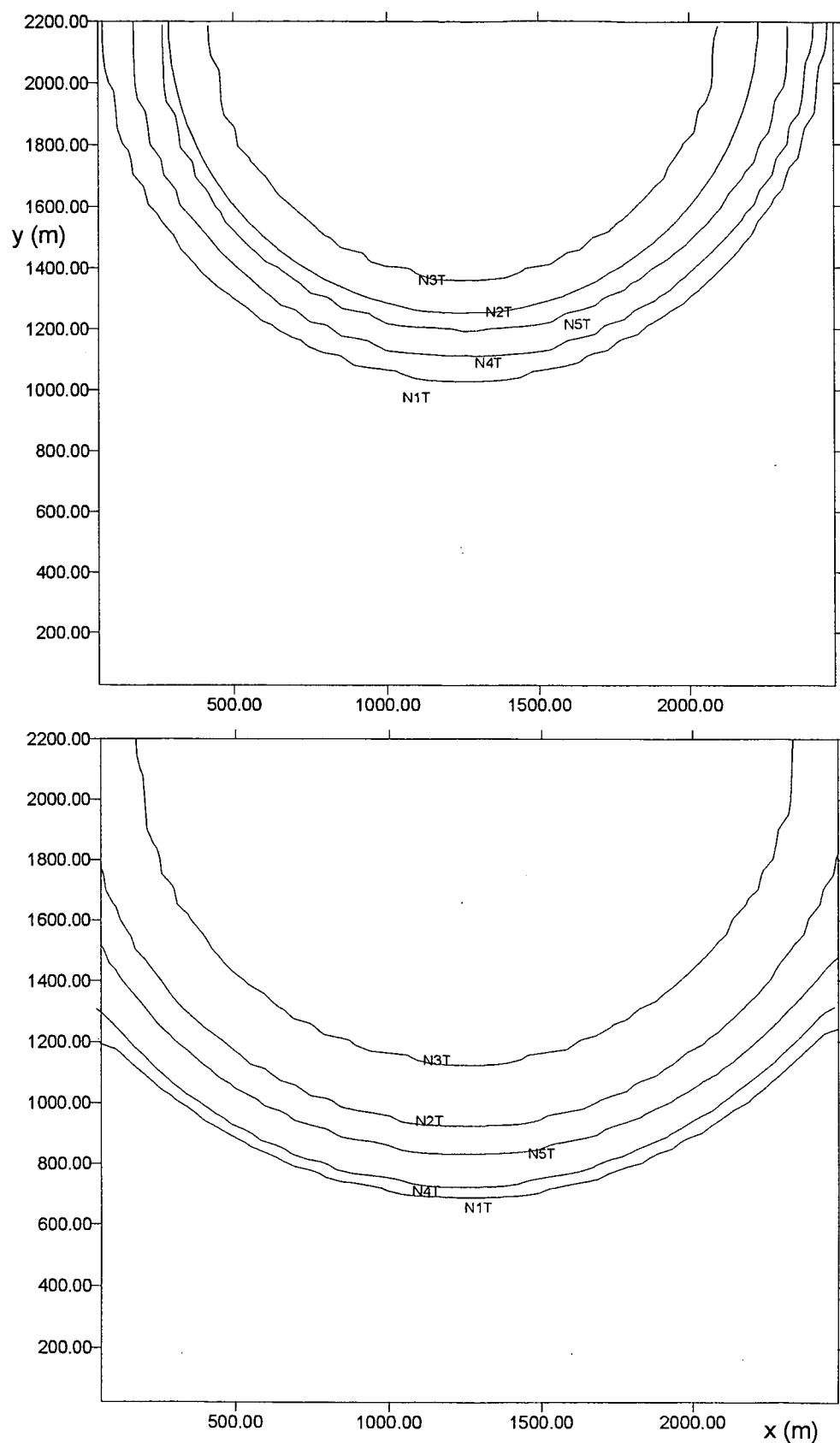


Fig.3.1.40 Comparison between runs N1T to N5T. Plot for $t=1h$ (top) and $t=2h$ (bottom)

3.2 EFFECT OF SLOPE CHANGES

Several numerical simulations have been carried out in order to test the model for different slopes of the inundated plain. All the runs have the same value of the roughness coefficient but different values of the slope in the x and y directions (Fig.3.2.1).

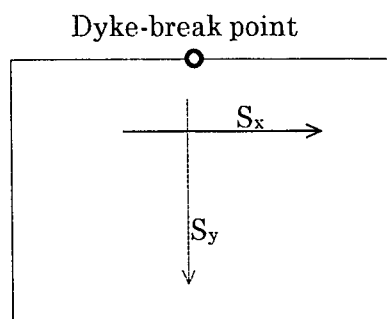


Fig.3.2.1 Slopes of the inundated plain

In Table 3.2.1 is reported a summary of this series of runs.

Table 3.2.1 Runs for the series S

Run	n_0	θ (%)	s_y	s_x	Input hydrograph
S1	0.05	0.0	0.002	0.000	U
S1B	0.05	0.0	0.001	0.000	U
S2	0.05	0.0	0.000	0.001	U
S3	0.05	0.0	0.001	0.001	U
S4	0.05	0.0	0.002	0.001	U
S1T	0.05	0.0	0.002	0.000	T
S1BT	0.05	0.0	0.001	0.000	T
S2T	0.05	0.0	0.000	0.001	T
S3T	0.05	0.0	0.001	0.001	T
S4T	0.05	0.0	0.002	0.001	T

For the runs S1 and S1B (S1T and S1TB for the case of triangular input hydrograph), the immission cell was the number 150 while for the other cases was the cell number 130 in

order to maintain a certain distance from the boundary during the routing of the flooding flow.

Figs. 3.2.2 to 3.2.16 show the results for the runs relative to uniform input hydrograph. In some case, the flow reaches the boundary of the plain and expand laterally due to the zero flux condition for the cells located at the border itself. This can easily be checked by looking at the relative vector plots.

From the graphs is evident that the direction of movement of the flow is that of maximum slope of the plane. Particular attention must be made in the evaluation of the surface plots; in fact they can give, sometimes, a false impression due to the fact that they represent only the depth of water relative to the plain and not the absolute water level.

Fig.3.2.17 reports the graphs of depth as a function of time. In this case, for the run S3, S4 and S5 the points are reported with an apex to denote that they are the equivalent, in term of position relative to the immission cell, to the same points without apex (see Fig.3.1.20).

In Fig.3.2.18 is reported a comparison between the various simulations. The first graph shows the comparison between runs N1 ($s_y=0.0$), S1B ($s_y=0.001$) and S1 ($s_y=0.002$) at time $t=1^h$. The behaviour is evident and the flooded zone is less width and more long with the increasing of the longitudinal slope. The second graph compares the runs N1 ($s_y=0.0$), S1B ($s_y=0.001$), S1 ($s_y=0.002$) and the runs S2, S3 and S4 that have a non-zero slope also in the transversal directions; also in this case, the effect of the slopes is evident.

Figs. 3.2.19 to 3.2.33 show the results for the case with triangular input hydrograph. Fig.3.2.34 reports the depth as a function of time as has been done for the case of uniform input flow.

Figs.3.2.35 and 3.2.36 show the comparison between the various simulations. In Fig. 3.2.35 are reported the fronts of the water for the runs N1T, S1BT and S1T at time $t=1^h$. Fig.3.2.36 shows the comparison, for $t=1$ and 2^h of the runs S2T ($s_y=0.0$ and $s_x=0.001$), S3T ($s_y=0.001$ and $s_x=0.001$) and S4T ($s_y=0.002$ and $s_x=0.001$).

Finally, Fig.3.2.37 reports the water front for all the runs of the series plus run N1T for which the inundated plan is horizontal.

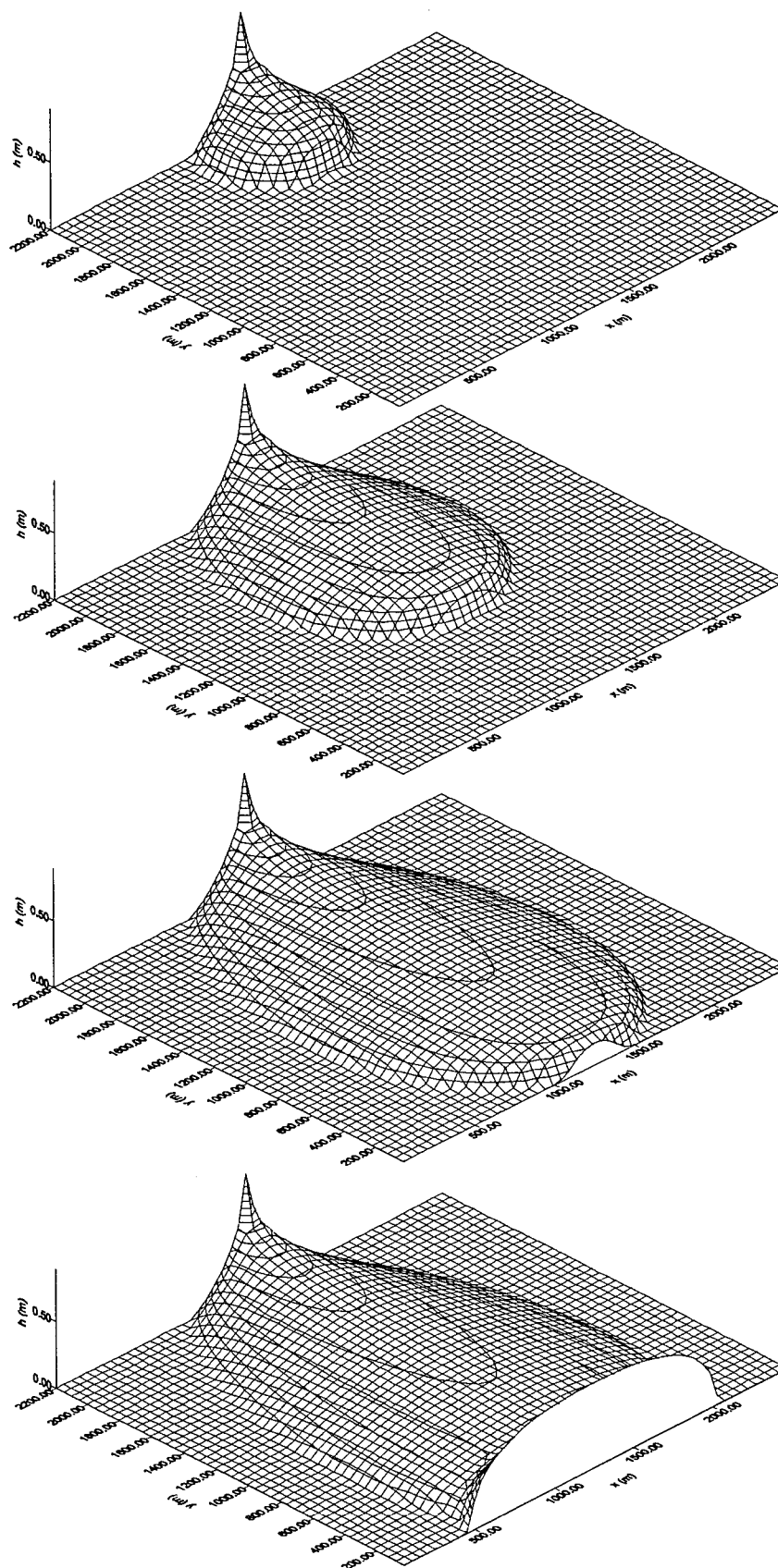


Fig.3.2.2 Surface plot for run S1. From top to bottom: $t=20'$, $t=1$ hour, $t=1\text{h}40'$ and $t=2$ hours (x , y and z scale in meters).

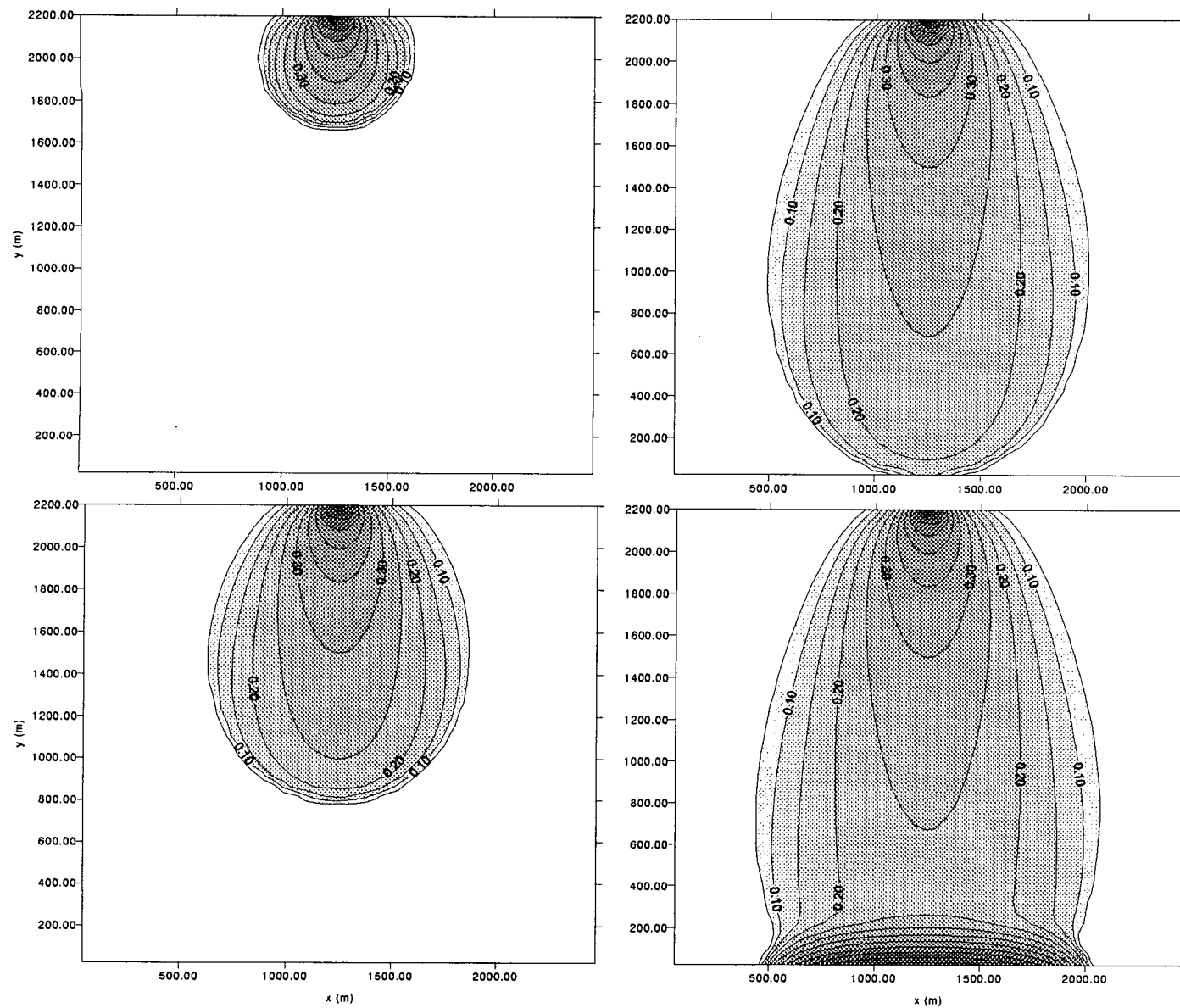


Fig.3.2.3 Contour plot for run S1. On the left: top $t=20'$, bottom $t=1\text{ hour}$; on the right: top $t=1\text{h}40'$, bottom $t=2\text{ hours}$ (scale in meter).

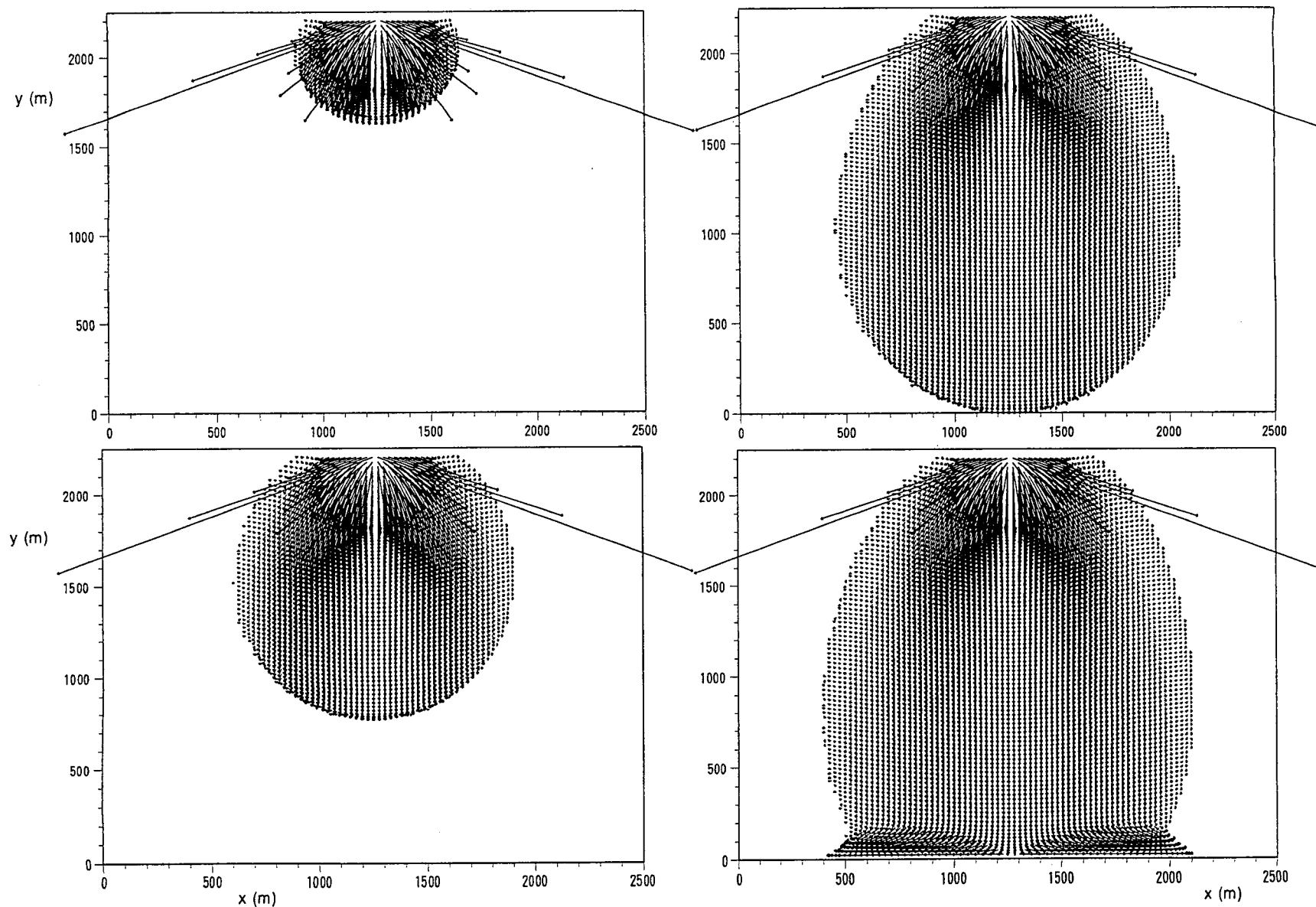


Fig.3.2.4 Vector plot for run S1. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 1000 times the plot unit.

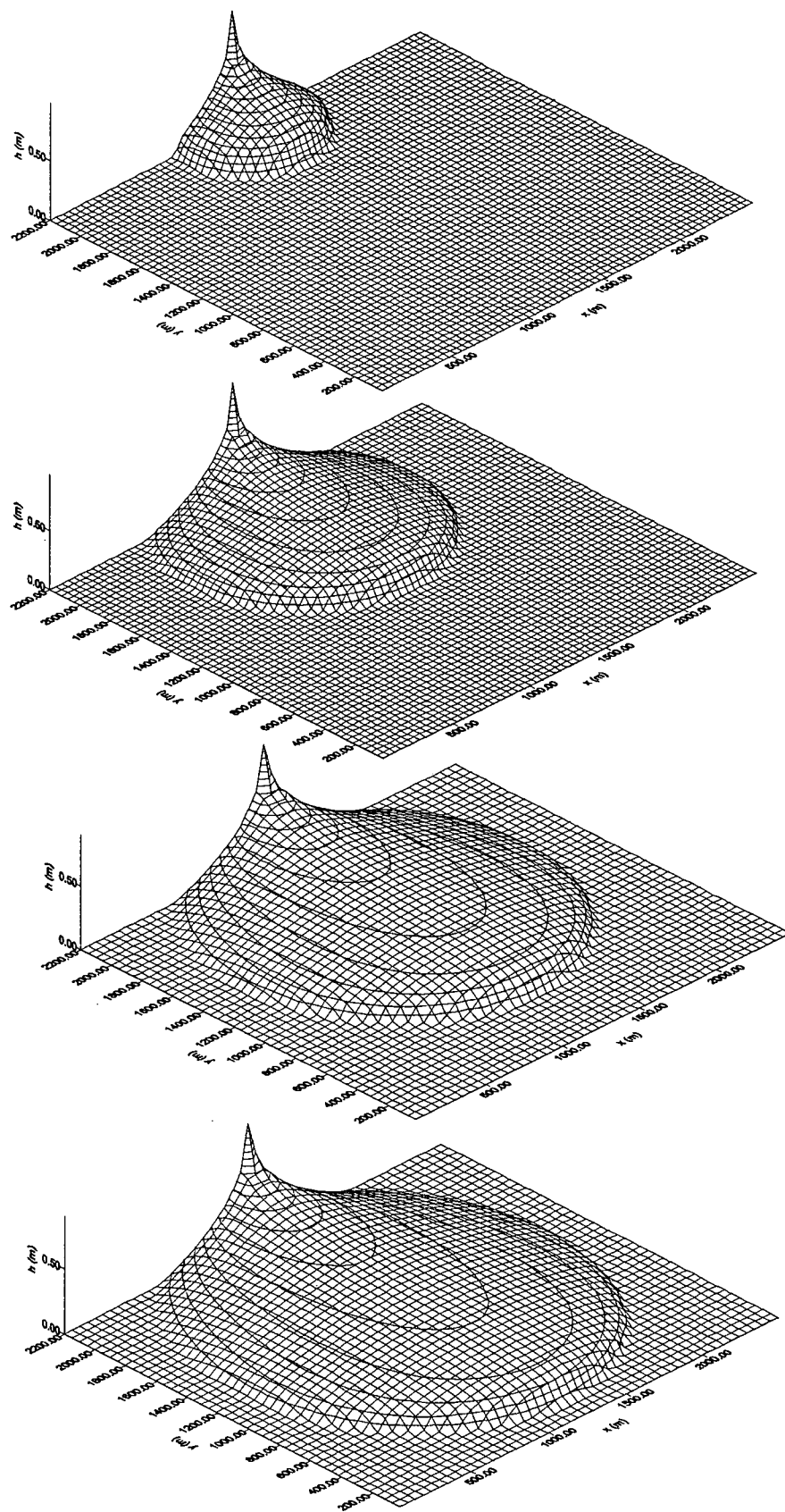


Fig.3.2.5 Surface plot for run S1B. From top to bottom: $t=20'$, $t=1$ hour, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

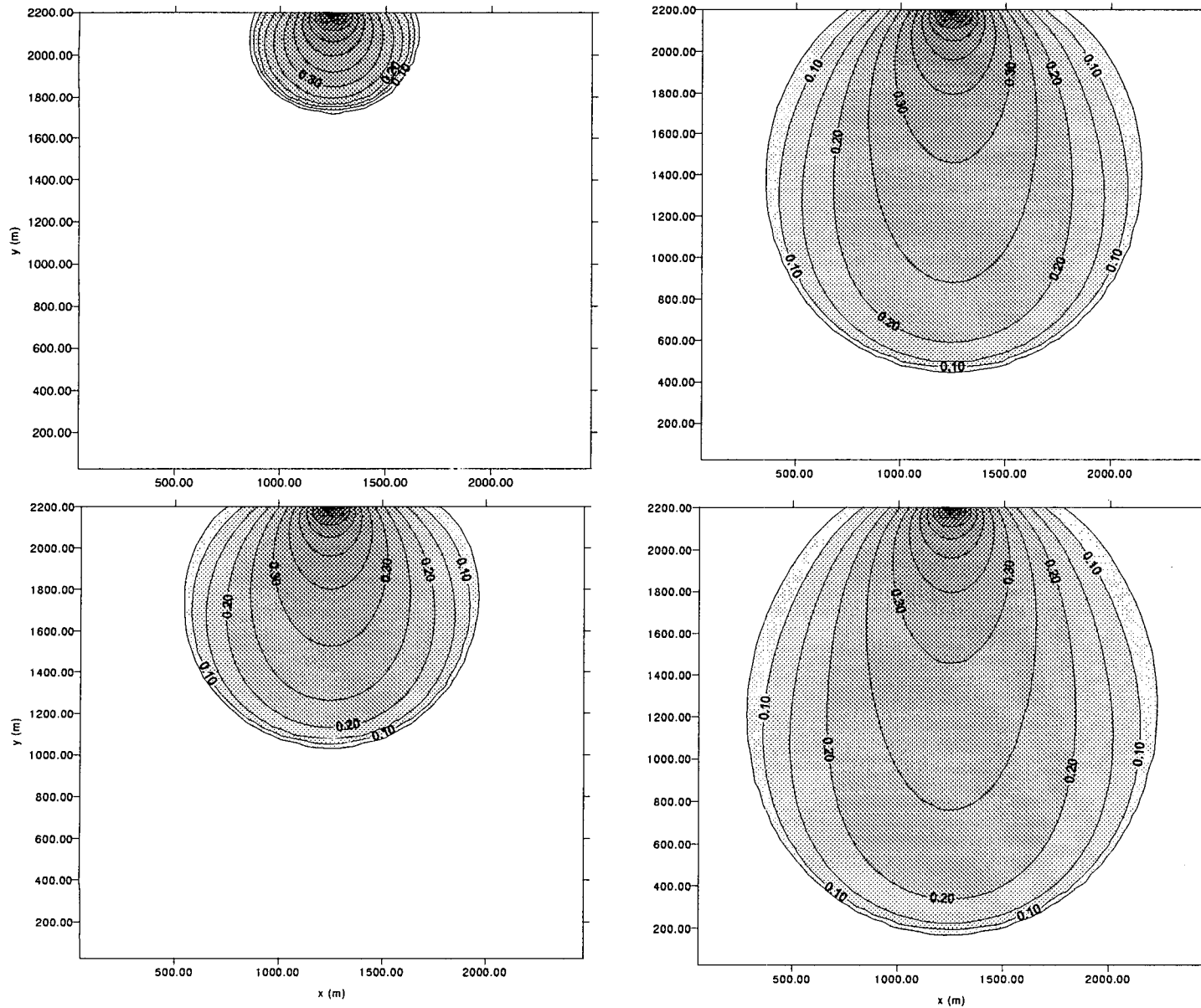


Fig.3.2.6 Contour plot for run S1B. On the left: top $t=20'$, bottom $t=1\text{ hour}$; on the right: top $t=1\text{h}40'$, bottom $t=2\text{ hours}$ (scale in meter).

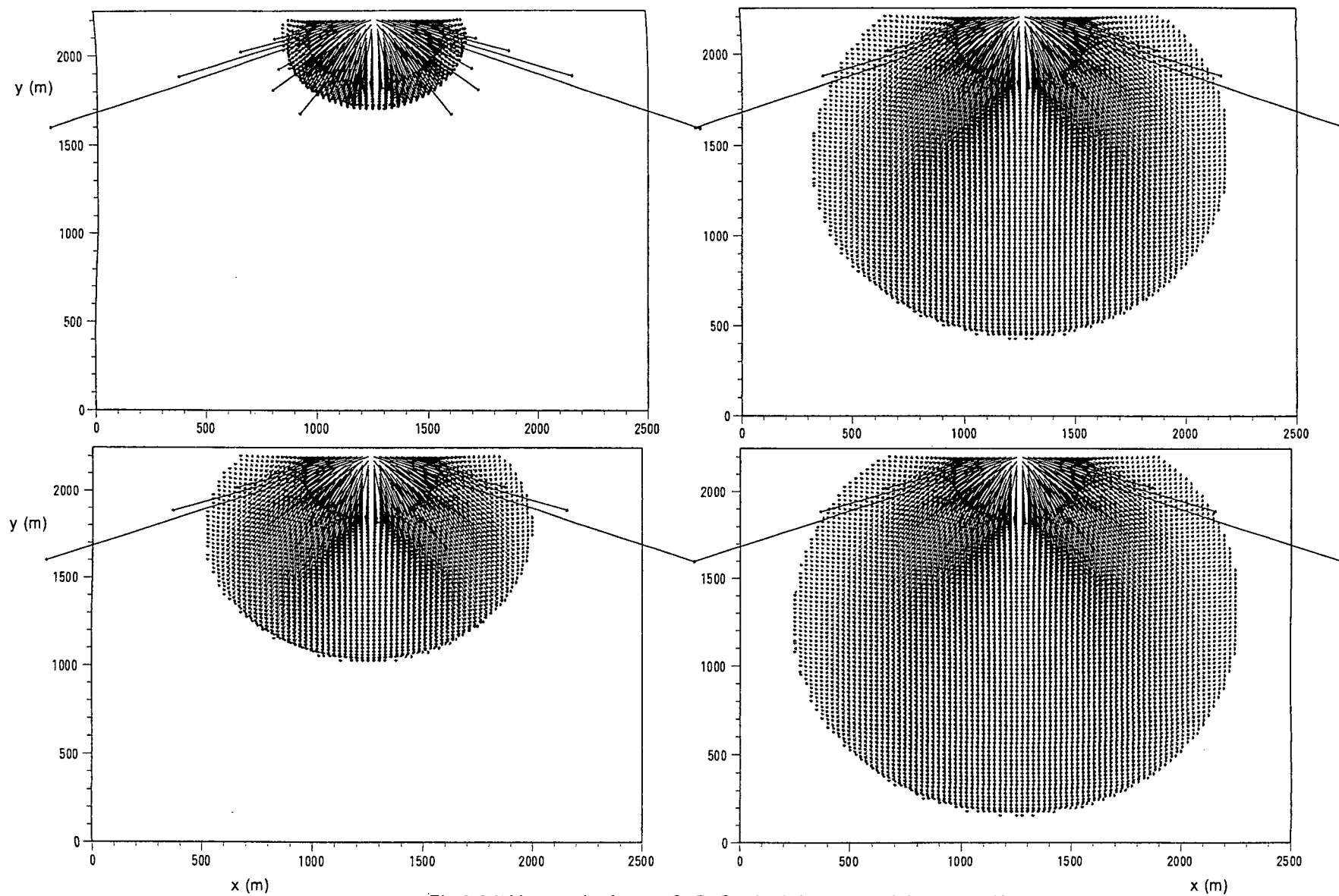


Fig.3.2.7 Vector plot for run S1B. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 1000 times the plot unit.

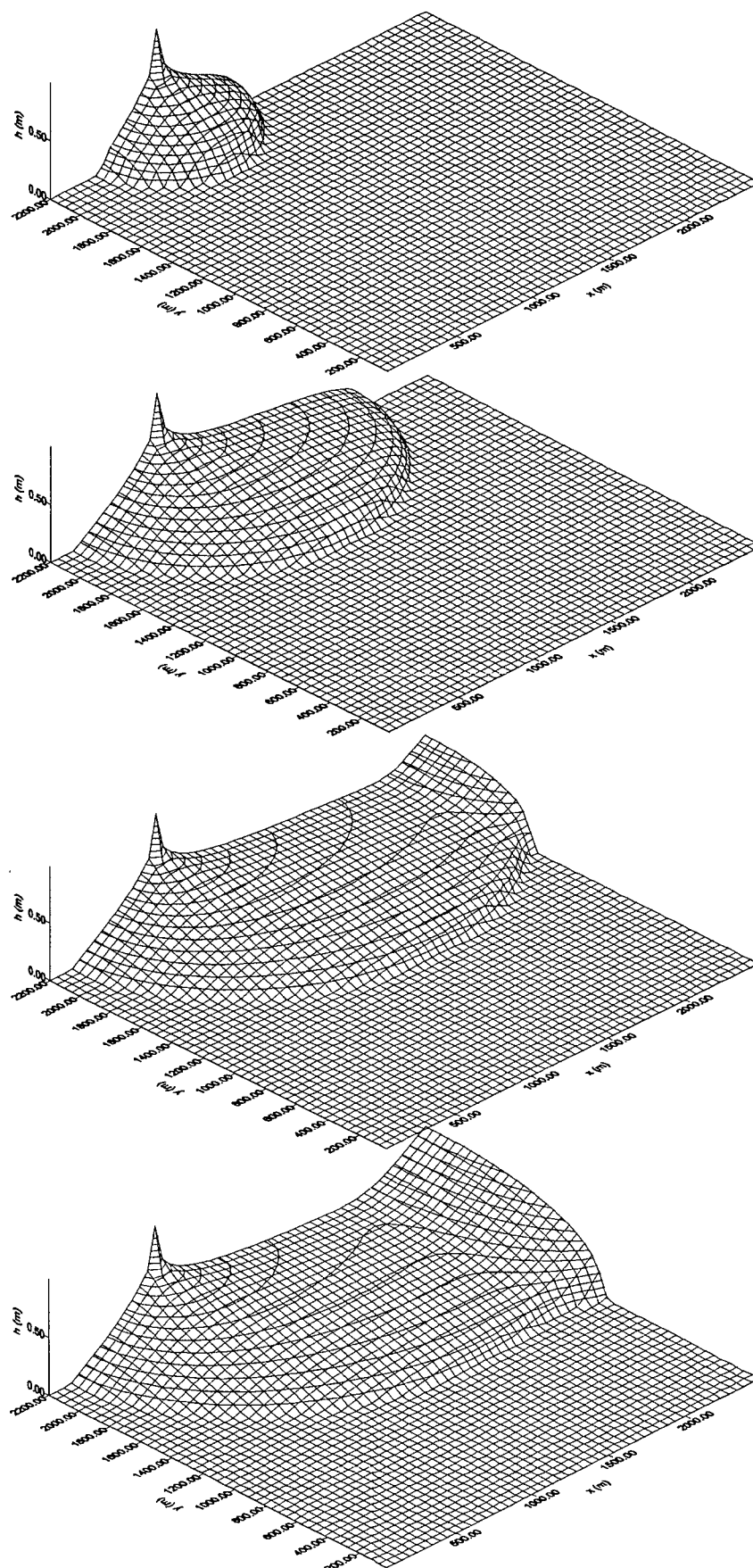


Fig.3.2.8 Surface plot for run S2. From top to bottom: $t=20'$, $t=1$ hour, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

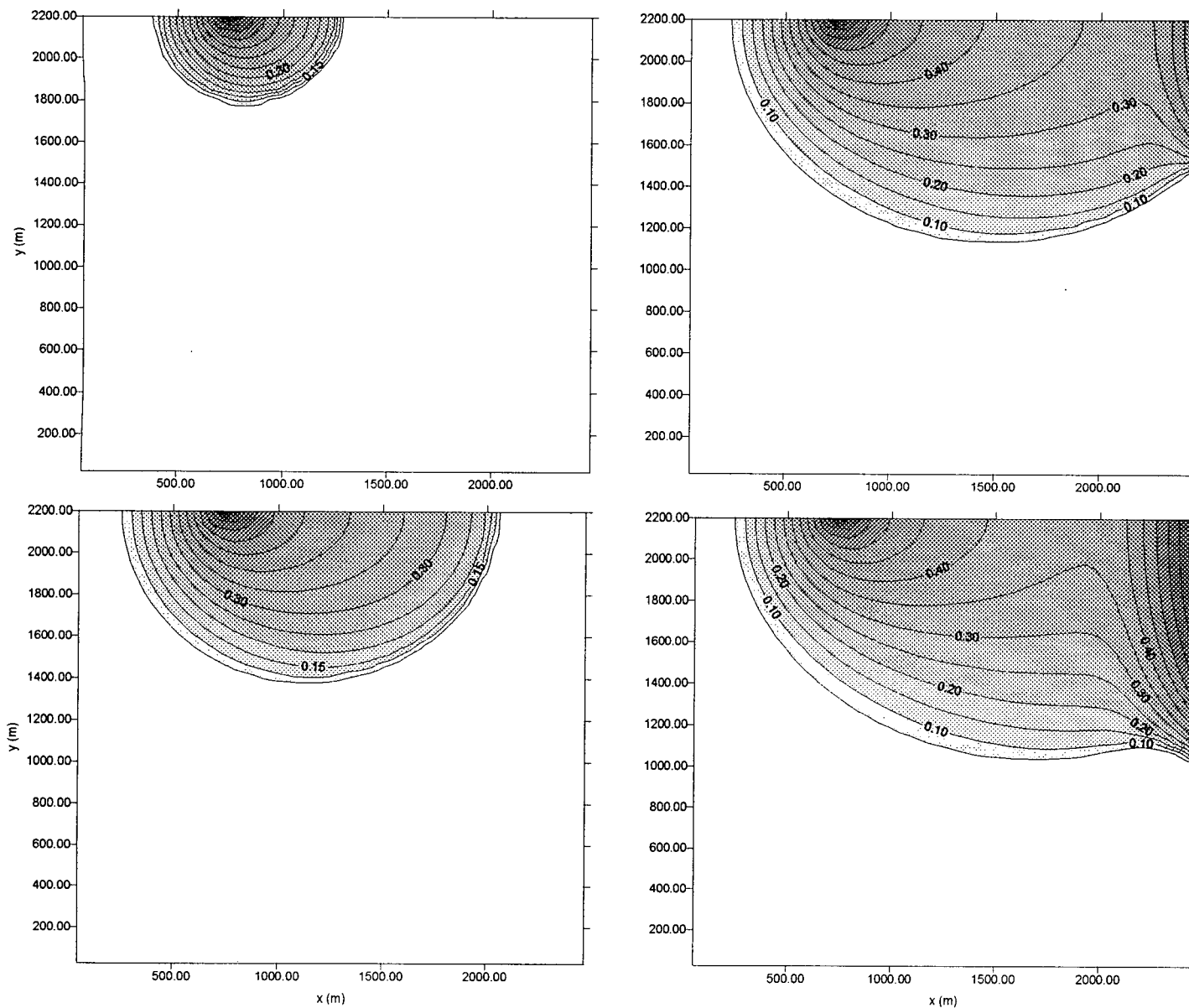


Fig.3.2.9 Contour plot for run S2. On the left: top $t=20'$, bottom $t=1$ hour; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

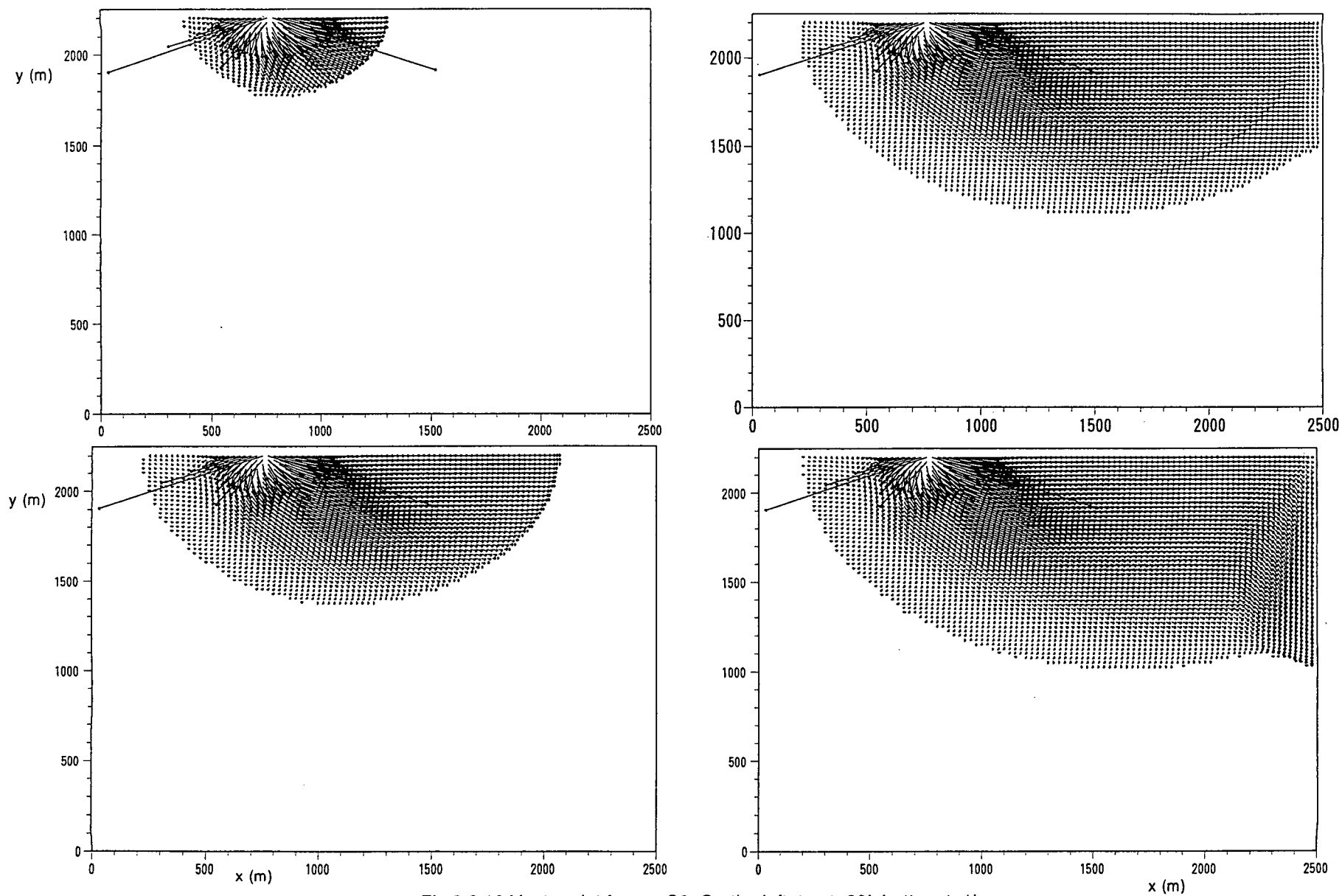


Fig.3.2.10 Vector plot for run S2. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 500 times the plot unit.

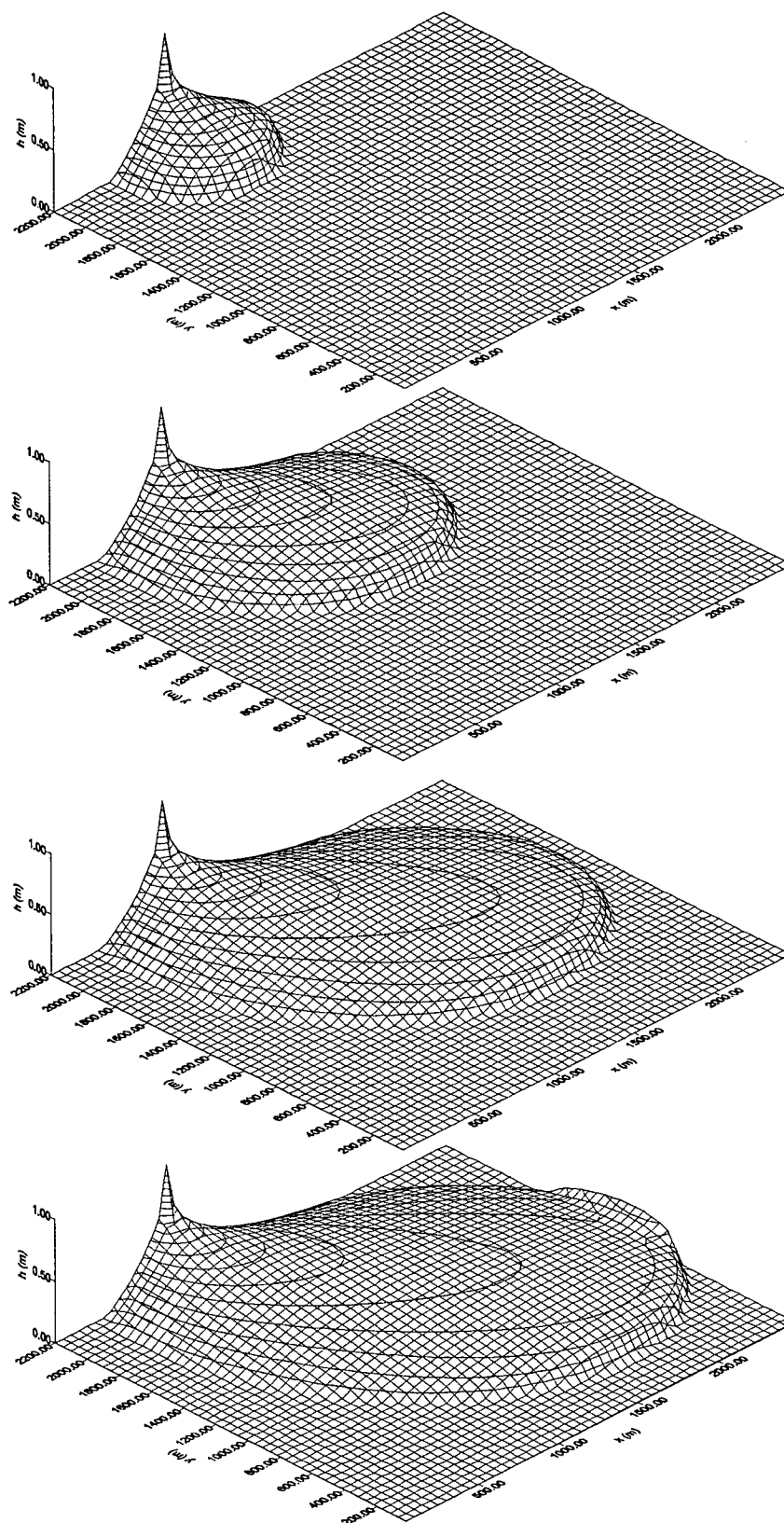


Fig.3.2.11 Surface plot for run S3. From top to bottom: $t=20'$, $t=1 \text{ hour}$, $t=1\text{h}40'$ and $t=2 \text{ hours}$ (x , y and z scale in meters).

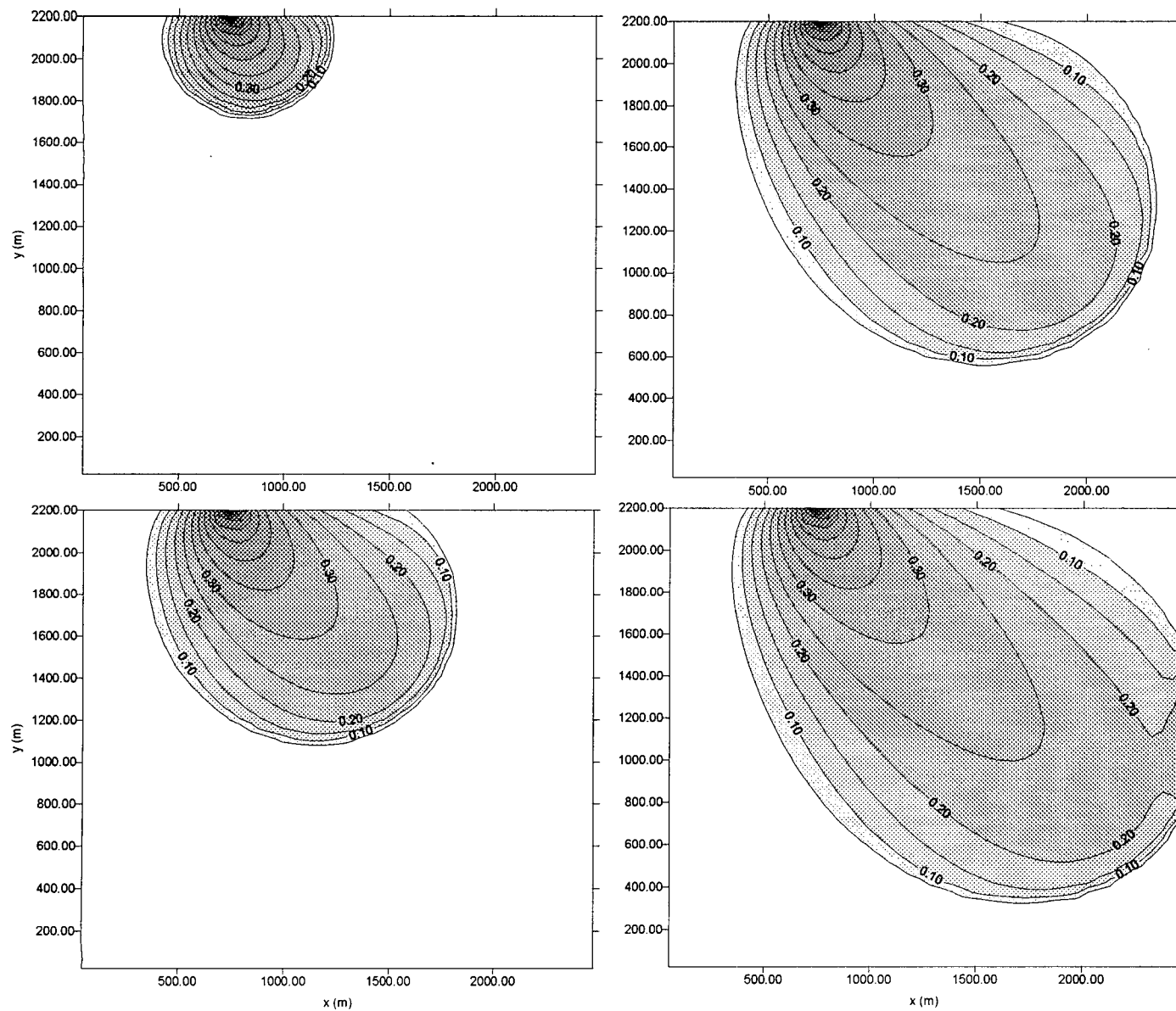


Fig.3.2.12 Contour plot for run S3. On the left: top $t=20'$, bottom $t=1$ hour; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

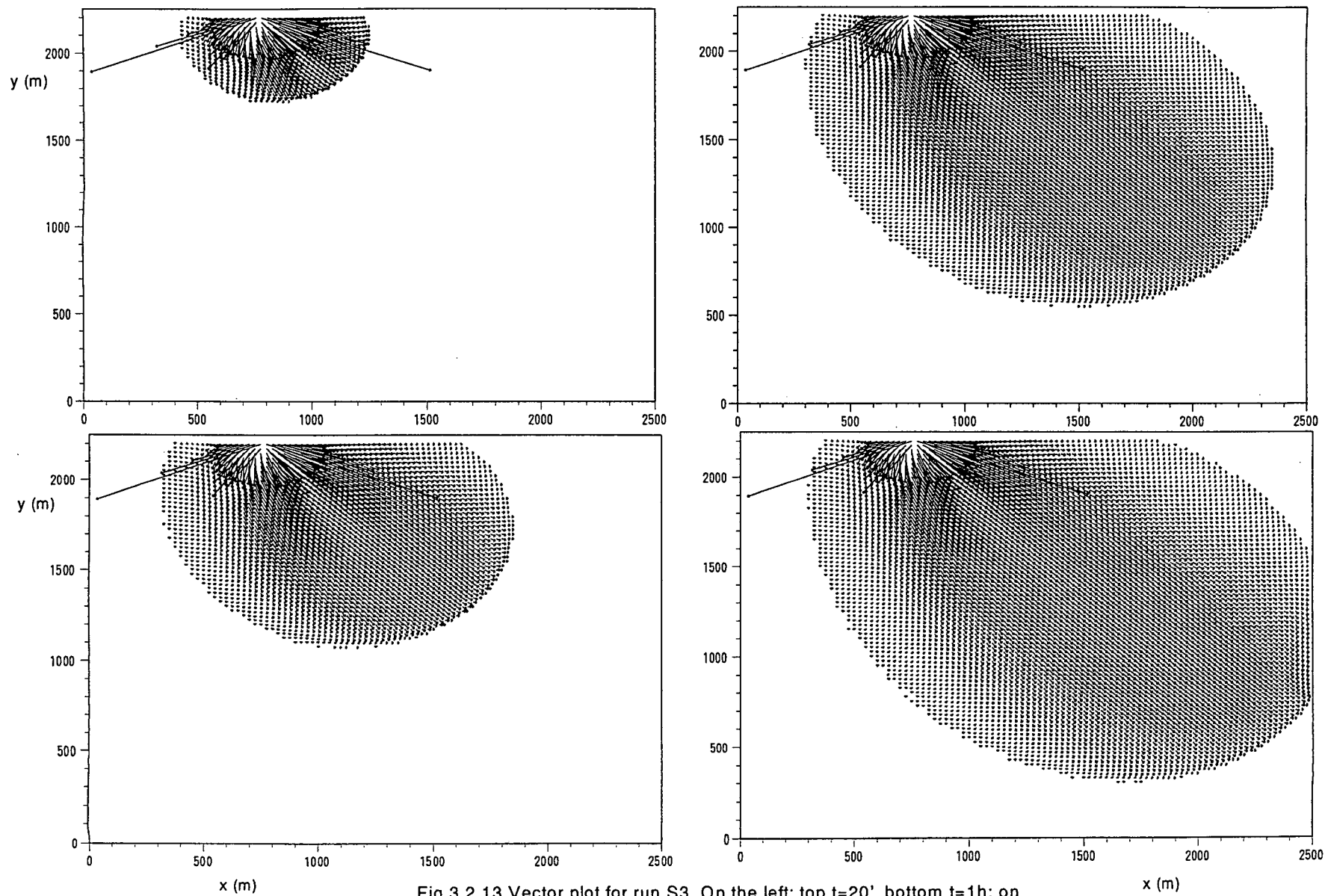


Fig.3.2.13 Vector plot for run S3. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 500 times the plot unit.

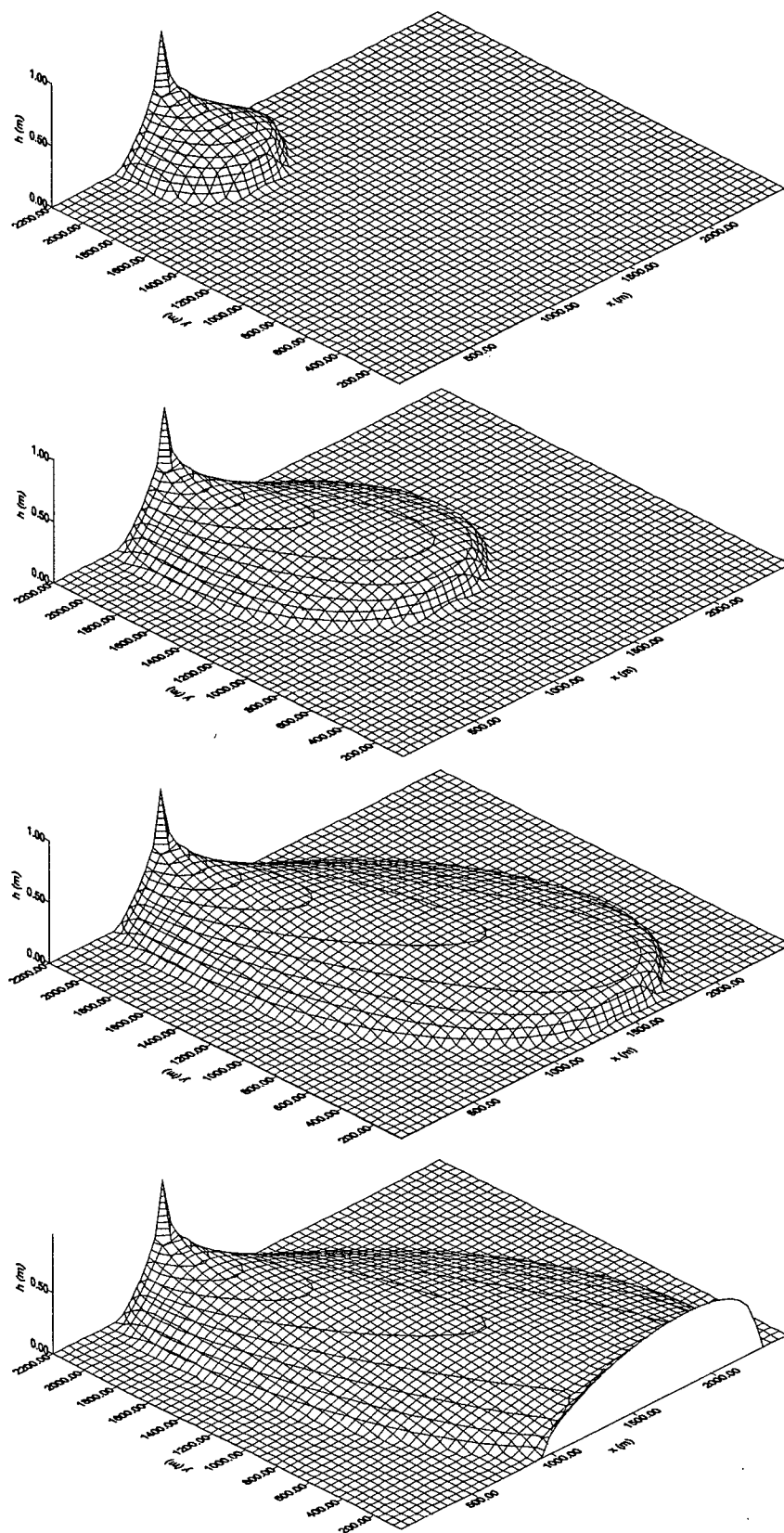


Fig.3.2.14 Surface plot for run S4. From top to bottom: $t=20'$, $t=1$ hour, $t=1\text{h}40'$ and $t=2$ hours (x , y and z scale in meters).

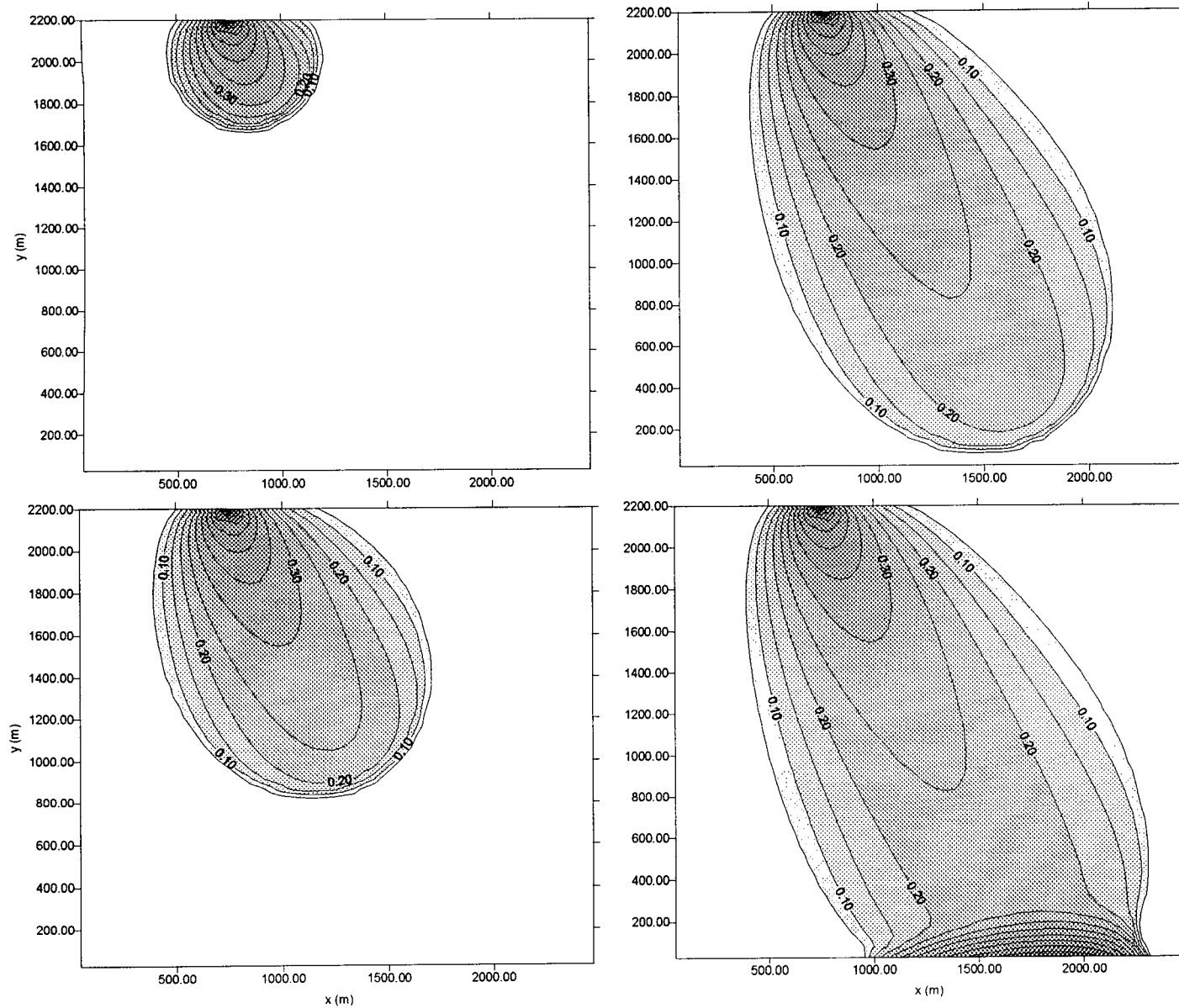


Fig.3.2.15 Contour plot for run S4. On the left: top $t=20'$, bottom $t=1$ hour; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

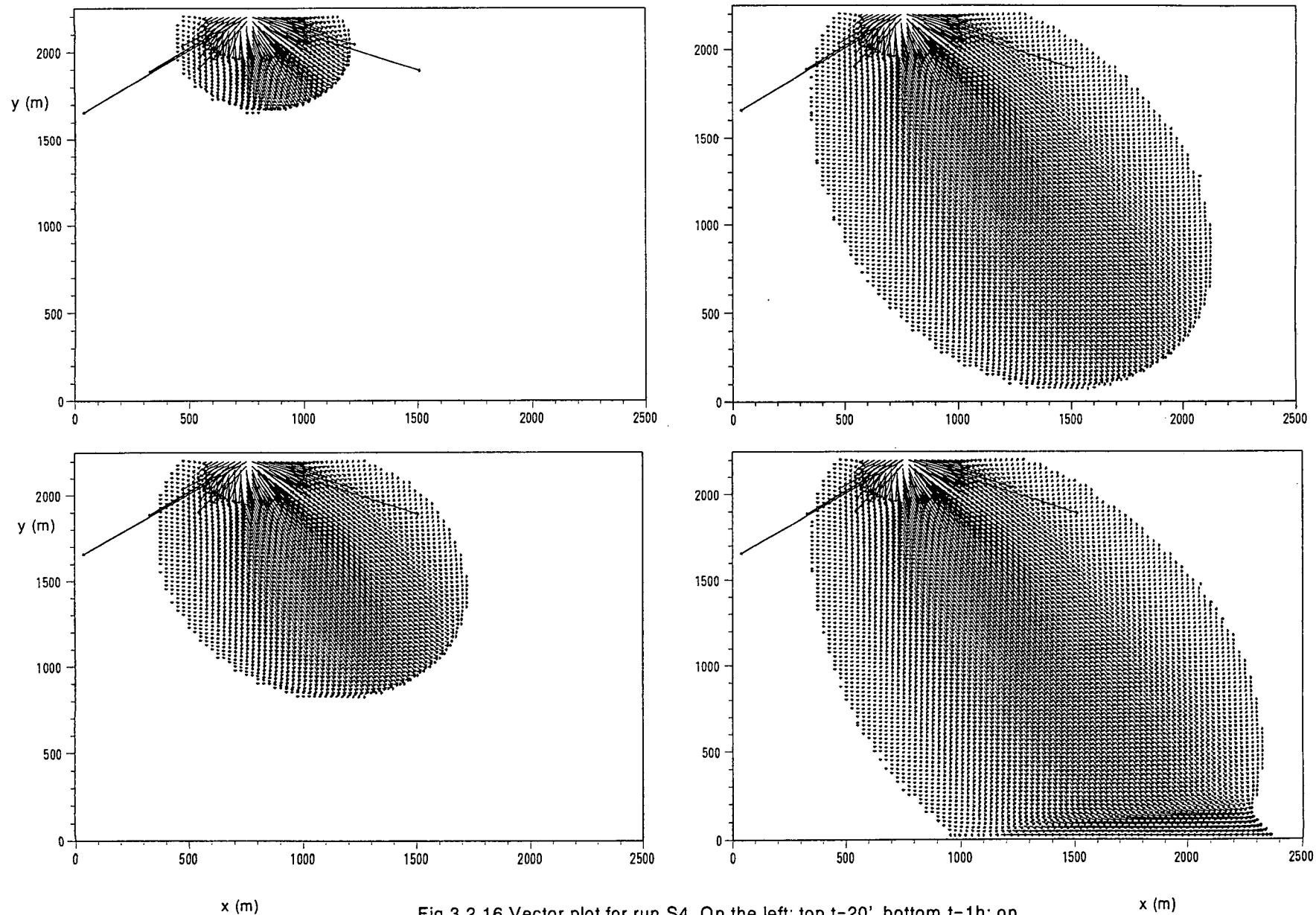


Fig.3.2.16 Vector plot for run S4. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 500 times the plot unit.

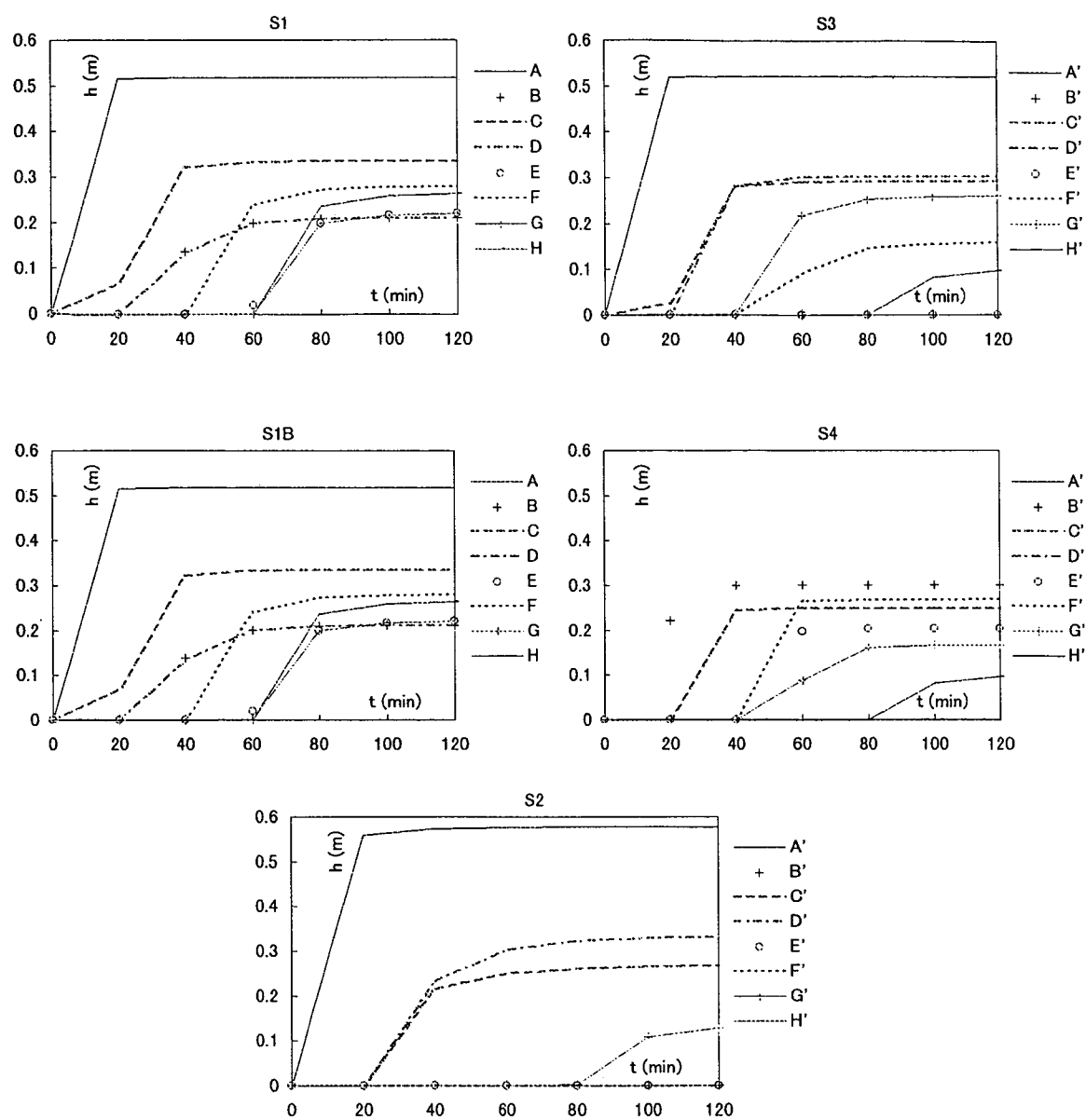


Fig.3.2.17 Water depth as a function of time for selected points for runs S1 to S4

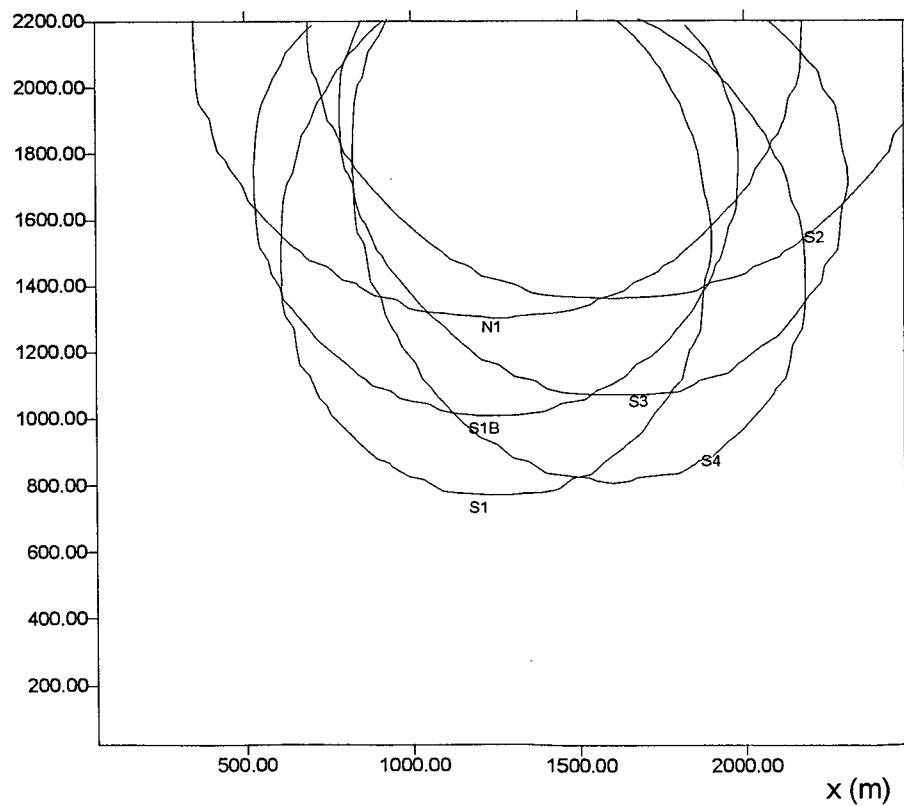
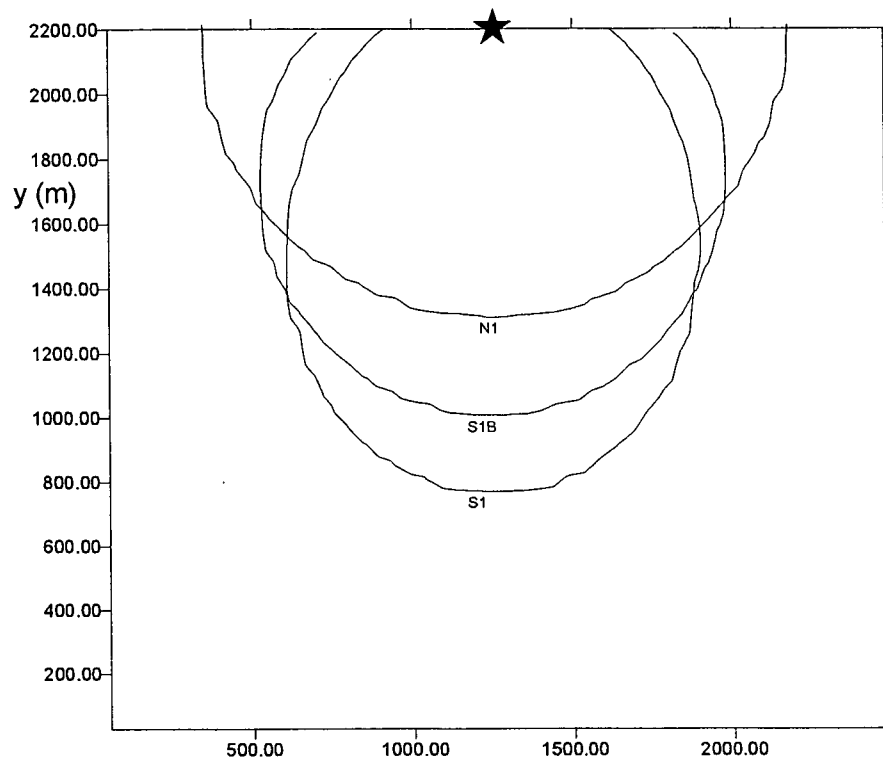


Fig.3.2.18 On the top: comparison between run N1, S1B and S1 for $t=1h$; on the bottom: comparison between run N1, S1B, S2, S3, S4 and S1 for $t=1h$.

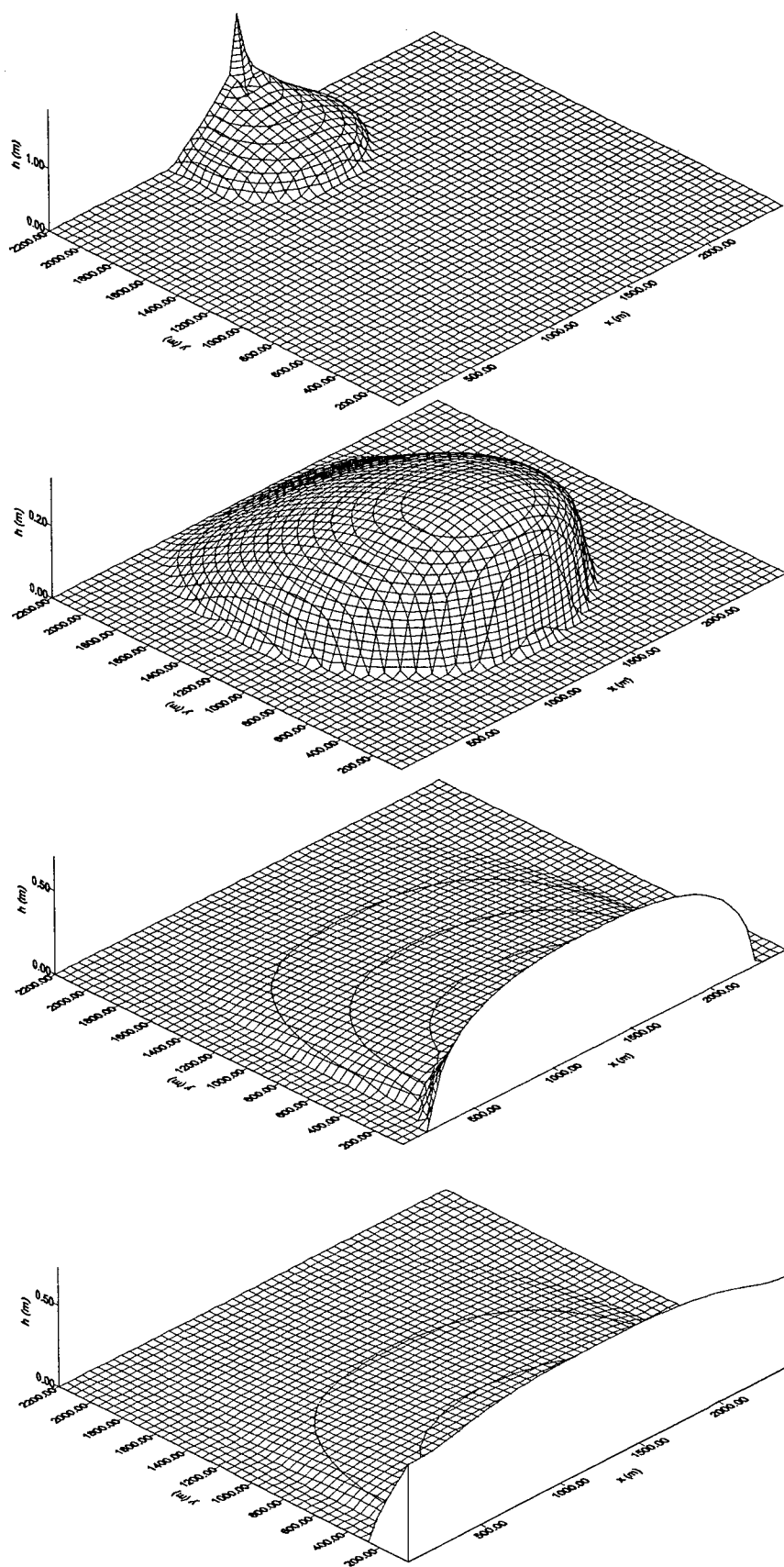


Fig.3.2.19 Surface plot for run S1T. From top to bottom: $t=20'$, $t=1$ hour, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

Fig.3.2.20 Contour plot for run S1T. On the left: top $t=20'$, bottom $t=1$ hour; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

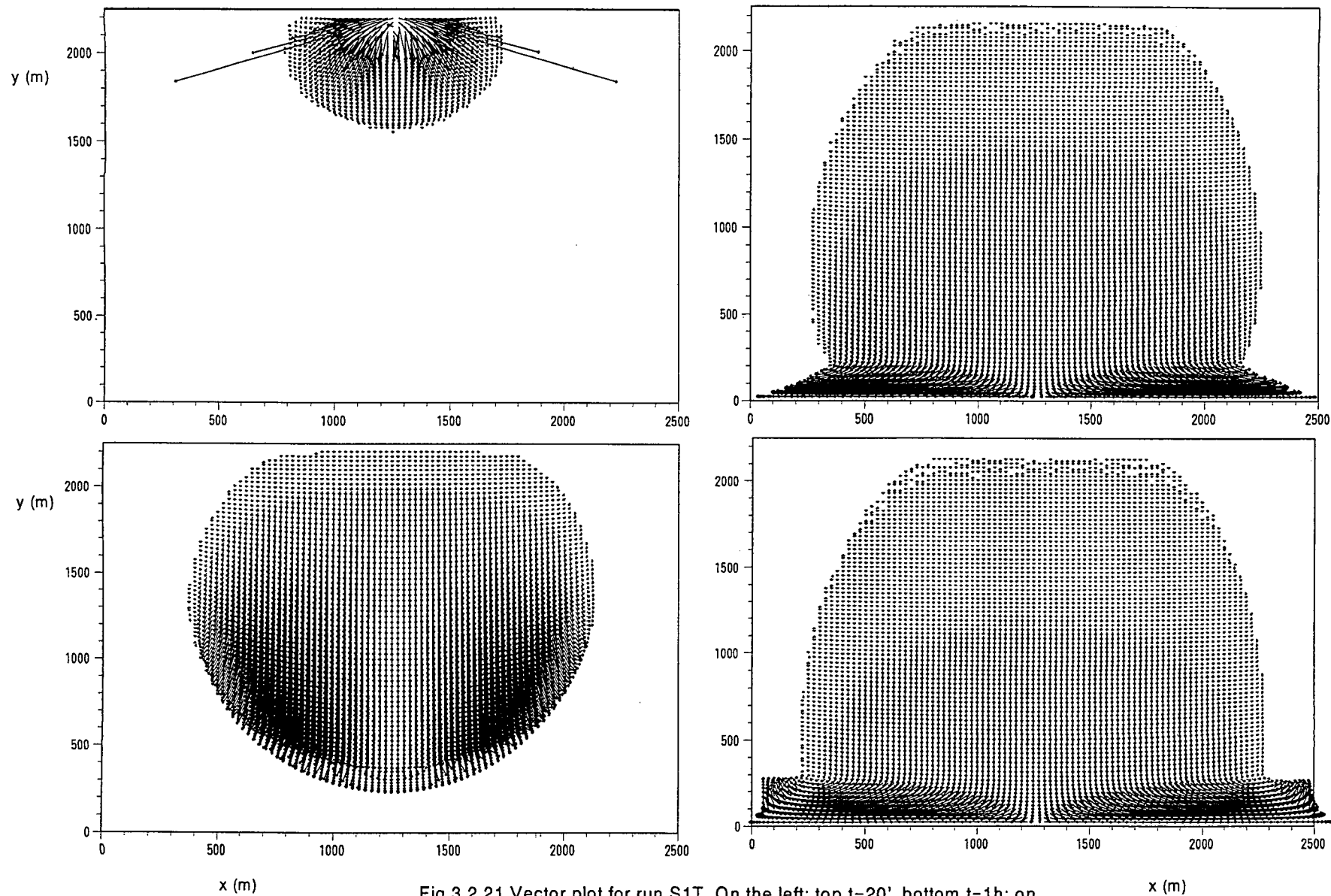


Fig.3.2.21 Vector plot for run S1T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 150 times the plot unit for $t=20'$ and 2000 for $t=1h$, $t=1h40'$, $t=2h$.

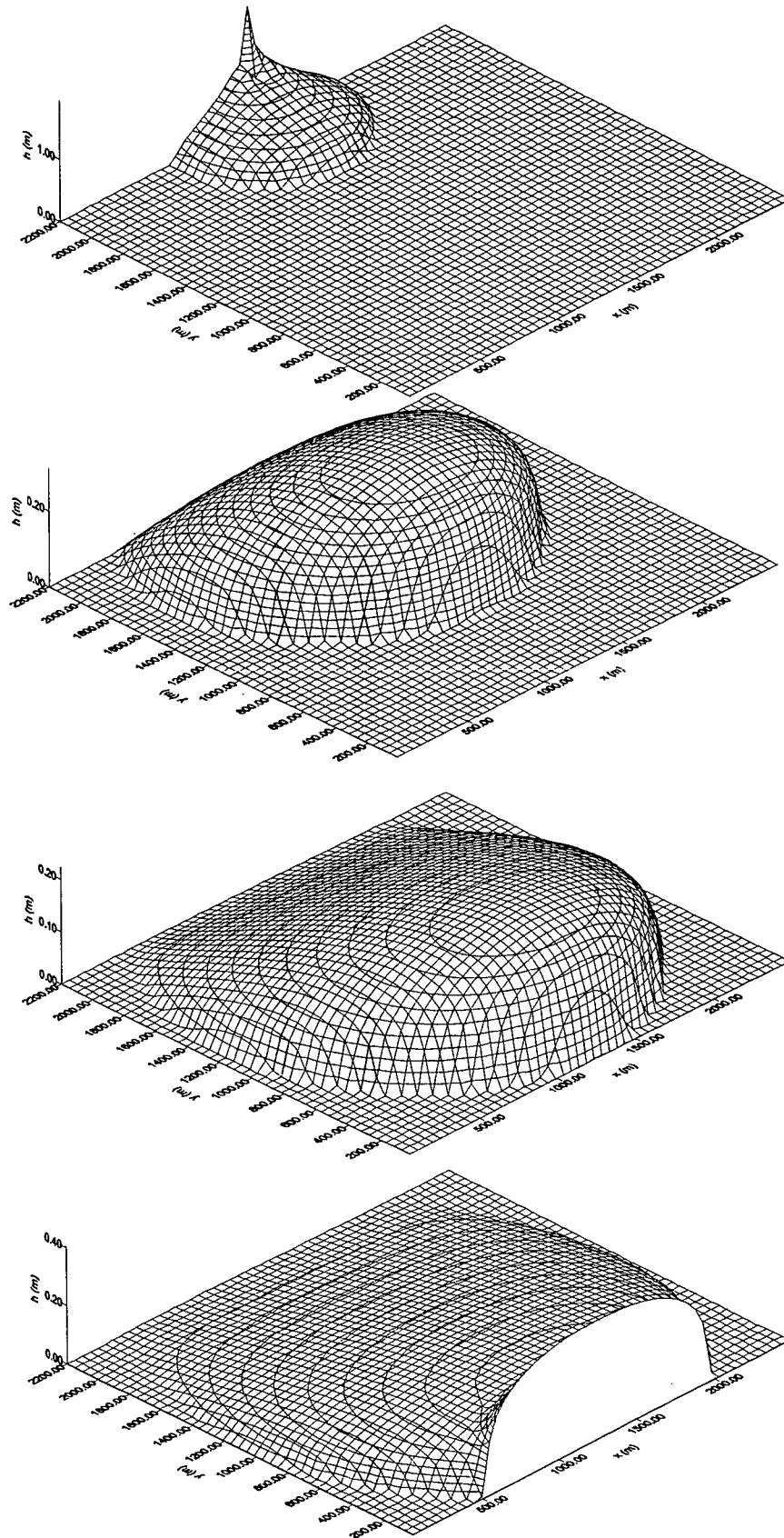


Fig.3.2.22 Surface plot for run S1BT. From top to bottom: $t=20'$, $t=1$ hour, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

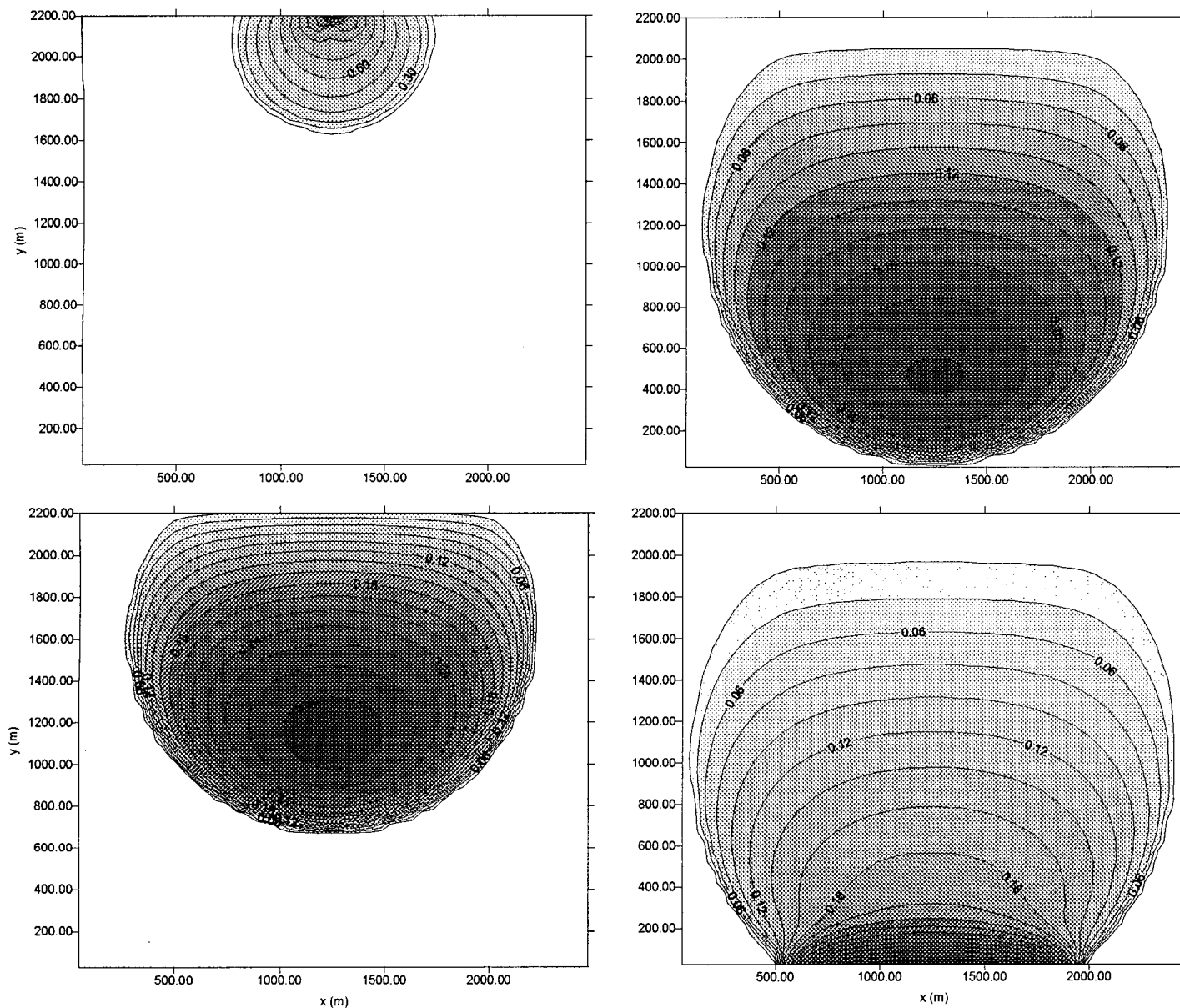


Fig.3.2.23 Contour plot for run S1BT. On the left: top t=20', bottom t=1 hour; on the right: top t=1h40', bottom t= 2 hours (scale in meter).

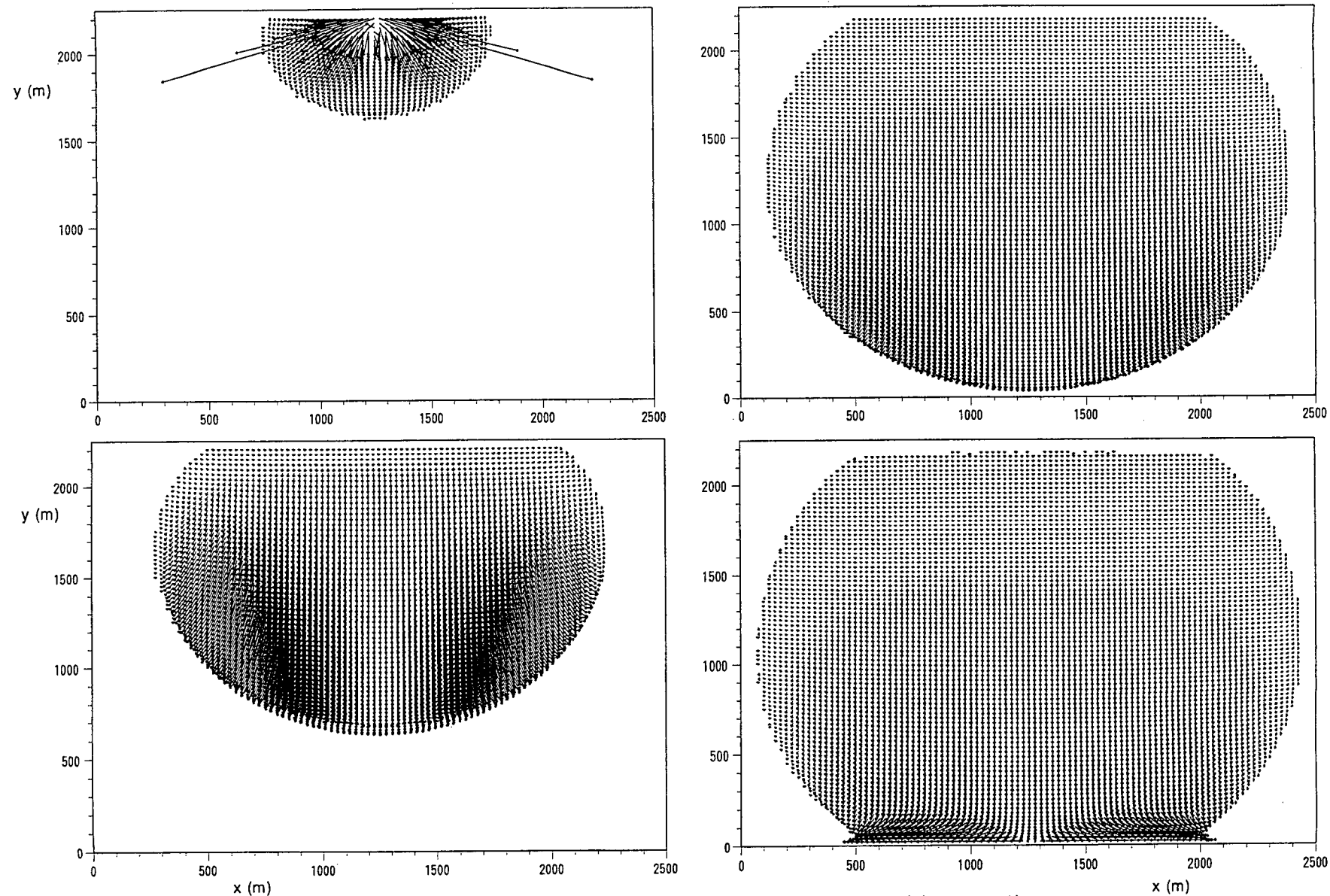


Fig.3.2.24 Vector plot for run S1BT. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 150 times the plot unit for $t=20'$ and 2000 for $t=1h$, $t=1h40'$, $t=2h$.

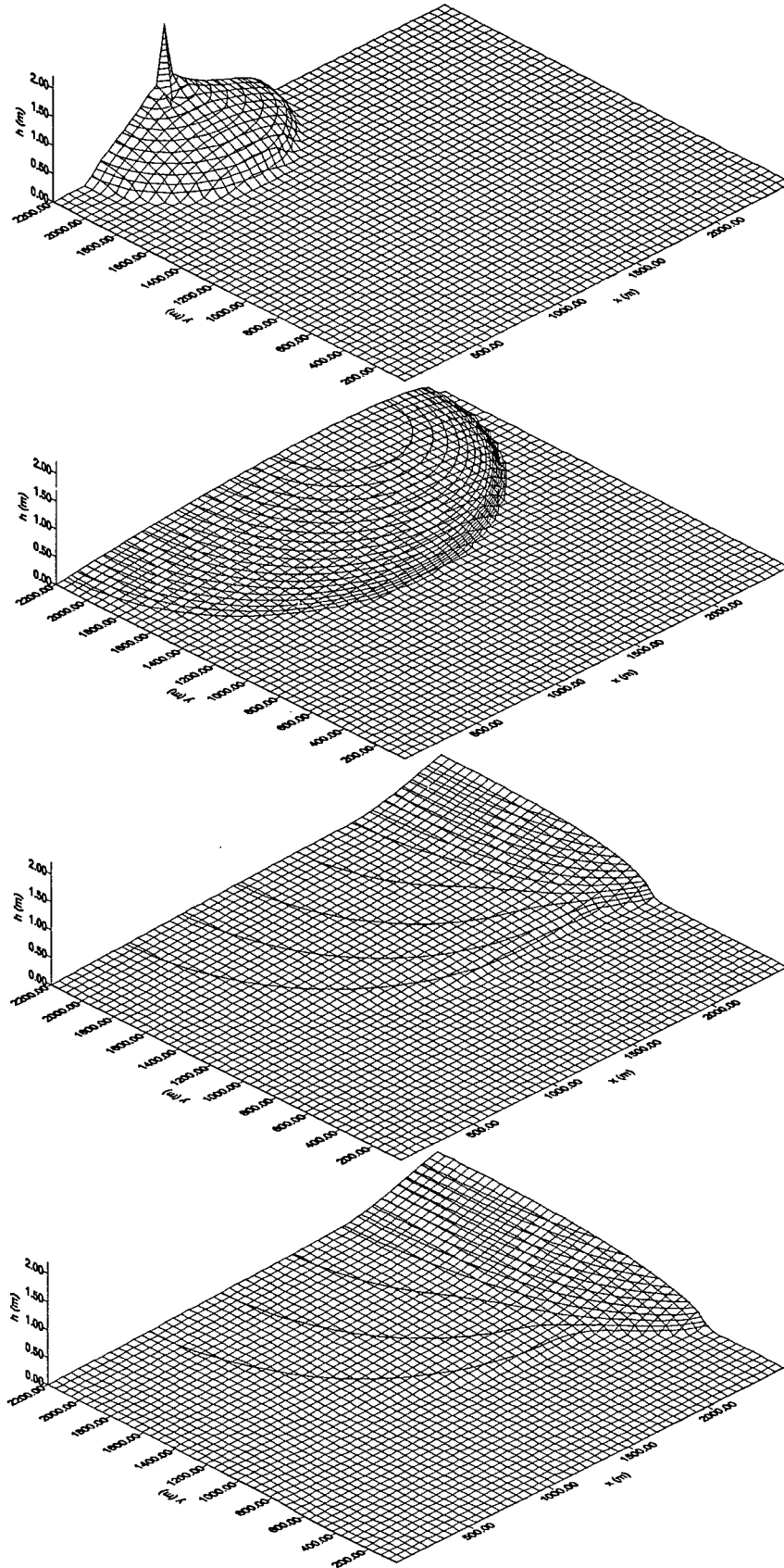


Fig.3.2.25 Surface plot for run S2T. From top to bottom: $t=20'$, $t=1$ hour, $t=1$ h40' and $t=2$ hours (x , y and z scale in meters).

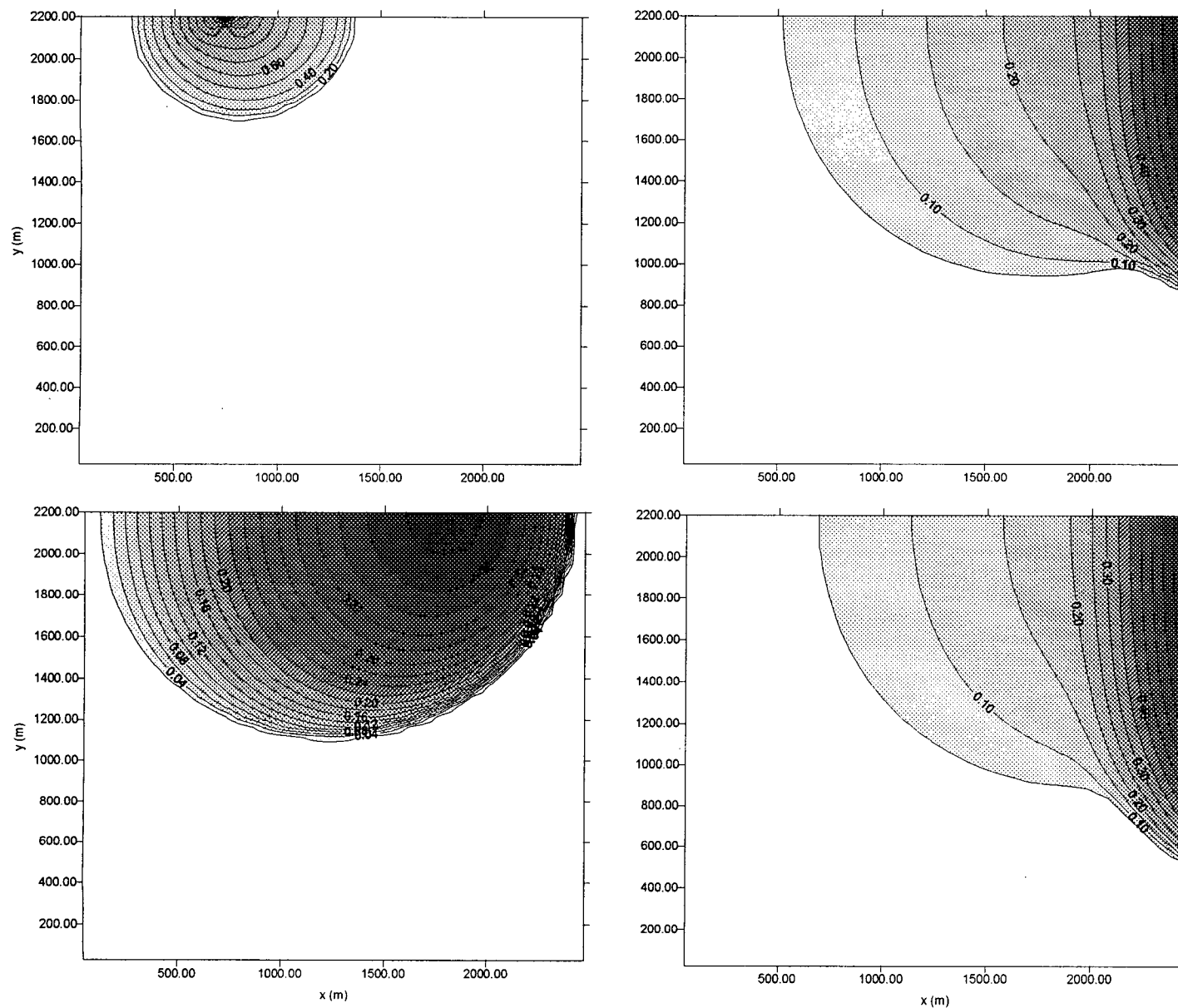


Fig.3.2.26 Contour plot for run S2T. On the left: top $t=20'$, bottom $t=1$ hour; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

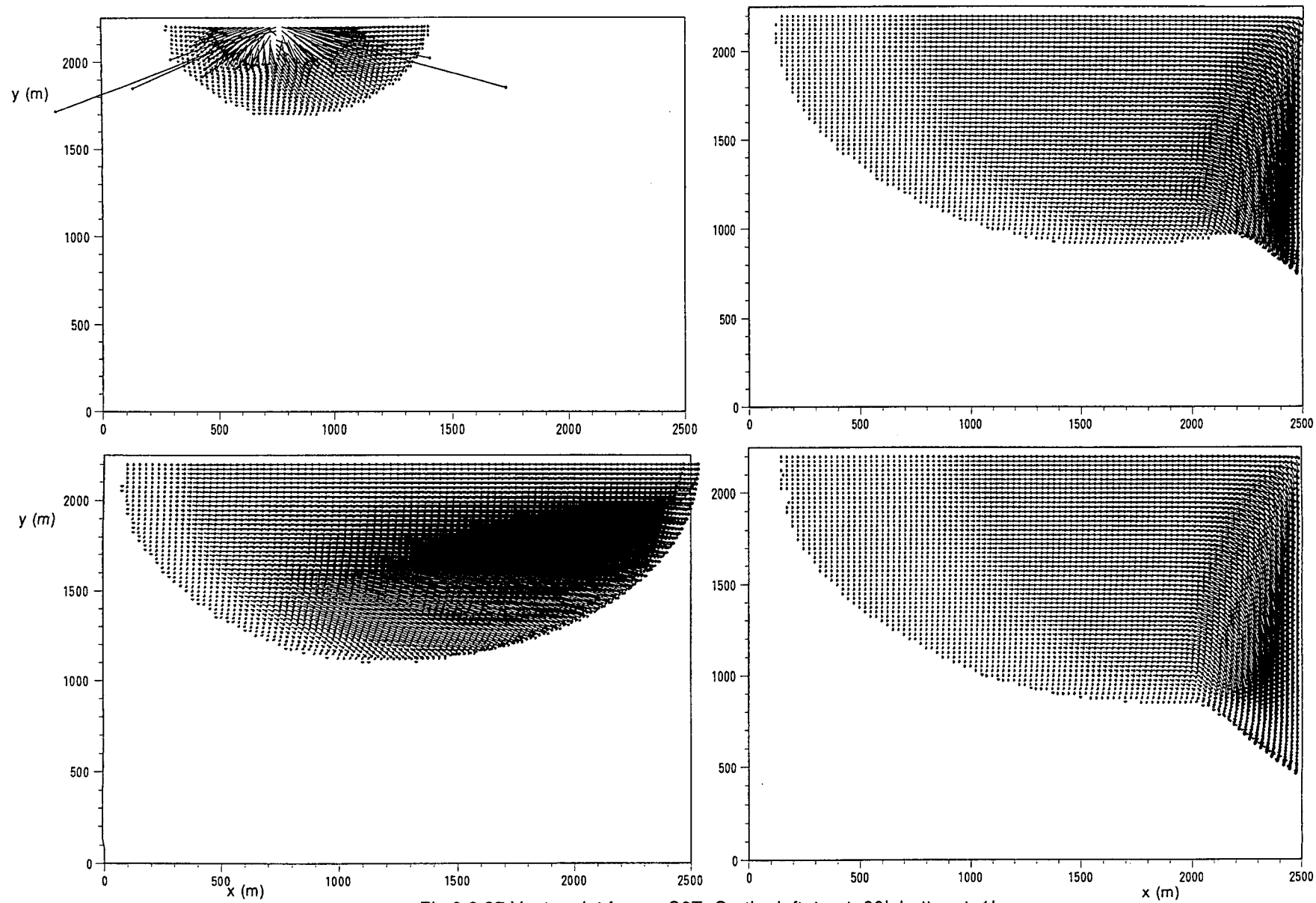


Fig.3.2.27 Vector plot for run S2T. On the left: top $t=20'$, bottom $t=1\text{h}$; on the right: top $t=1\text{h}40'$, bottom $t=2\text{h}$. The scale for the vector flux (m^2/s) is 150 times the plot unit for $t=20'$ and 2000 for $t=1\text{h}$, $t=1\text{h}40'$, $t=2\text{h}$.

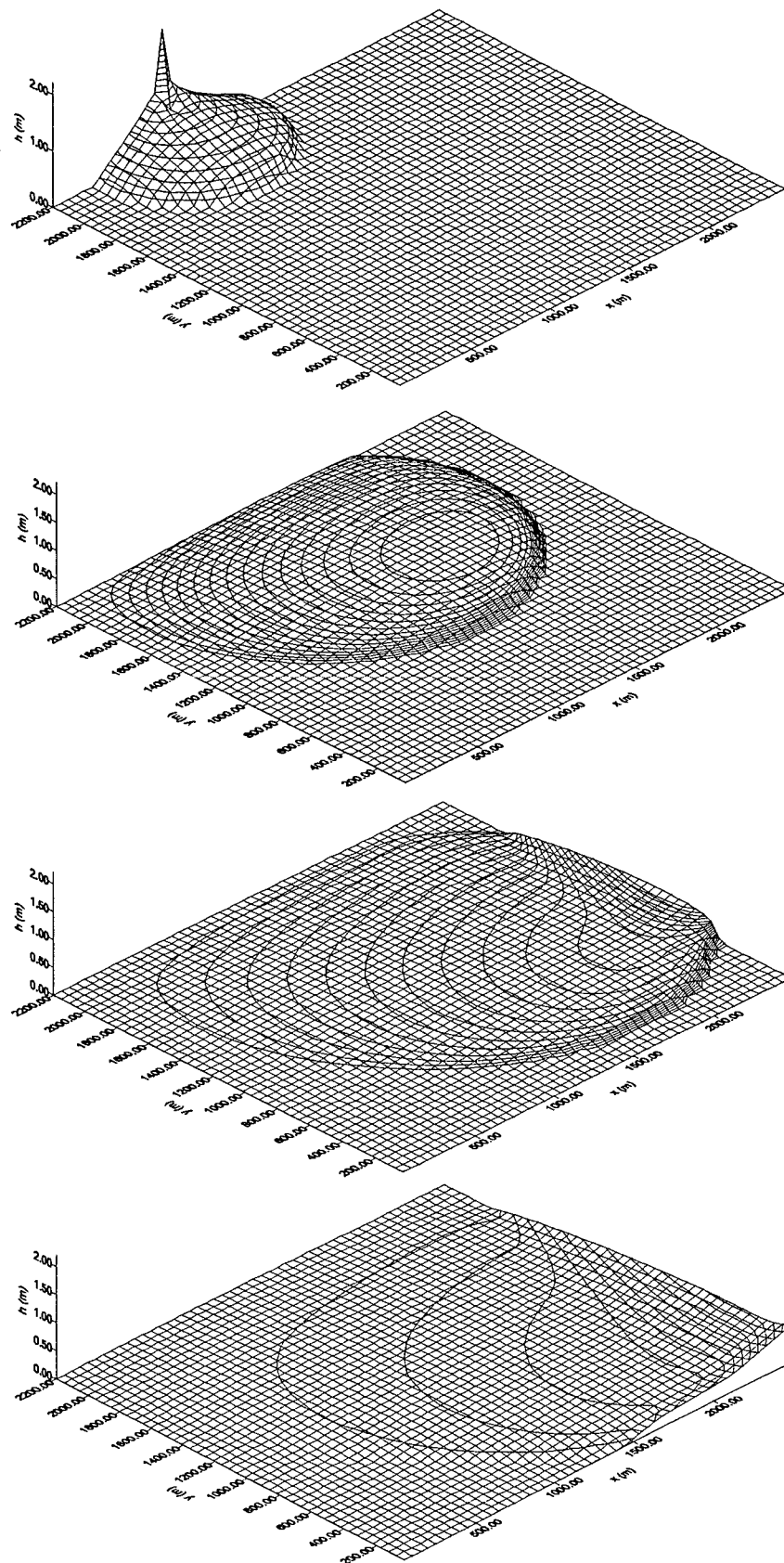
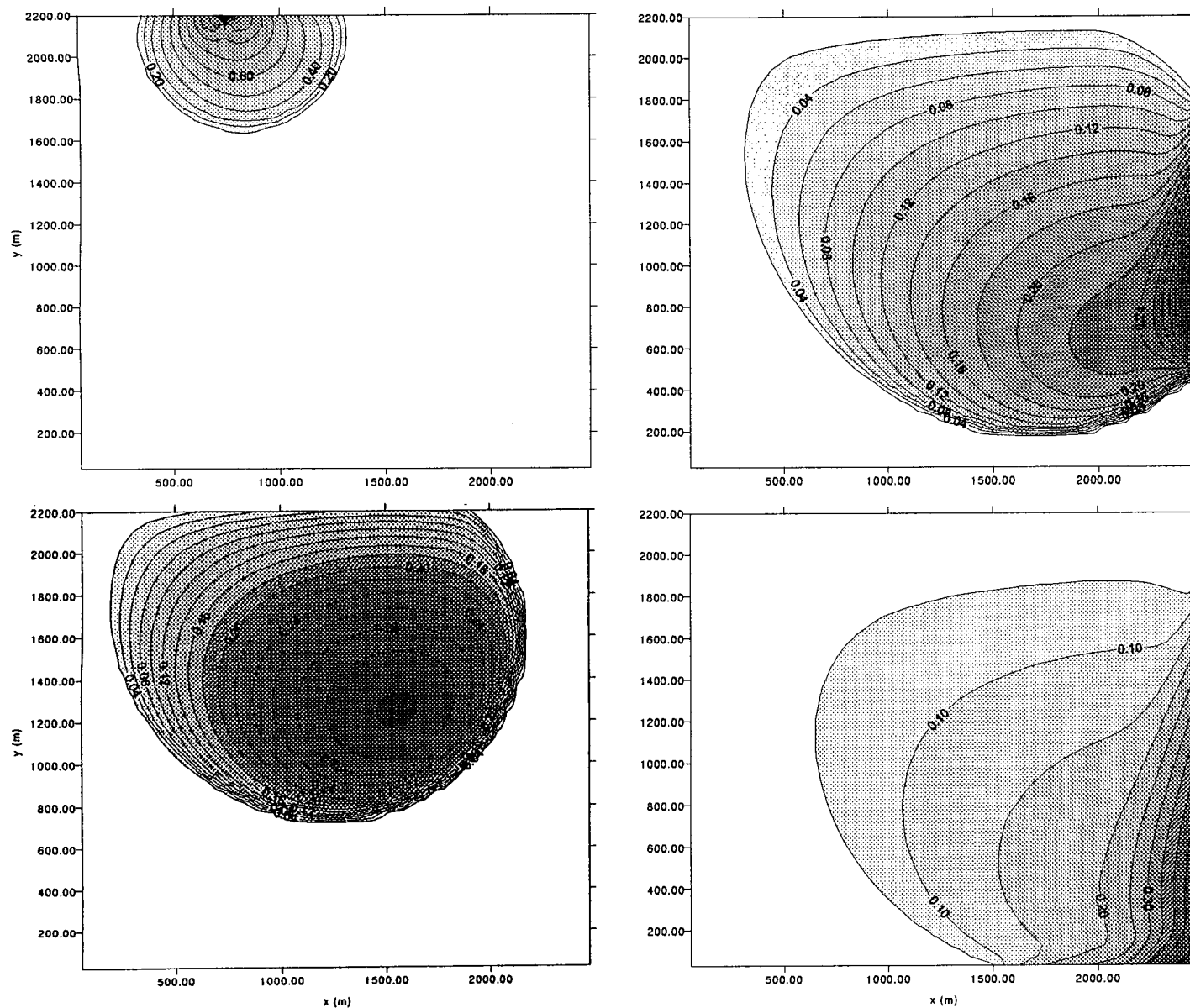


Fig.3.2.28 Surface plot for run S3T. From top to bottom: $t=20'$, $t=1$ hour, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).



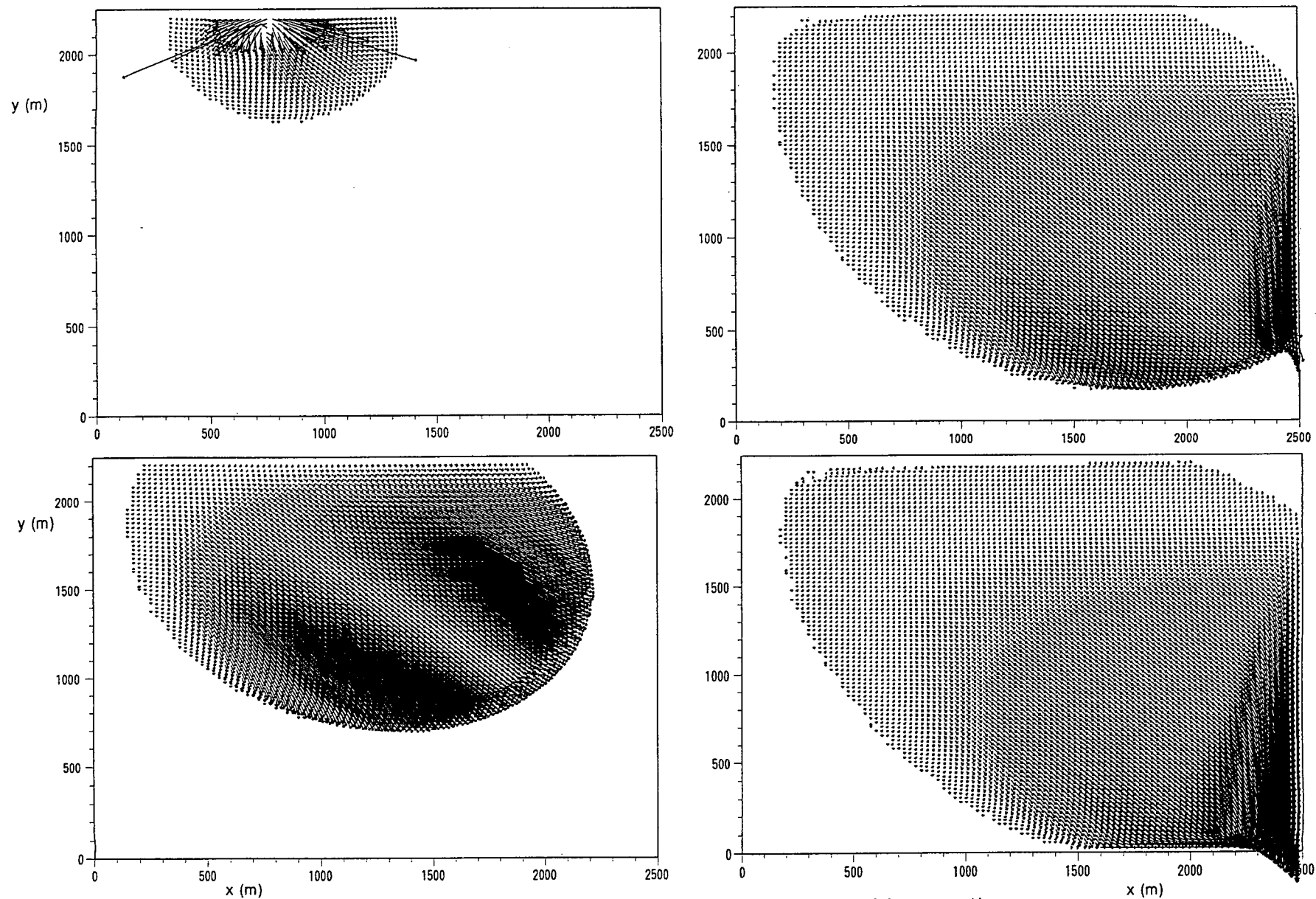


Fig.3.2.30 Vector plot for run S3T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 100 times the plot unit for $t=20'$ and 2000 for $t=1h$, $t=1h40'$, $t=2h$.

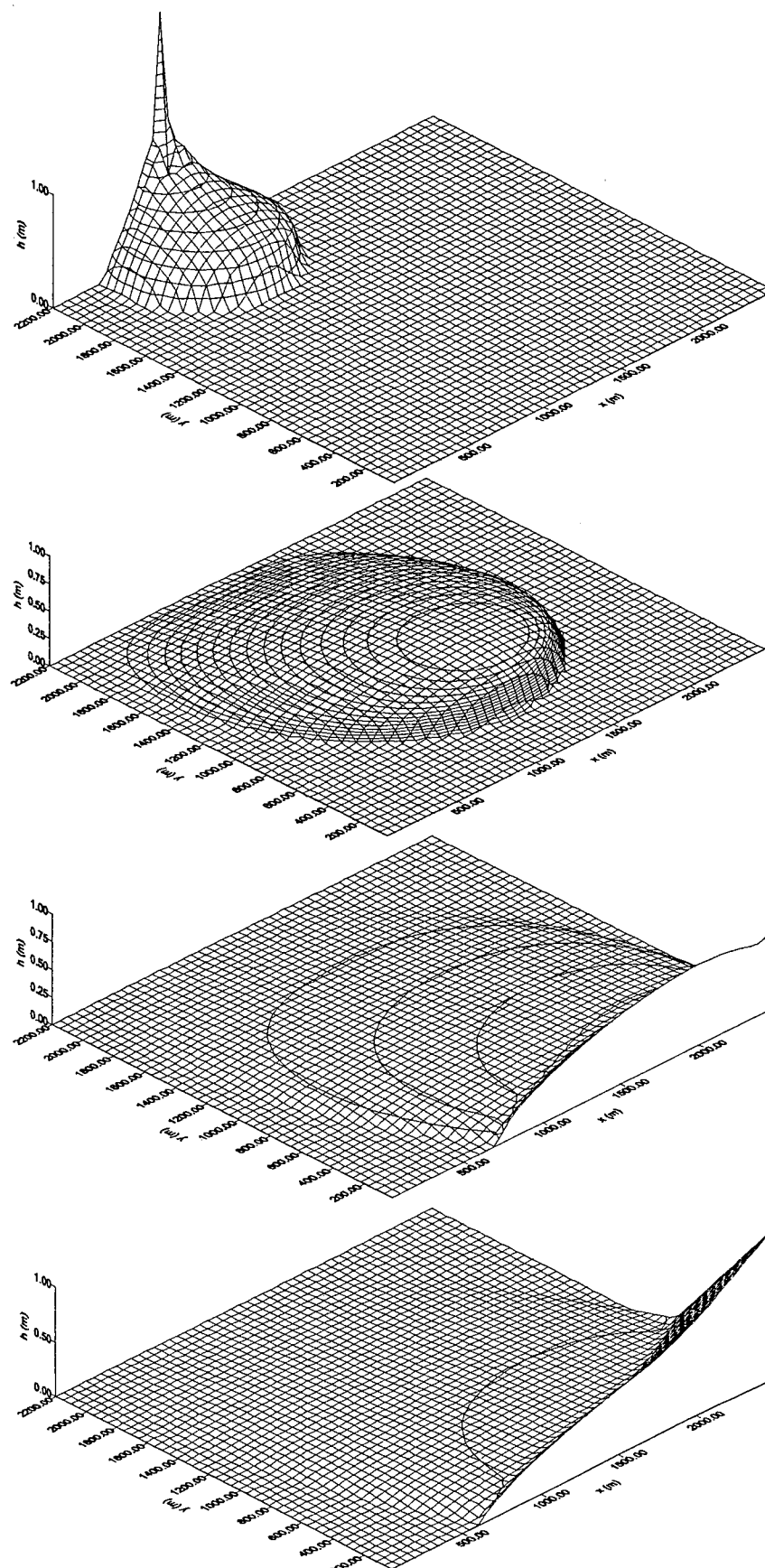


Fig.3.2.31 Surface plot for run S4T. From top to bottom: $t=20'$, $t=1 \text{ hour}$, $t=1\text{h}40'$ and $t=2 \text{ hours}$ (x , y and z scale in meters).

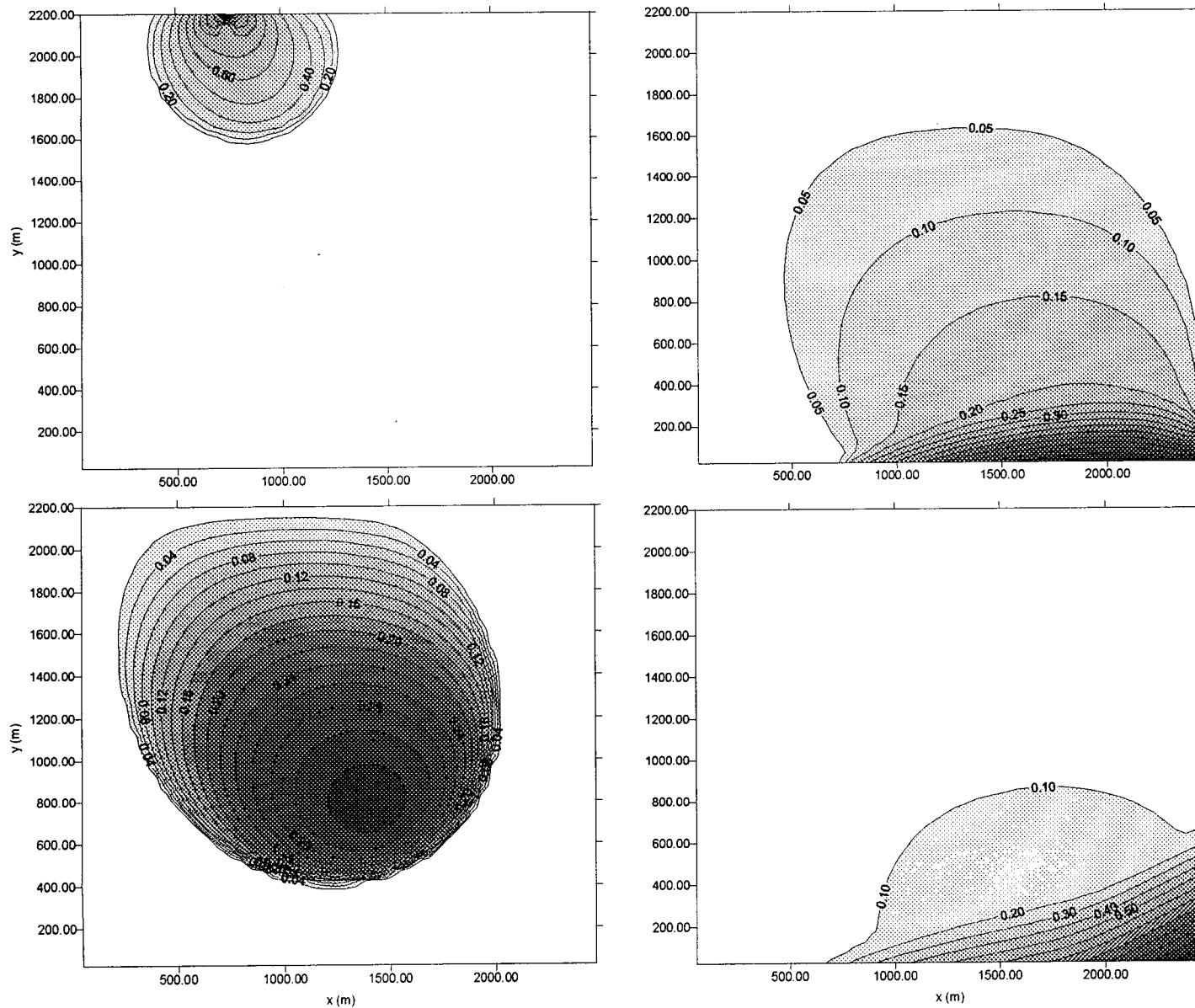


Fig.3.2.32 Contour plot for run S4T. On the left: top $t=20'$, bottom $t=1$ hour; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

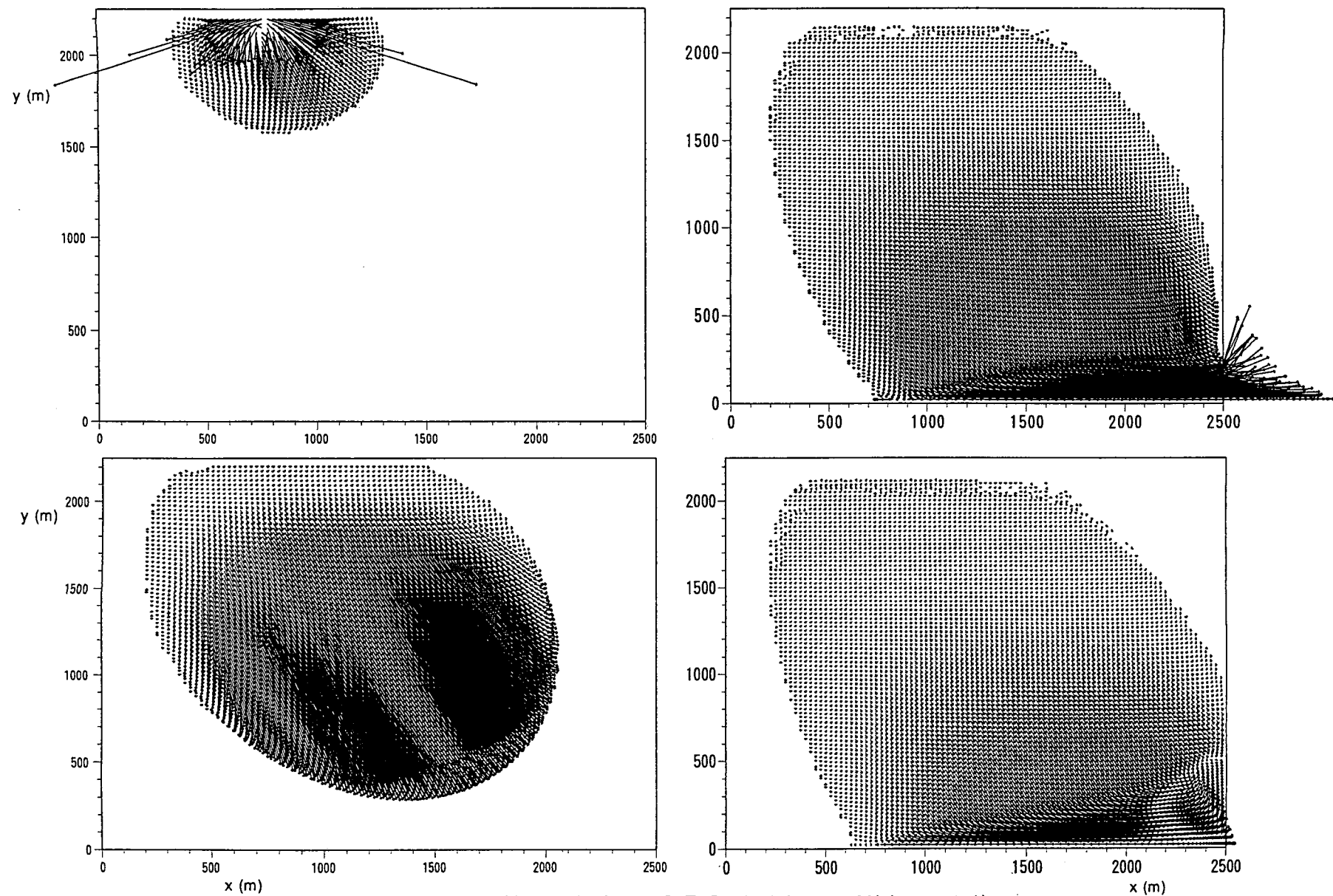


Fig.3.2.33 Vector plot for run S4T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m²/s) is 150 times the plot unit for $t=20'$ and 2000 for $t=1h$, $t=1h40'$, $t=2h$.

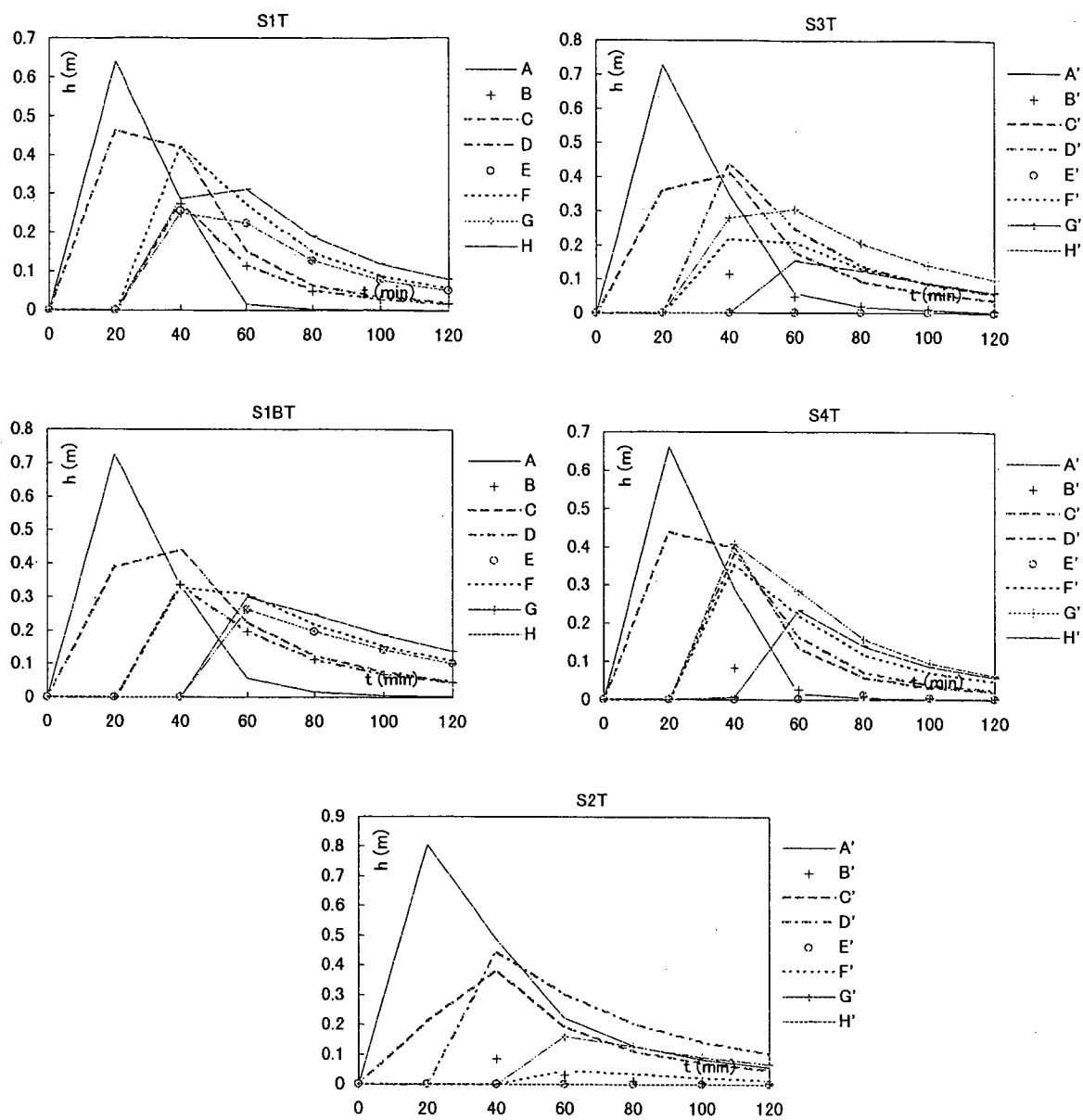


Fig.3.2.34 Water depth as a function of time for run S1T to S4T

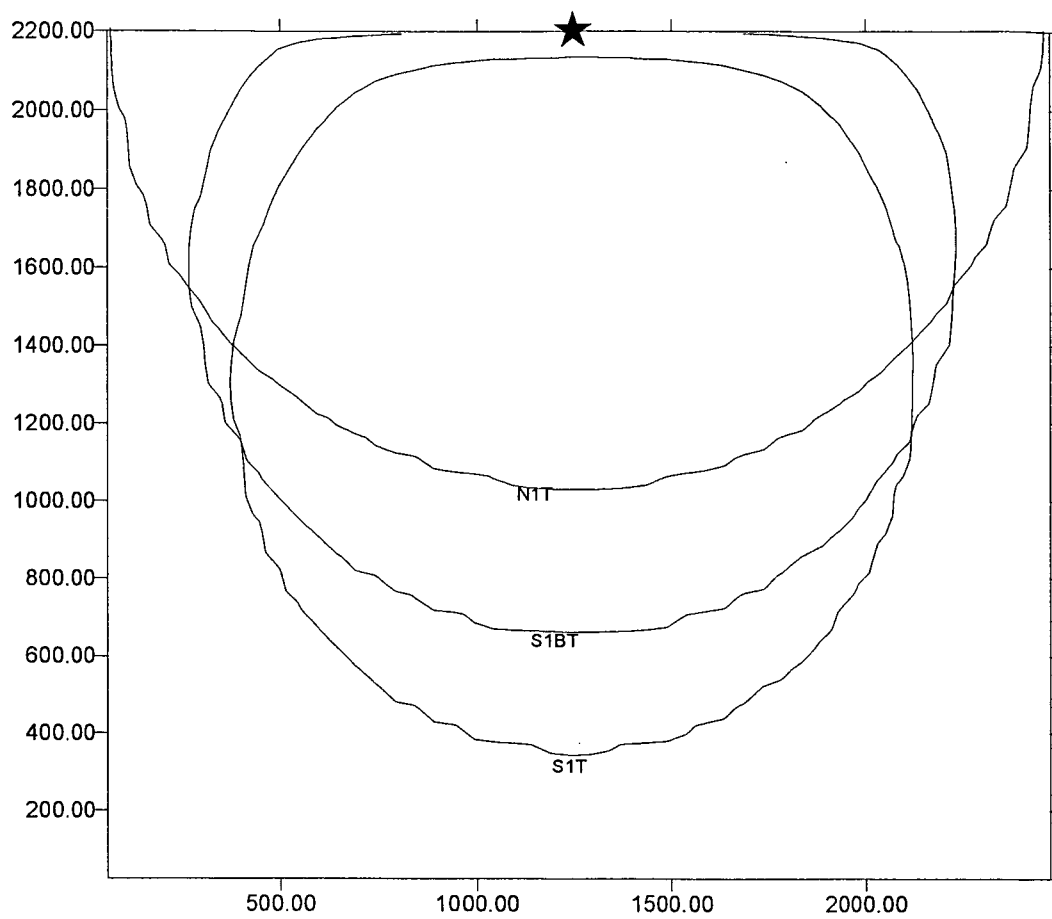


Fig.3.2.35 Comparison between run N1T, S1BT and S1T for t=1h

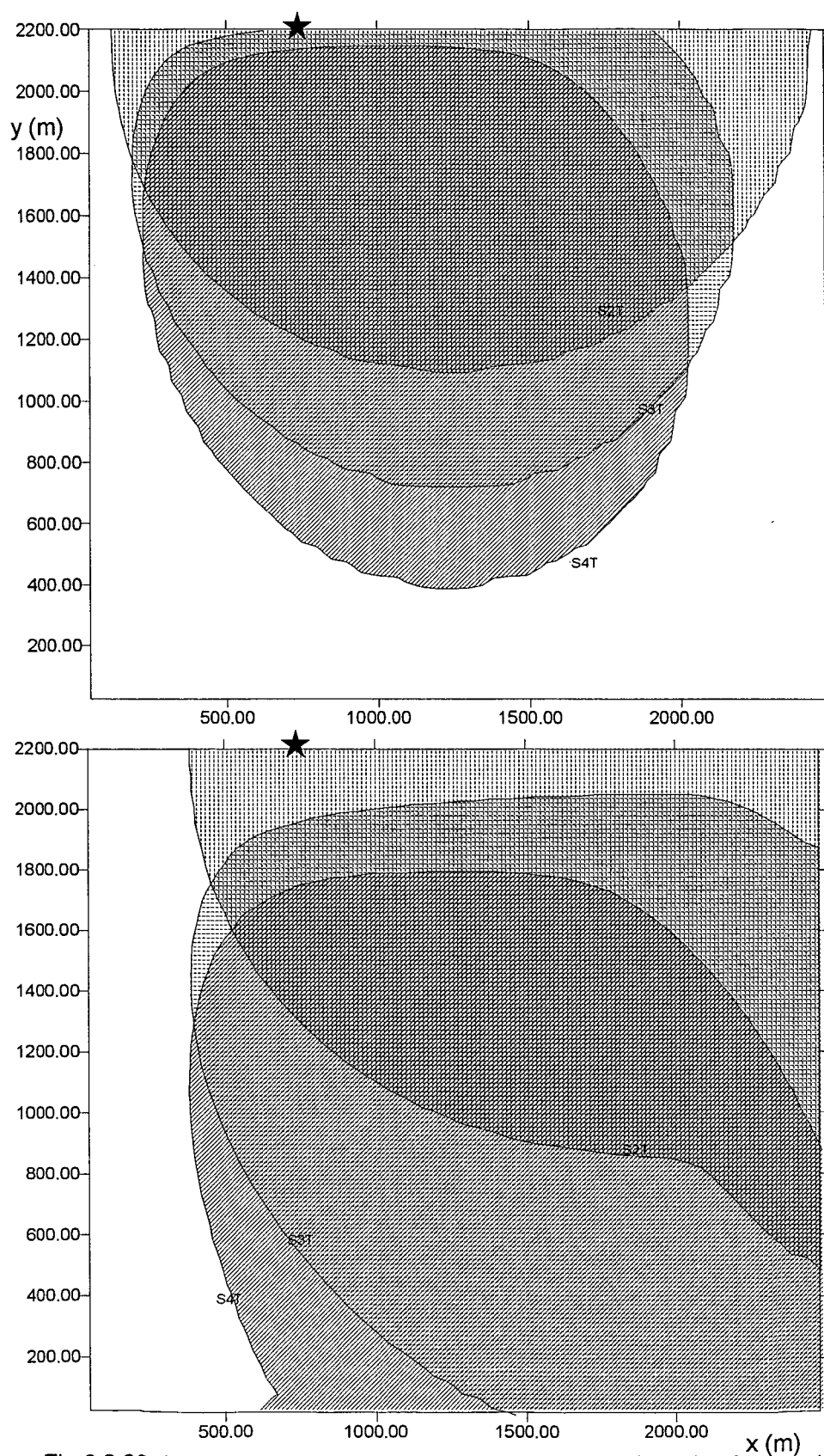


Fig.3.2.36 On the top: comparison between run S2T, S3T and S4T for $t=1h$; on the bottom: comparison between run S2T, S3T and S4T for $t=2h$.

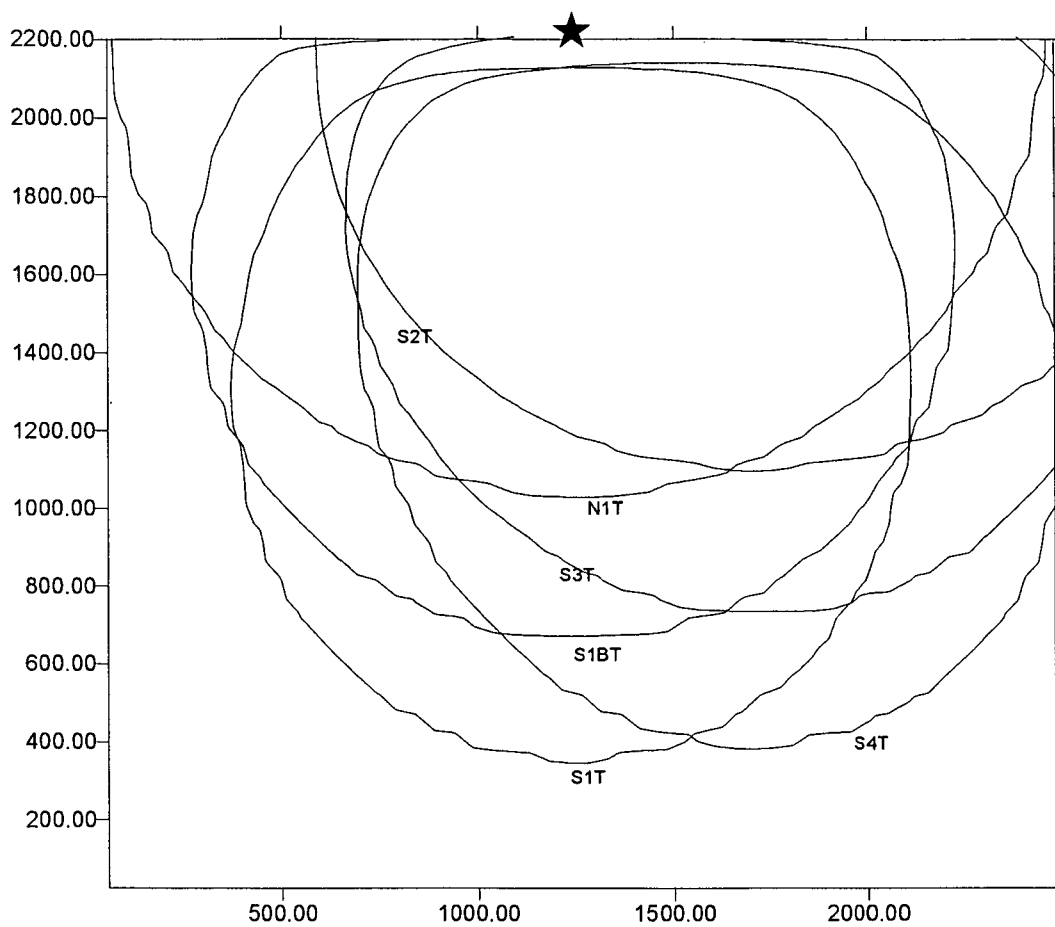


Fig.3.2.37 Comparison between run S2T, S3T, S4T, S1T, S1BT and N1T for t=1h

3.3 EFFECT OF BANKS AND CULVERTS

Banks and culverts represent an important element in an inundated plan. In fact, small levees, railways, roads, highways and walls represent barriers for the water and can change considerably the flow pattern.

The model accounts for these kind of structures by simulating them as broad crested weirs (Fig.3.3.1).

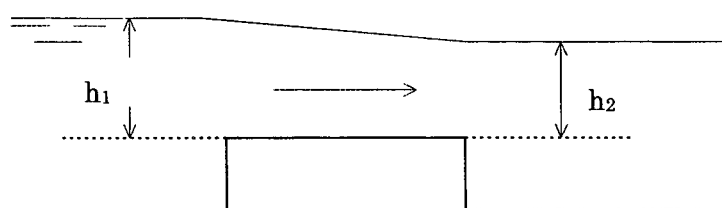


Fig. 3.3.1 Broad crested weir

The following equations are assumed:

$$q = 0.35h_1\sqrt{2gh_1} \quad h_2/h_1 < 2/3$$

$$q = 0.91h_2\sqrt{2g(h_1 - h_2)} \quad h_2/h_1 \geq 2/3$$

The culverts, eventually present along the banks, are simulated, in a simplified way, by means of the following equations (Fig.3.3.2):

Case a)

$$q = 0.7518H\sqrt{2g(h_1 - h_2)} \quad \text{for } h_2 \geq H$$

Case b)

$$q = 0.5075H\sqrt{2gh_1} \quad \text{for } h_2 < H \text{ or } h_1 \geq 3/2H$$

Case c)

$$q = 0.7893 \cdot \frac{2}{3}h_1\sqrt{\frac{2}{3}gh_1} \quad \text{for } h_2 < H \text{ or } 3/2h_2 \leq h_1 < 3/2H$$

Case d)

$$q = 0.7914h_2\sqrt{2g(h_1 - h_2)} \quad \text{for } h_2 < H \text{ or } 3/2h_2 > h_1$$

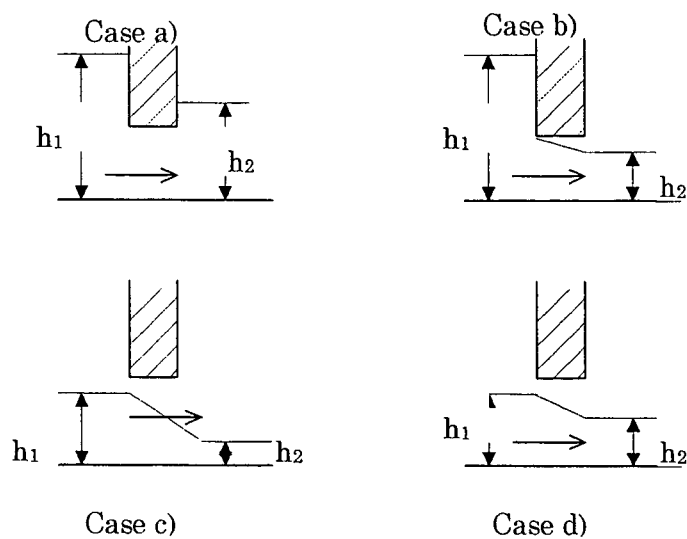


Fig.3.3.2 Simplified simulation of culverts

A total of ten simulations has been done with different configurations of banks and culverts. A sketch of the simulated plan is shown in Fig.3.3.3.

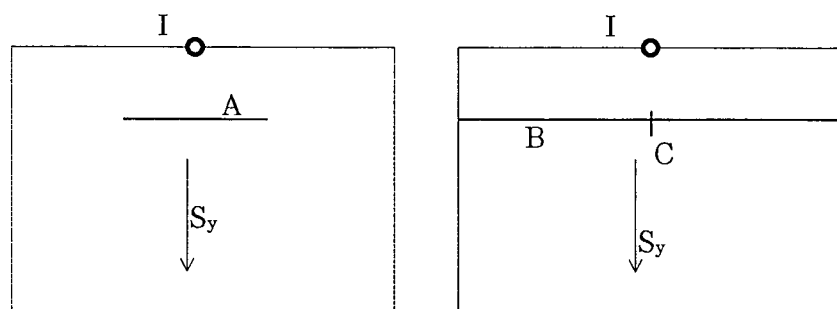


Fig. 3.3.3 Sketch for the series B

In which:

I = immission cell; represents the cell in which the discharge is introduced (cell No. 150 for the specific case);

A = short bank;

B = long bank;

C = culvert.

Table 3.3.1 reports a summary about each run of the series.

Table 3.3.1 Summary for the series B

Run	n_0	θ (%)	s_y	s_x	Input hydrograph	Bank and/or culvert element (Fig.3.3.3)
B1	0.05	0.0	0.000	0.0	H	A (high)
B2	0.05	0.0	0.002	0.0	H	A (high)
B3	0.05	0.0	0.002	0.0	H	B (low)
B4	0.05	0.0	0.002	0.0	H	B (low) + C
B5	0.05	0.0	0.002	0.0	H	B (high) + C
B1T	0.05	0.0	0.000	0.0	T	A (high)
B2T	0.05	0.0	0.002	0.0	T	A (high)
B3T	0.05	0.0	0.002	0.0	T	B (low)
B4T	0.05	0.0	0.002	0.0	T	B (low) + C
B5T	0.05	0.0	0.002	0.0	T	B (high) + C

In Table 3.3.1 the term "high" means a bank that cannot be submerged, while the term "low" is for a submergible bank (in the specific case it was 0.4 m high). In all the case the bank is located in the row with cells from 2001 and 2100. The culvert presents in the runs B4, B5 and B4T and B5T has dimensions 75x0.3 m. The width of the culvert corresponds to the size of three cells.

Figg.3.3.4 to 3.3.18 show the results for B runs. The plots relative to the runs B1 and B2 are relative to times $t=20'$, $40'$ 1^h and 2^h in order to better capture the behaviour of the flow around the obstacle constitute by the short and high bank; the other runs are, as always, for time values of $20'$, 1^h , $1^h40'$ and 2^h . In the case of run B3 is evident the storage effect due to the presence of the bank. For the run B5, the inundation downstream of the bank is due only to the presence of the culvert.

Fig. 3.3.19 shows the curves of water depth as a function of time. For the points located in the cells 350 and 2050 the depth of water is higher due to the storage upstream of the bank itself.

Fig.3.3.20 shows a comparison between runs N1 ($s_y=0.0$), B1 ($s_y=0.0$ + short bank), S2

($s_y=0.002$) and B2 ($s_y=0.002+\text{short bank}$). It is interesting to note the differences between the front of the flow of the runs N1 and S1 with, respectively, the front of the runs B1 and B2. At time $t=1^h$ the difference is stressed by the presence of the bank that slow down the flow for the runs B1 and B2; at time $t=2^h$ the difference is decreased and for bigger value of time the difference becomes less and less important.

Fig.3.3.21 shows a comparison between runs S1, B3 and B4. All these runs have the same value of the slope and the difference is constituted by the presence of a low bank (0.4 m height) and, for the prove B4 from the presence of a culvert; the effect of storage of the bank retards the flow in respect to the one of the prove S1; of course an important parameter in the evaluation of this delay is the ratio between the volume of the flood and the volume of the storage due to the presence of the bank itself.

In Figg.3.3.22 to 3.3.36 are reported the results for the BT runs relative to triangular-shape input hydrograph, while Fig. 3.3.37 shows the curves of depth as a function of time. The maximum depth is achieved in the cell No.350 that is located just downstream of the immission point.

Fig.3.3.38 shows a comparison between the runs B1T, B2T, S1T and N1T for $t=1^h$ and $t=2^h$. Also in this case, the differences tend to become less important with the increase of time. An important difference respect to the case of uniform input hydrograph is the fact that for $t=2^h$, the cells immediately downstream the obstacle are not inundated.

Fig.3.3.39 shows the front of the flow for the runs B3T, B4T and S1T for time $t=1$ and 2^h . The presence of the bank retards the routing of the flow and big differences are present with respect to the flow-front relative to the prove S1T. No appreciable difference is present between runs B3T and B4T due to the limited discharge from the culvert.

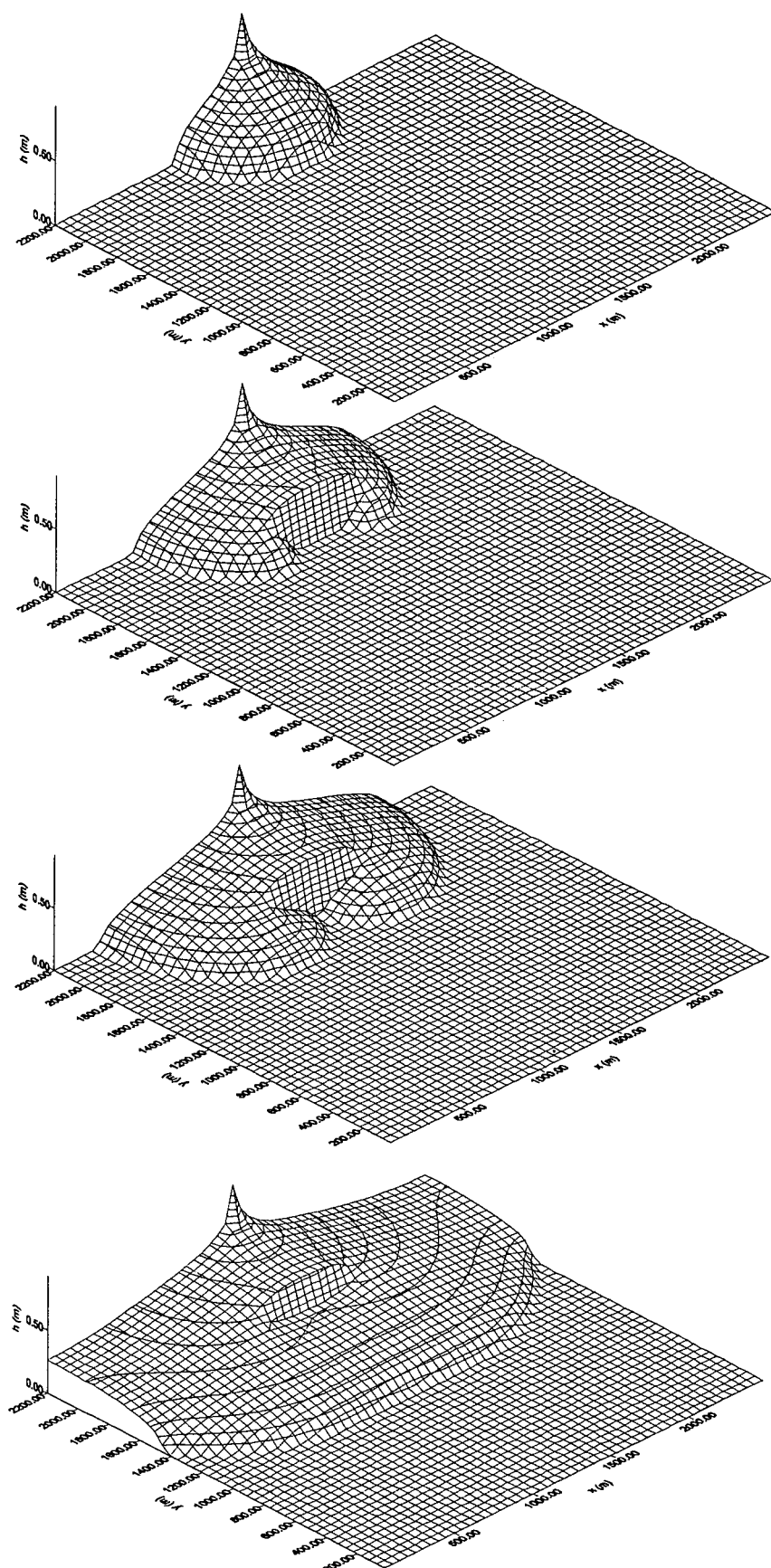


Fig.3.3.4 Surface plot for run B1. From top to bottom: $t=20'$, $t=40'$, $t=1\text{h}$ and $t=2 \text{ h}$ (x, y and z scale in meters).

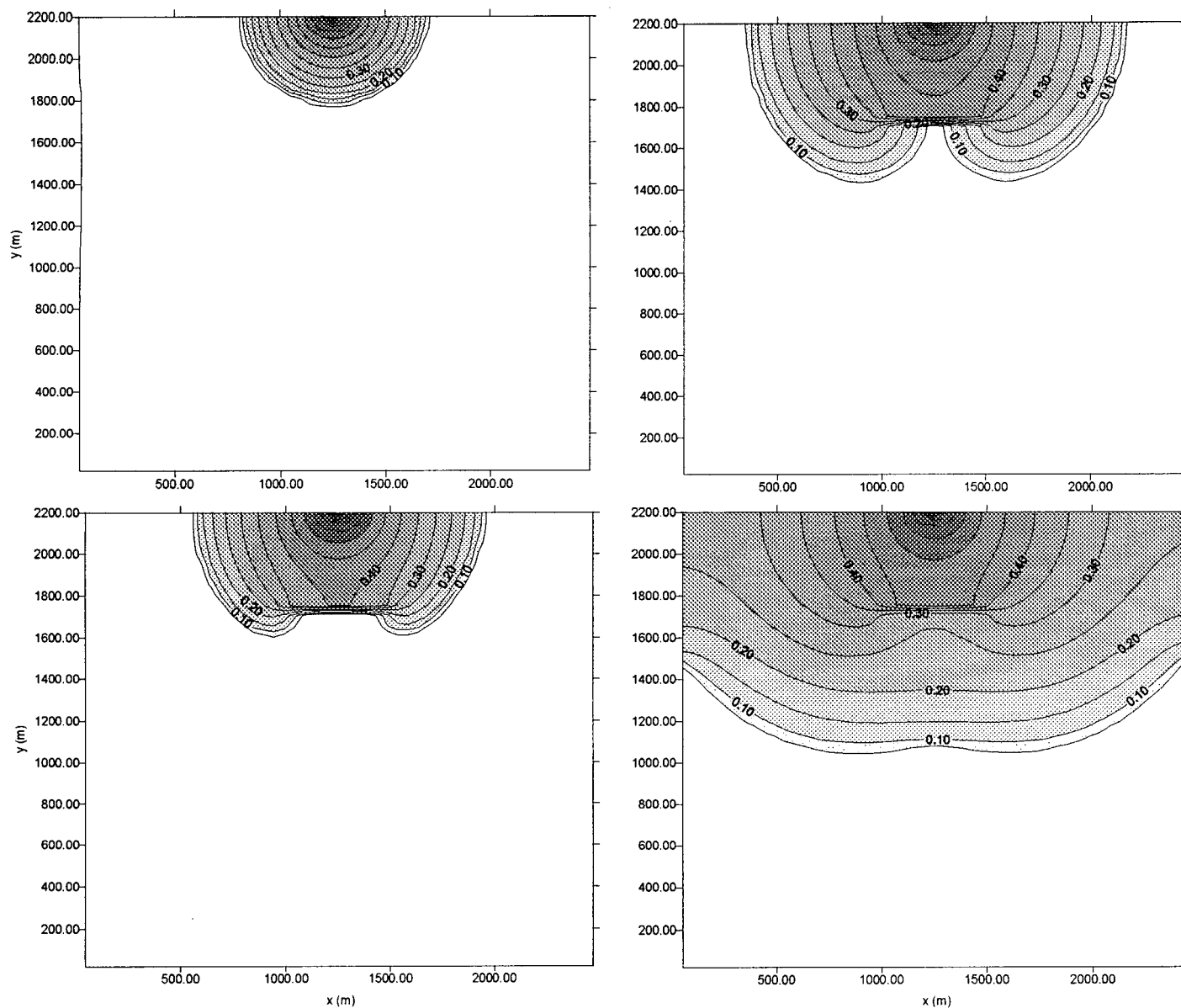


Fig.3.3.5 Contour plot for run B1. On the left: top $t=20'$, bottom $t=40'$; on the right: top $t=1h$, bottom $t=2$ hours (scale in meter).

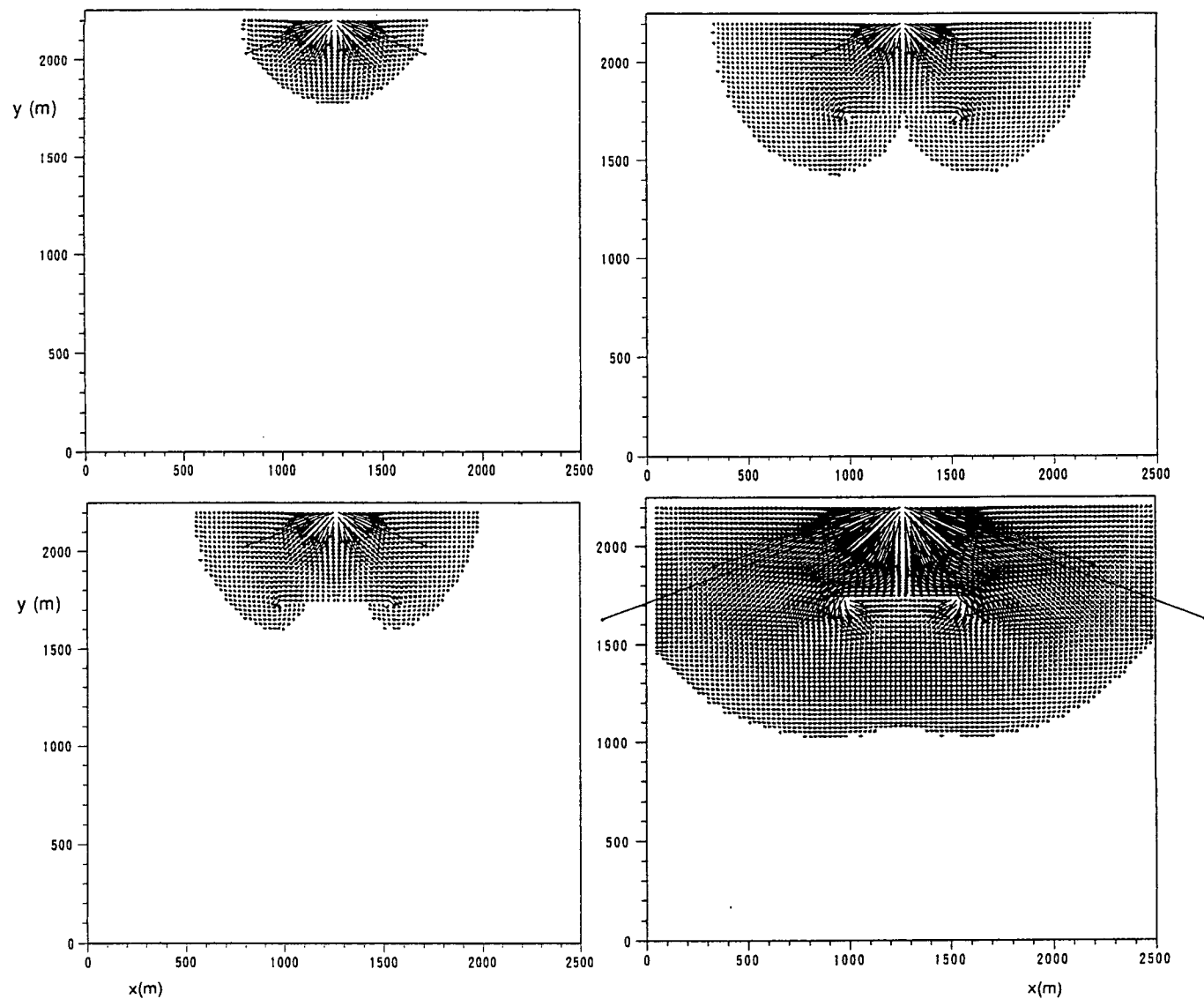


Fig.3.3.6 Vector plot for run B1. On the left: top $t=20'$, bottom $t=40'$; on the right: top $t=1h$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 1000 times the plot unit for $t=2h$ and 300 for $t=20'$, $40'$ and $1h$.

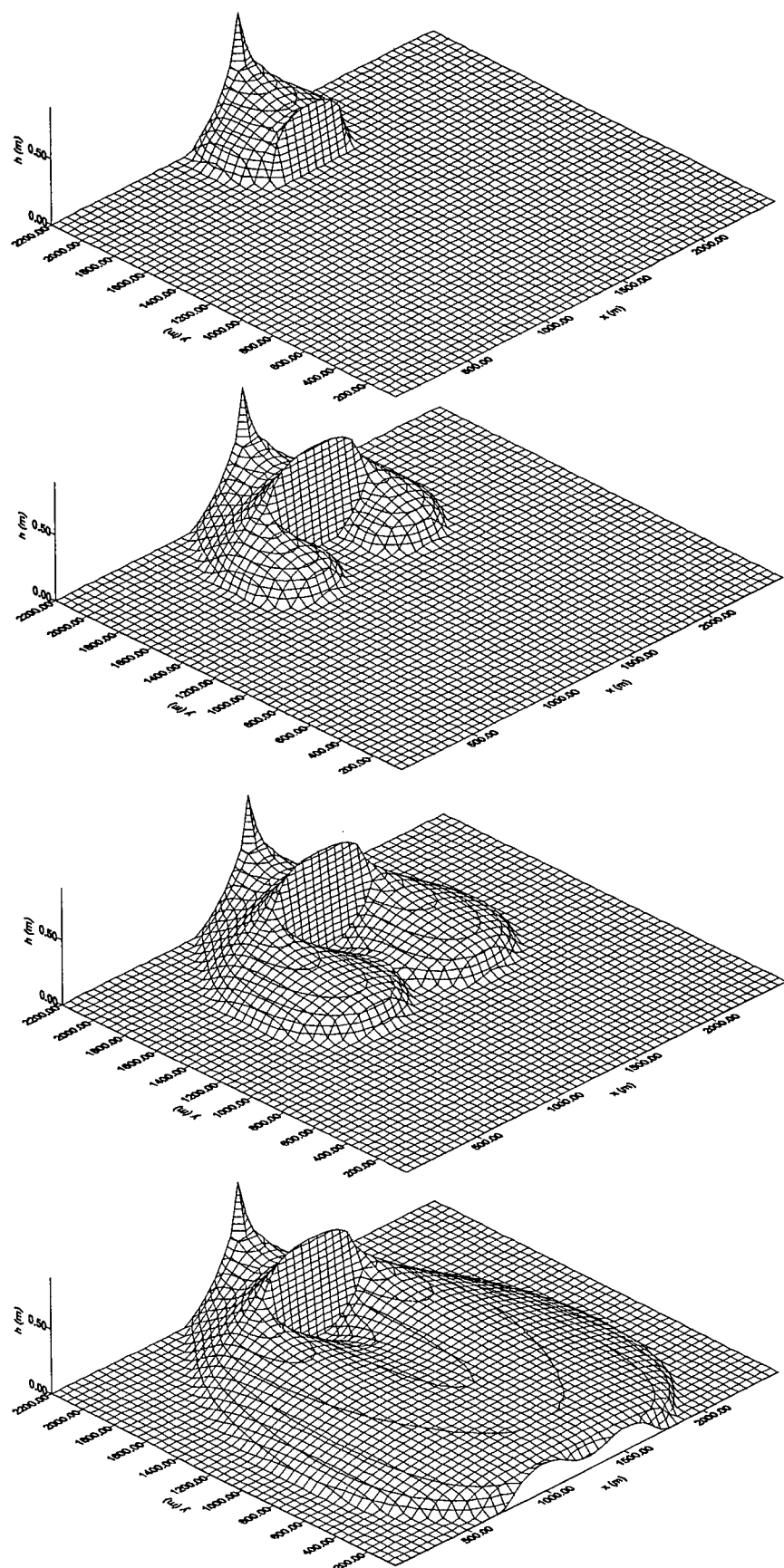


Fig.3.3.7 Surface plot for run B2. From top to bottom: $t=20'$, $t=40'$, $t=1h$ and $t=2h$ (x, y and z scale in meters).

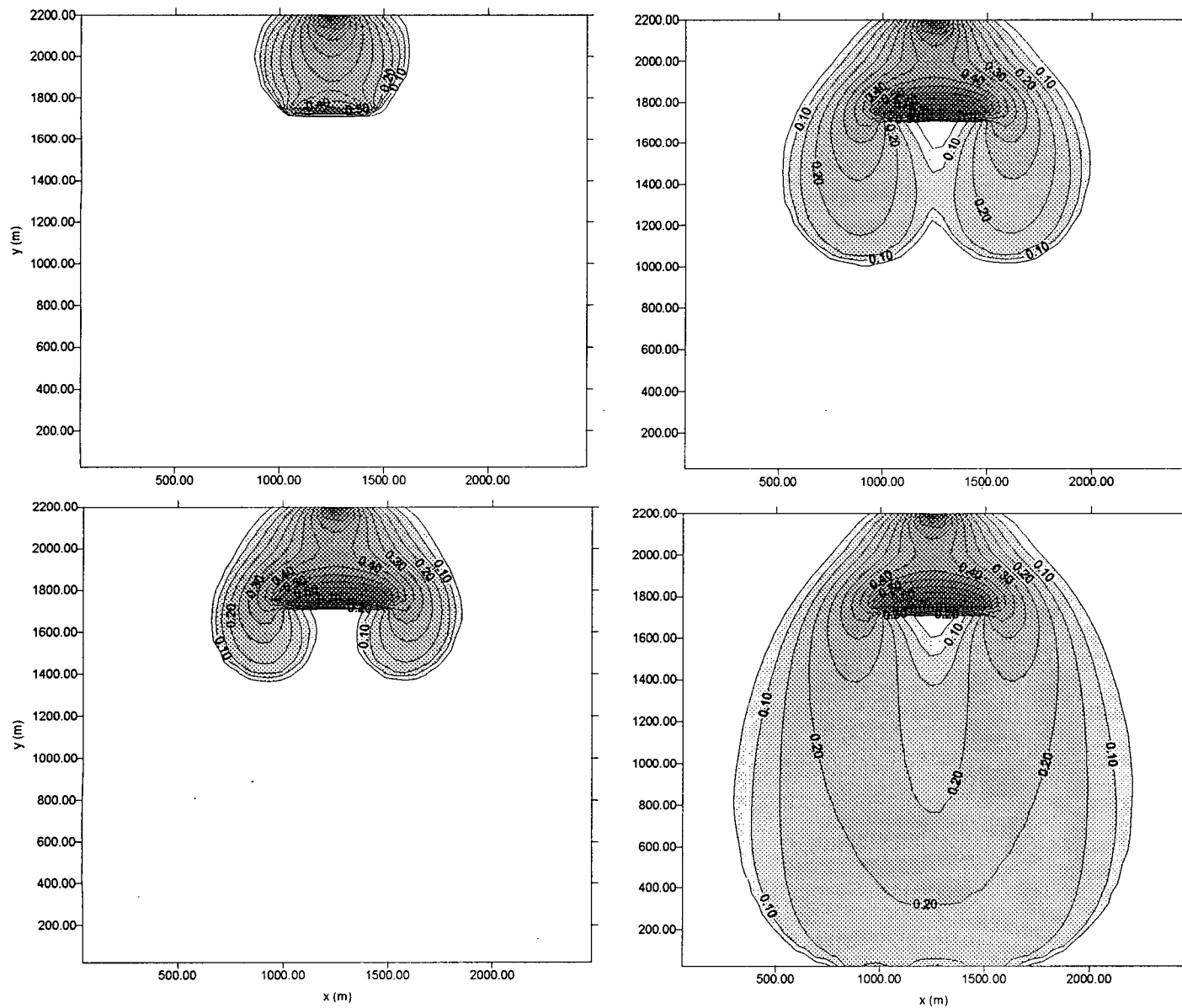


Fig.3.3.8 Contour plot for run B2. On the left: top $t=20'$, bottom $t=40'$; on the right: top $t=1h$, bottom $t=2$ hours (scale in meter).

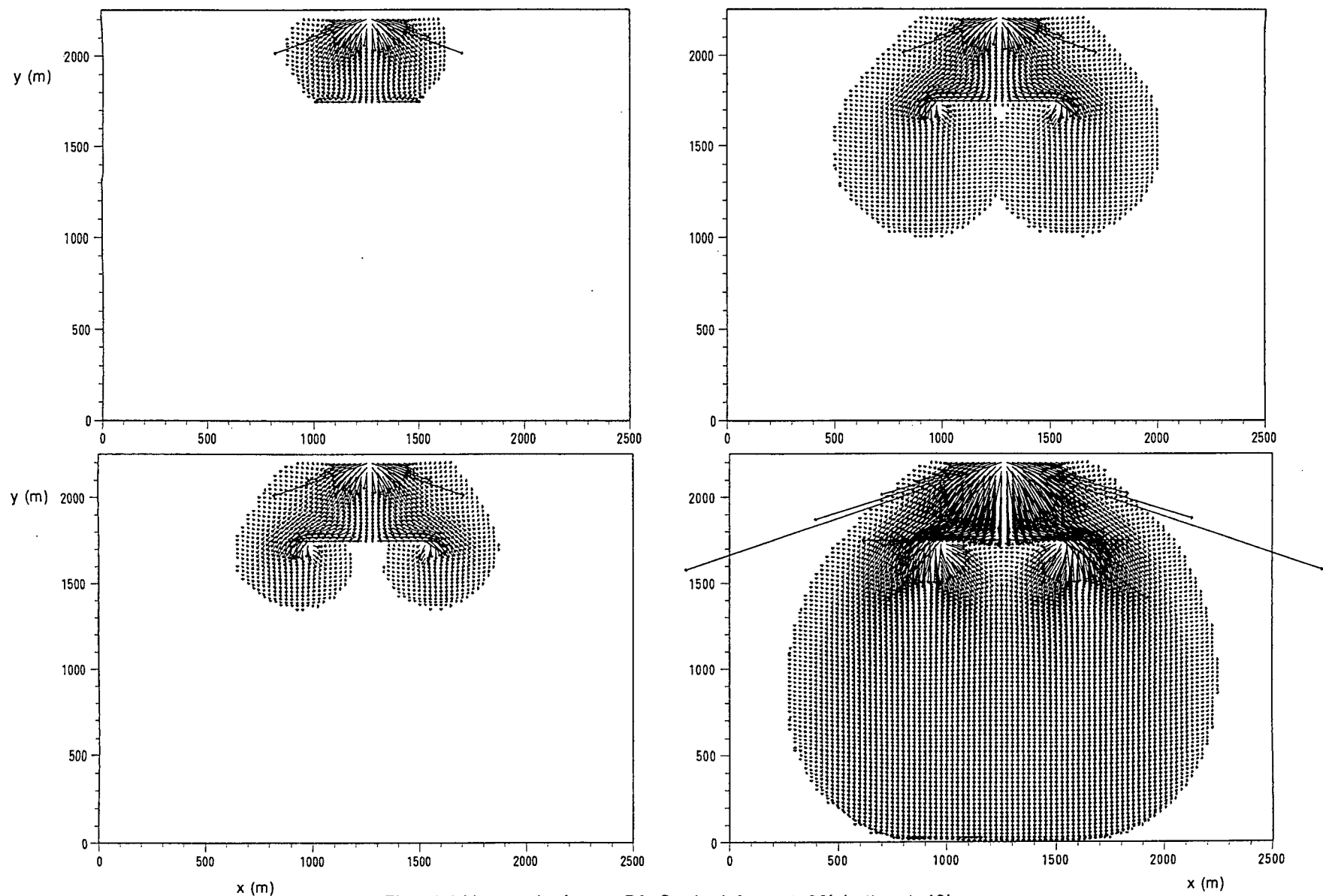


Fig.3.3.9 Vector plot for run B2. On the left: top $t=20'$, bottom $t=40'$; on the right: top $t=1h$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 1000 times the plot unit for $t=2h$ and 300 for $t=20'$, $40'$ and $1h$.

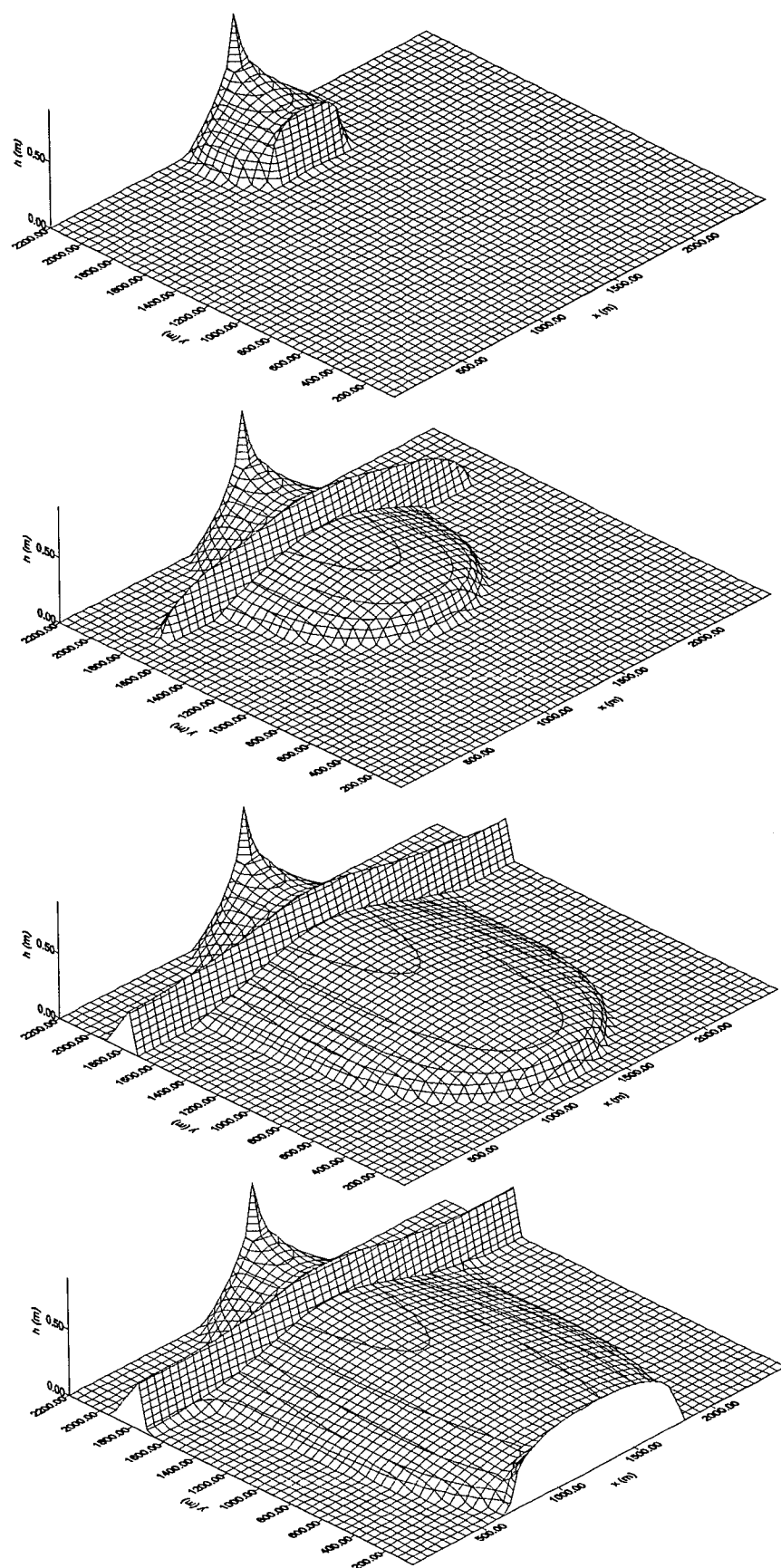


Fig.3.3.10 Surface plot for run B3. From top to bottom: $t=20'$, $t=1\text{h}$, $t=1\text{h}40'$ and $t=2\text{ hours}$ (x , y and z scale in meters).

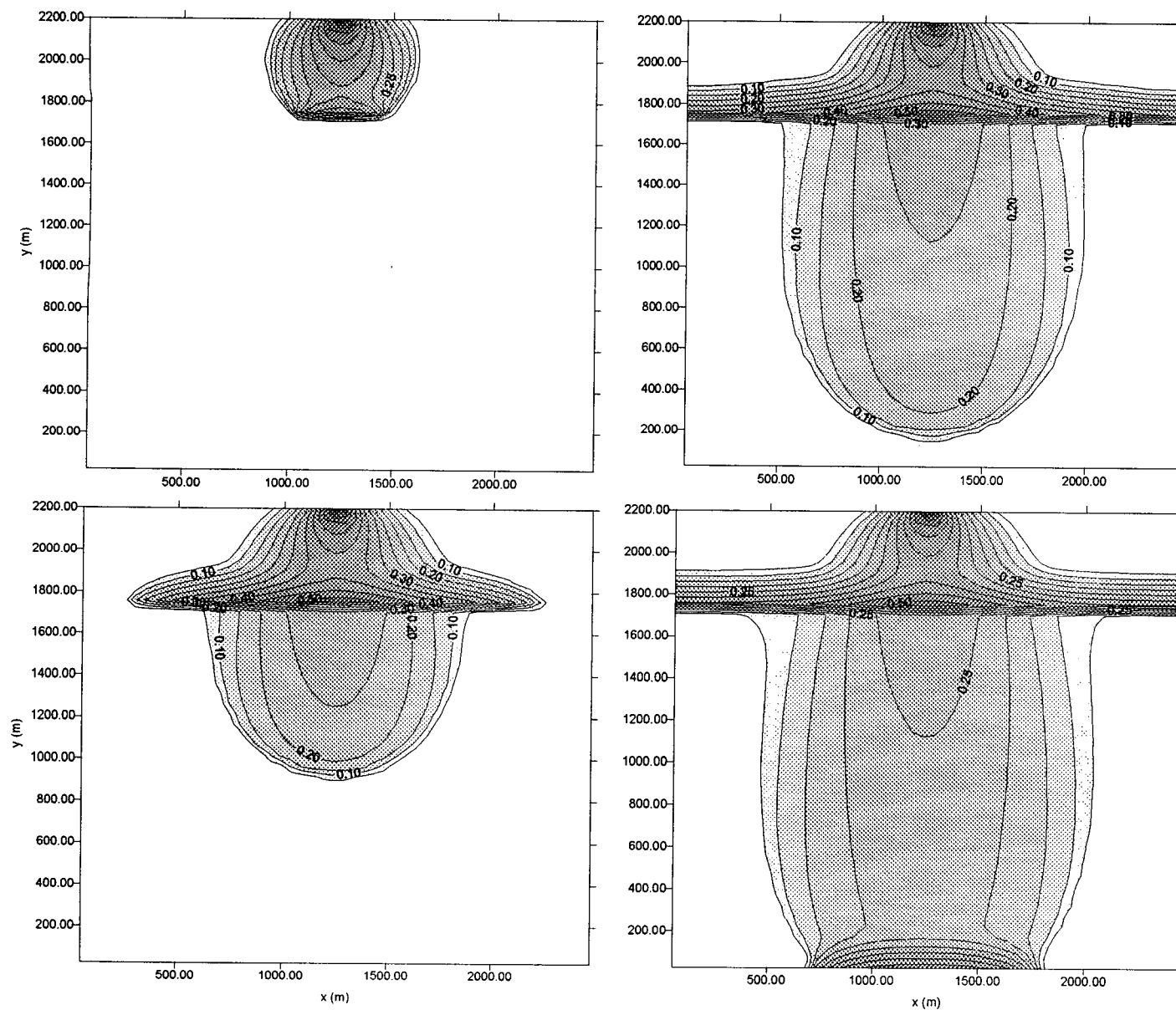


Fig.3.3.11 Contour plot for run B3. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

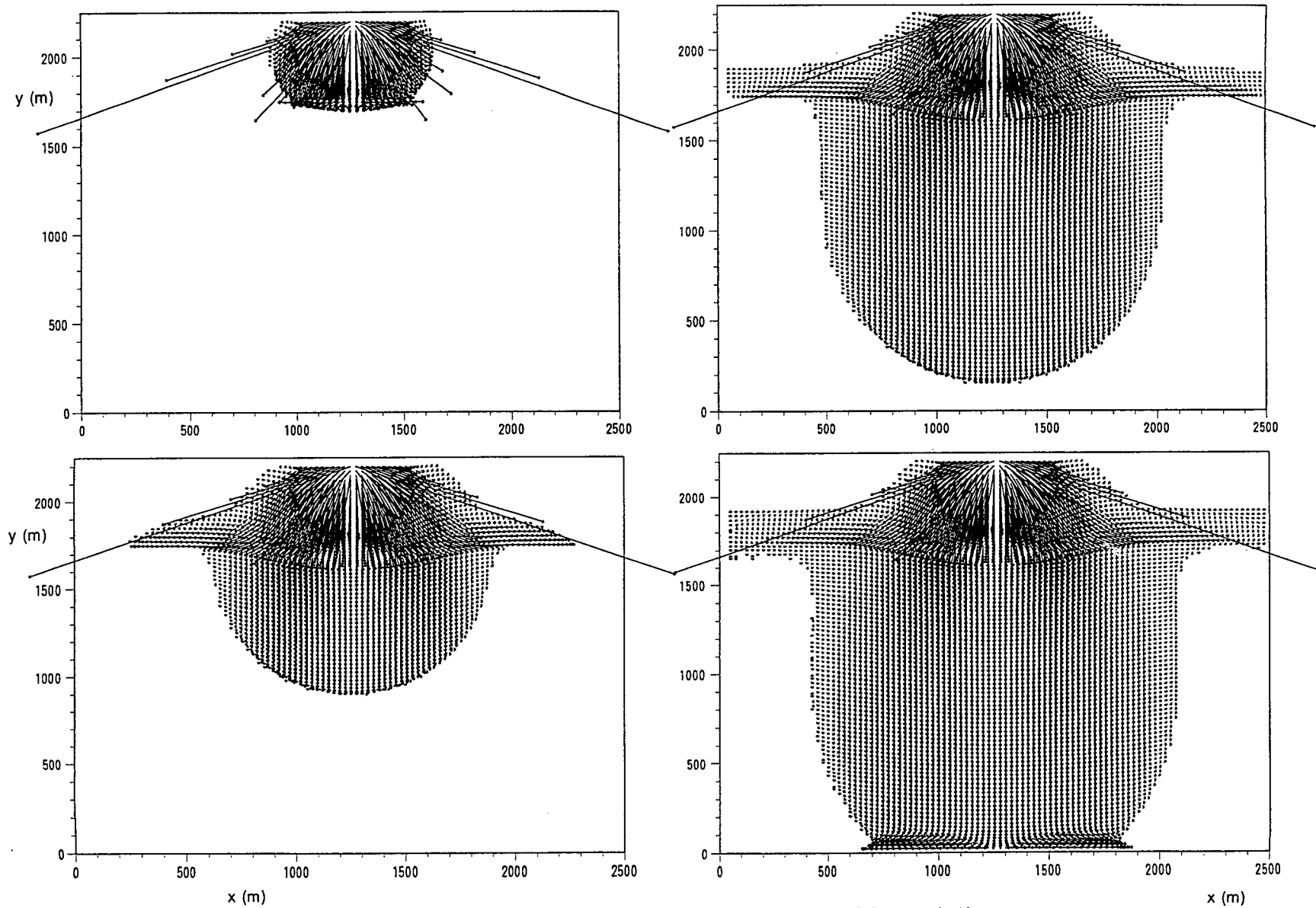


Fig.3.3.12 Vector plot for run B3. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 1000 times the plot unit for $t=2h$ and 300 for $t=20'$, $1h$ and $1h40'$.

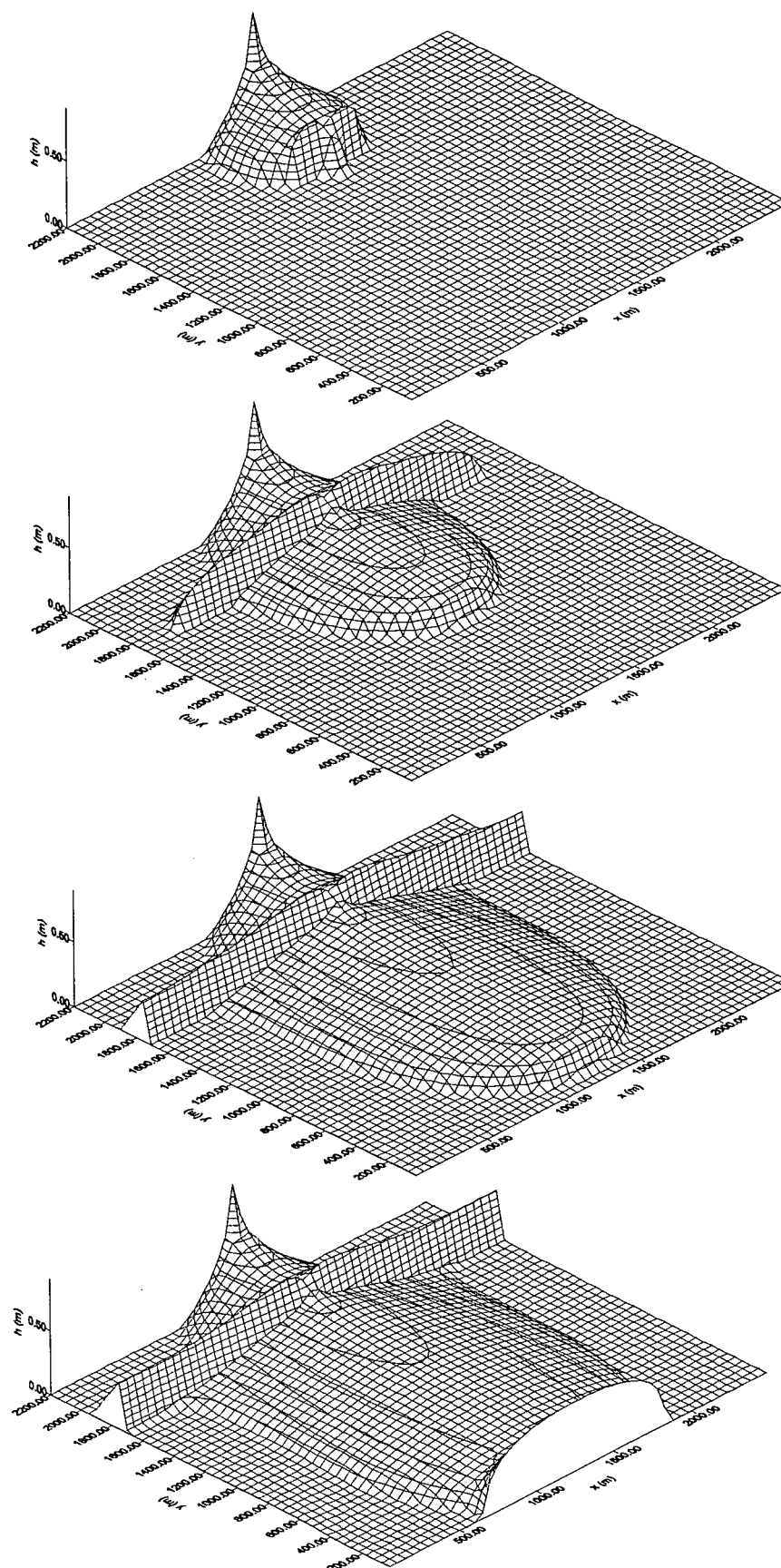


Fig.3.3.13 Surface plot for run B4. From top to bottom: $t=20'$, $t=1\text{h}$, $t=1\text{h}40'$ and $t=2 \text{ hours}$ (x , y and z scale in meters).

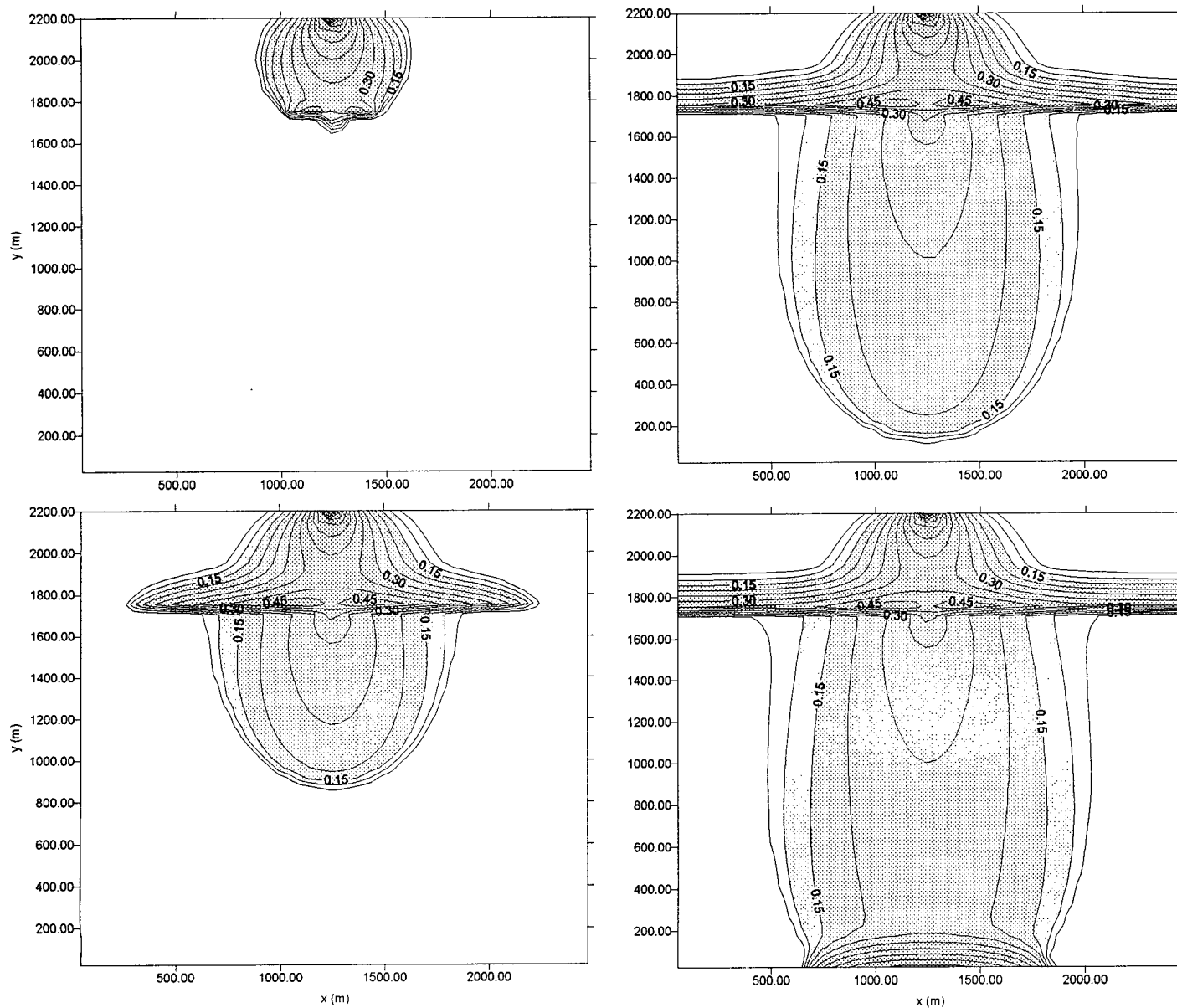


Fig.3.3.14 Contour plot for run B4. On the left: top t=20', bottom t=1h; on the right: top t=1h40', bottom t= 2 hours (scale in meter).

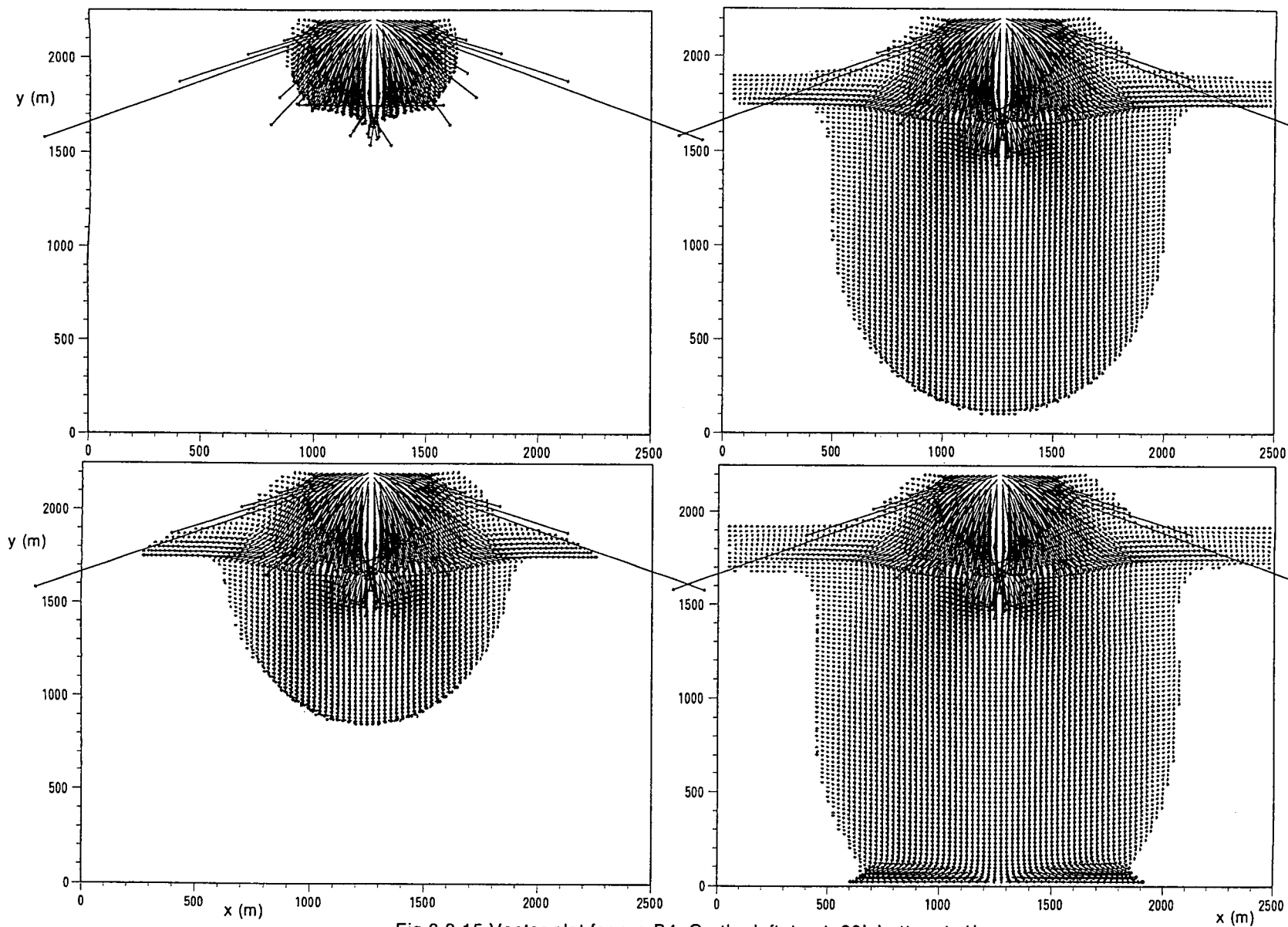


Fig.3.3.15 Vector plot for run B4. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 1000' times the plot unit.

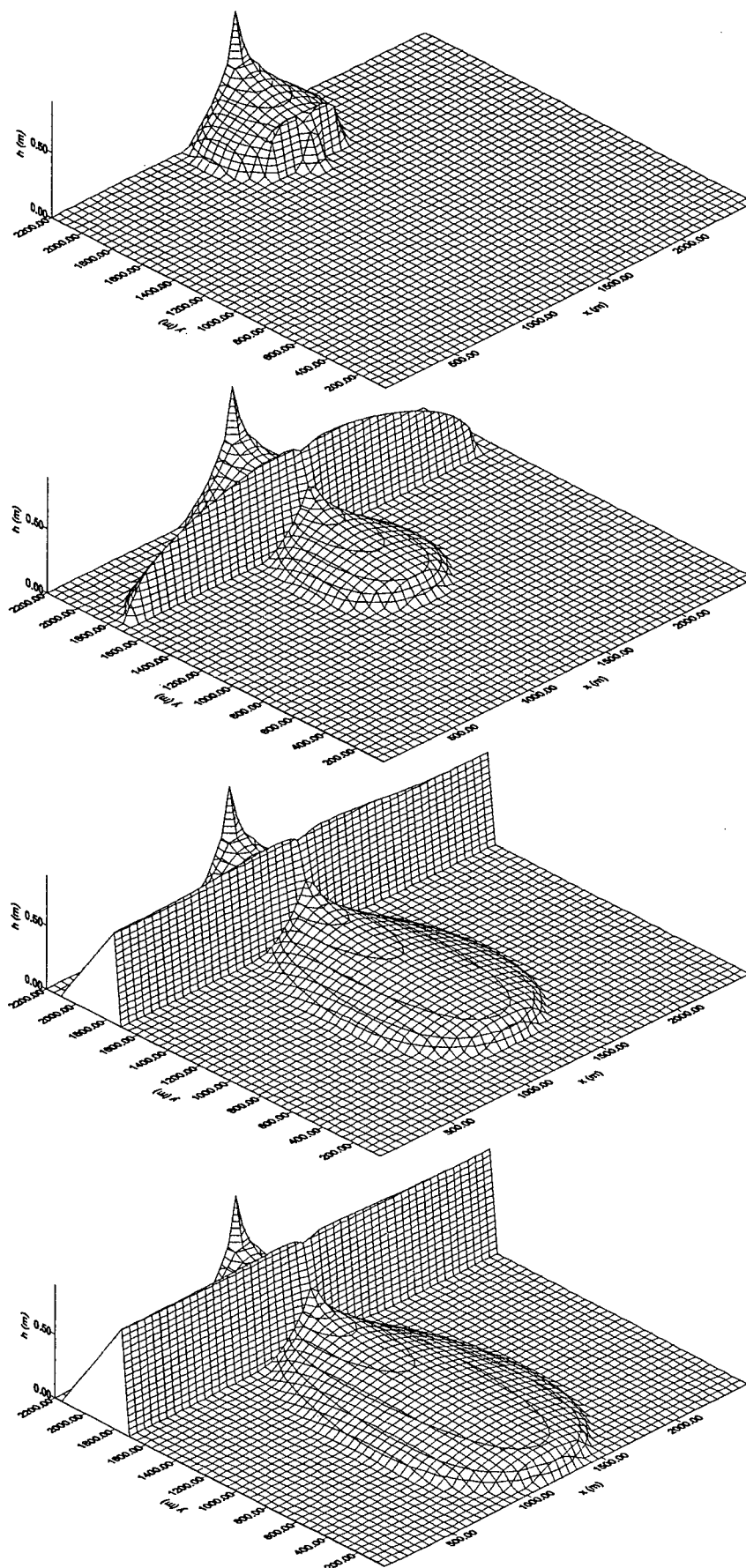


Fig.3.3.16 Surface plot for run B5. From top to bottom: $t=20'$, $t=1h$, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

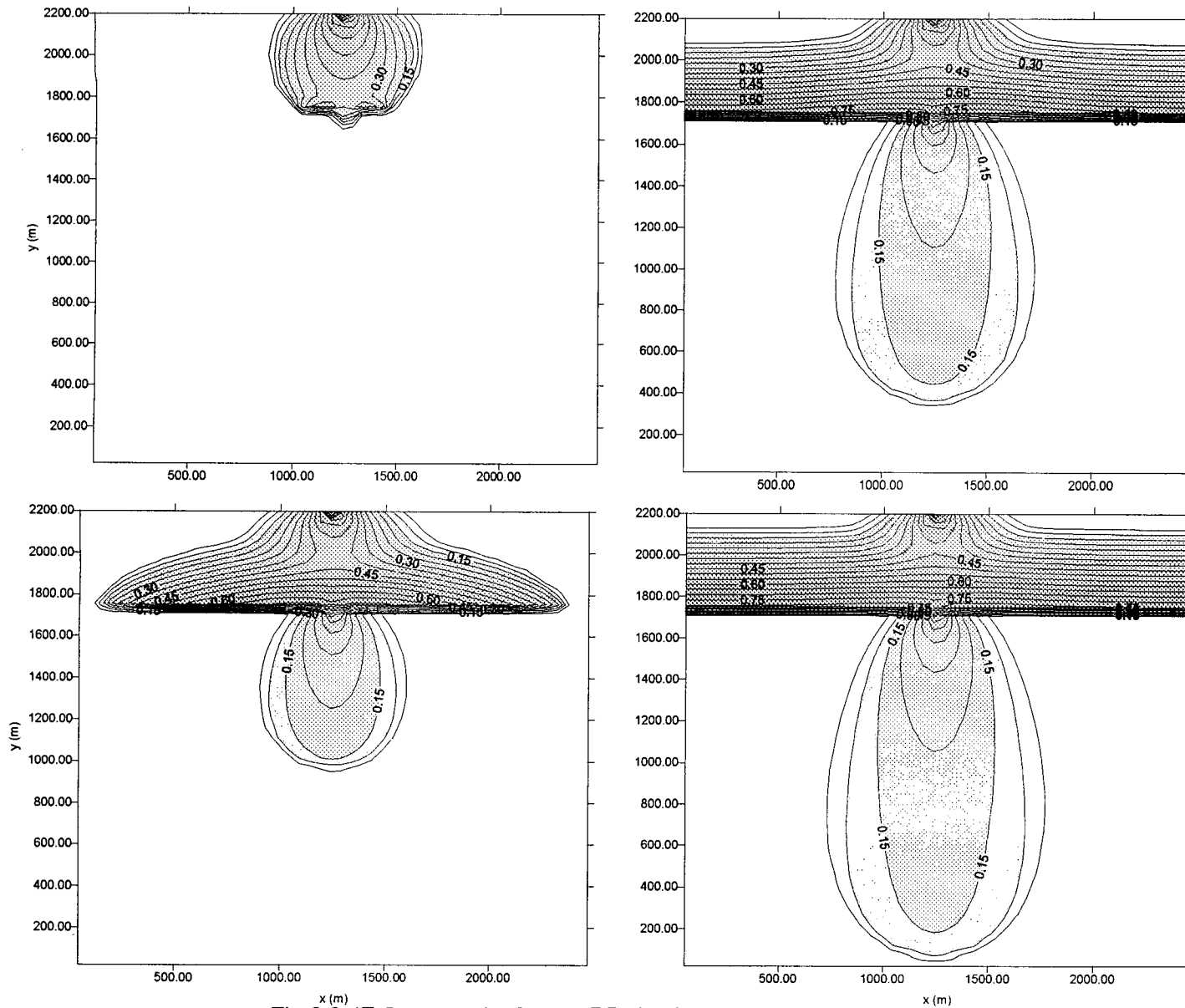


Fig.3.3.17 Contour plot for run B5. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

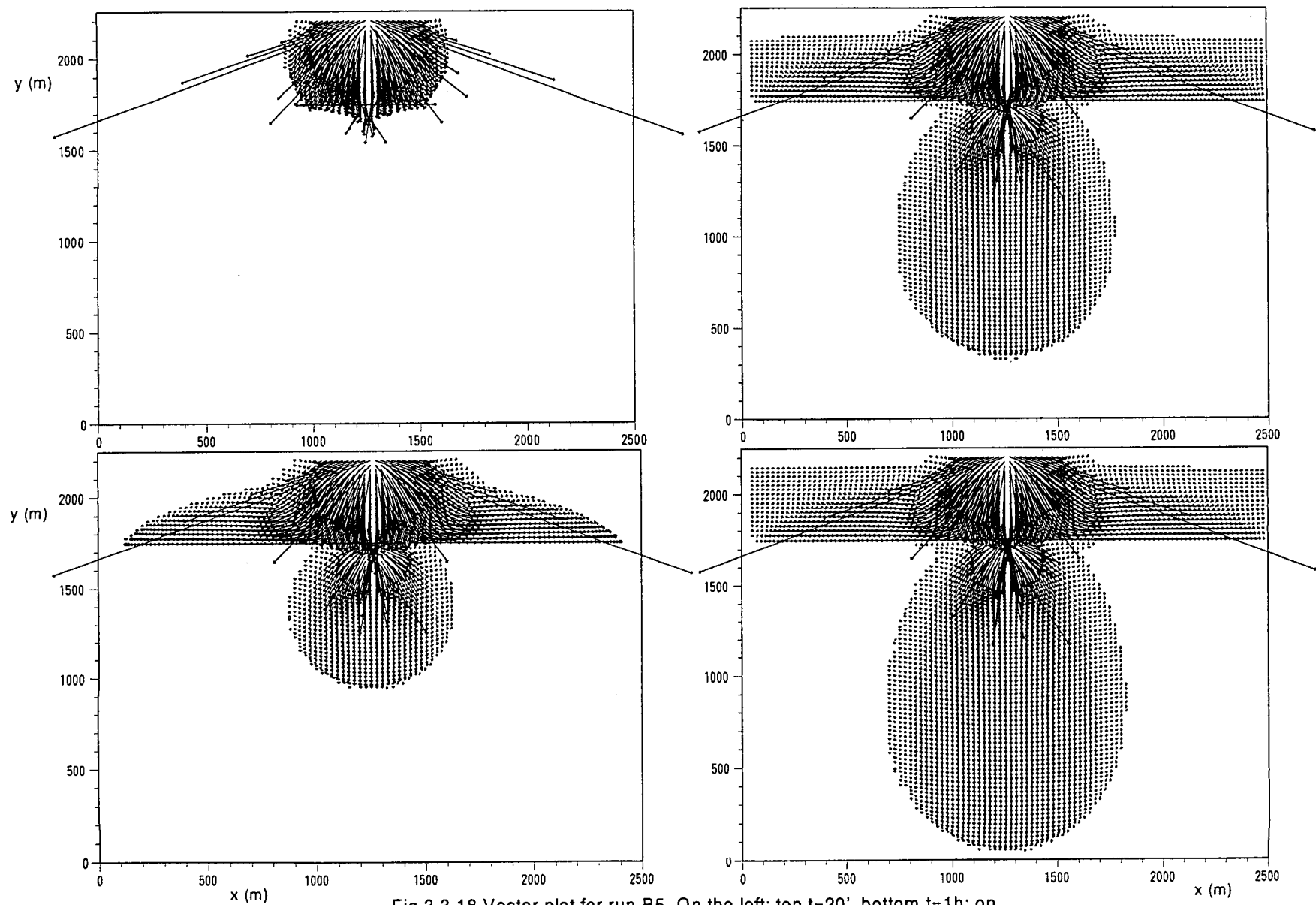


Fig.3.3.18 Vector plot for run B5. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 1000 times the plot unit.

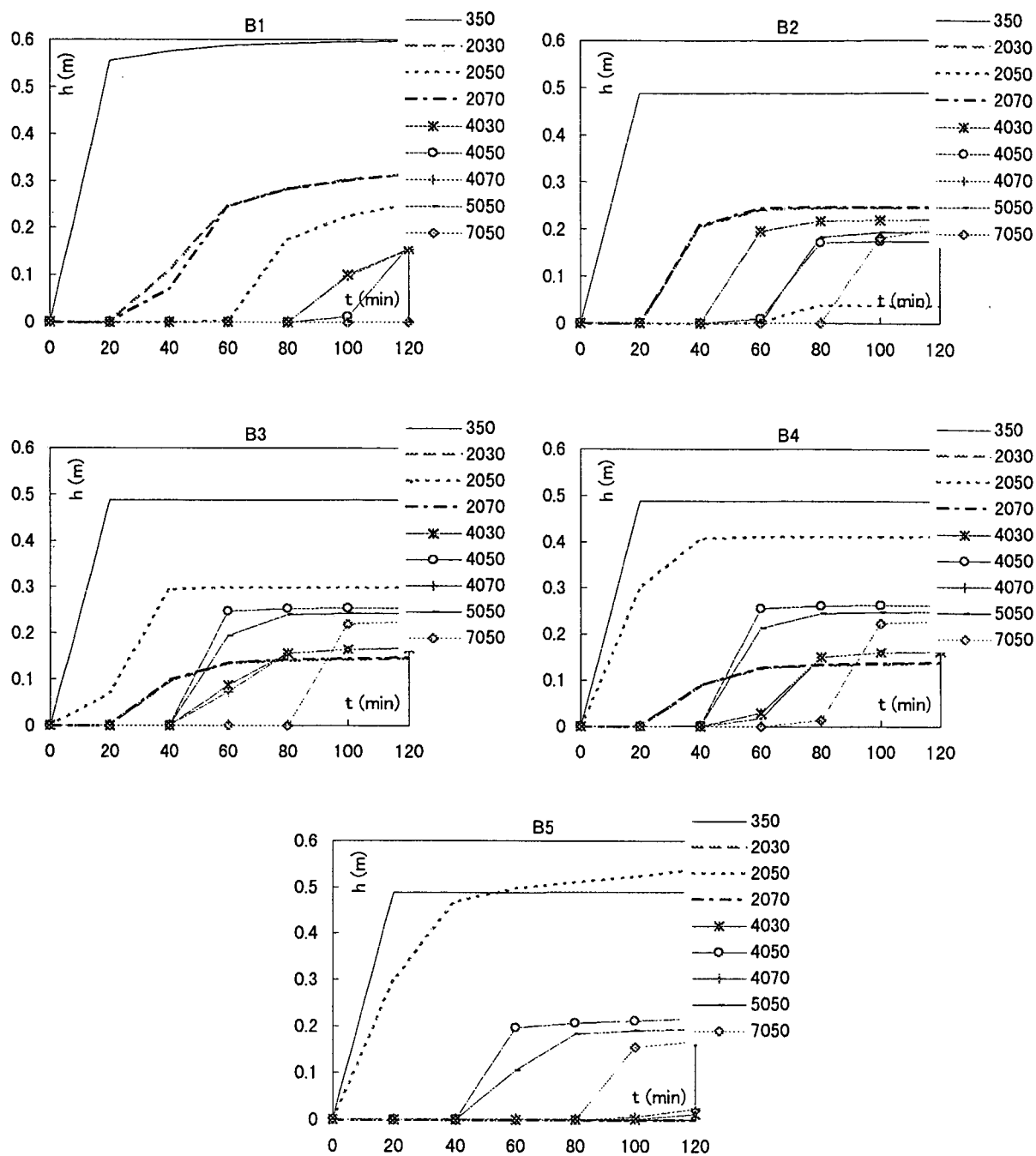


Fig.3.3.19 Water depth as a function of time for runs B1 to B5

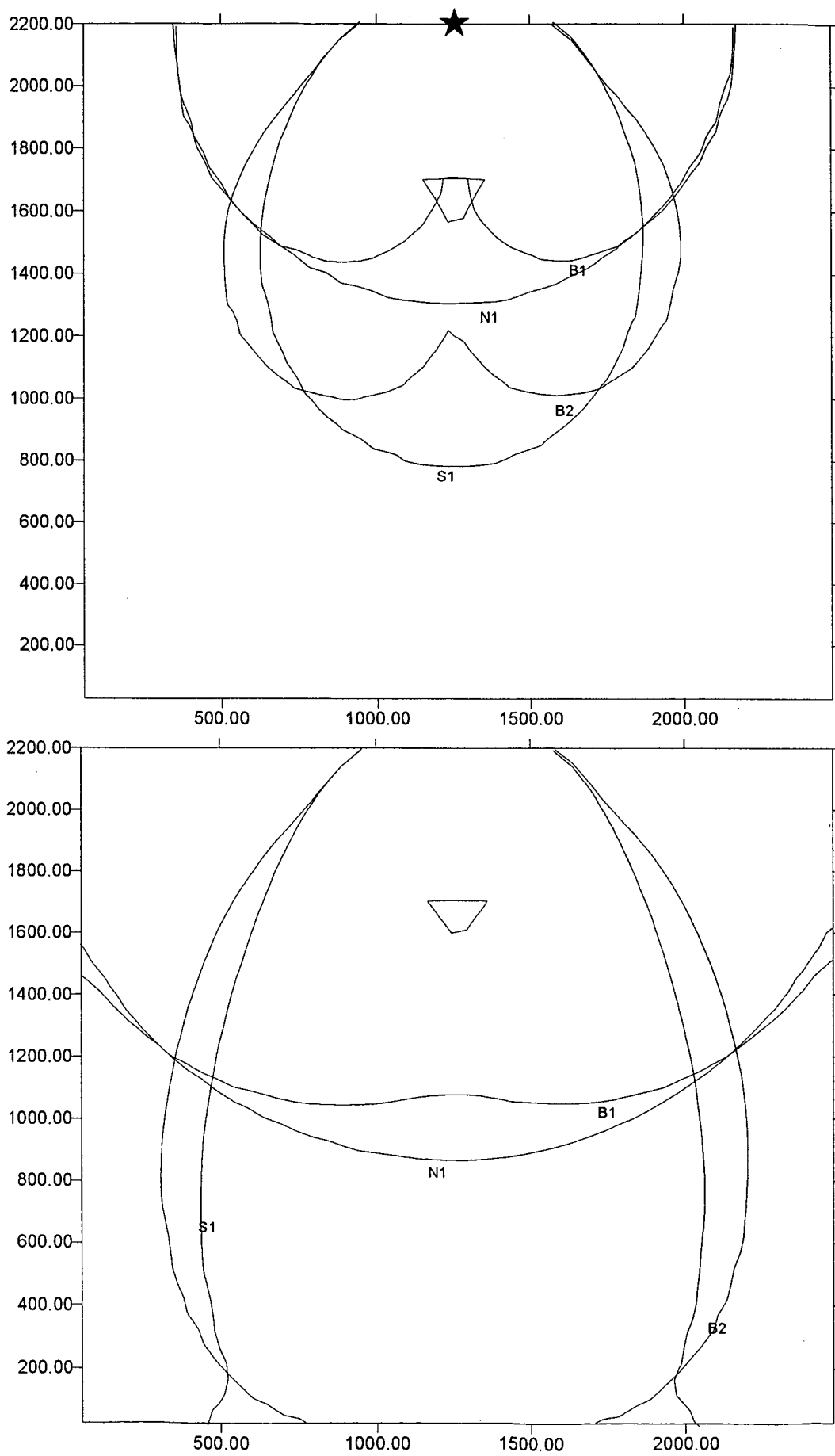


Fig.3.3.20 On the top: comparison between run N1, B1,B2 and S1 for $t=1h$;
on the bottom: comparison between run N1, B1, B2 and S1 for $t=2h$.

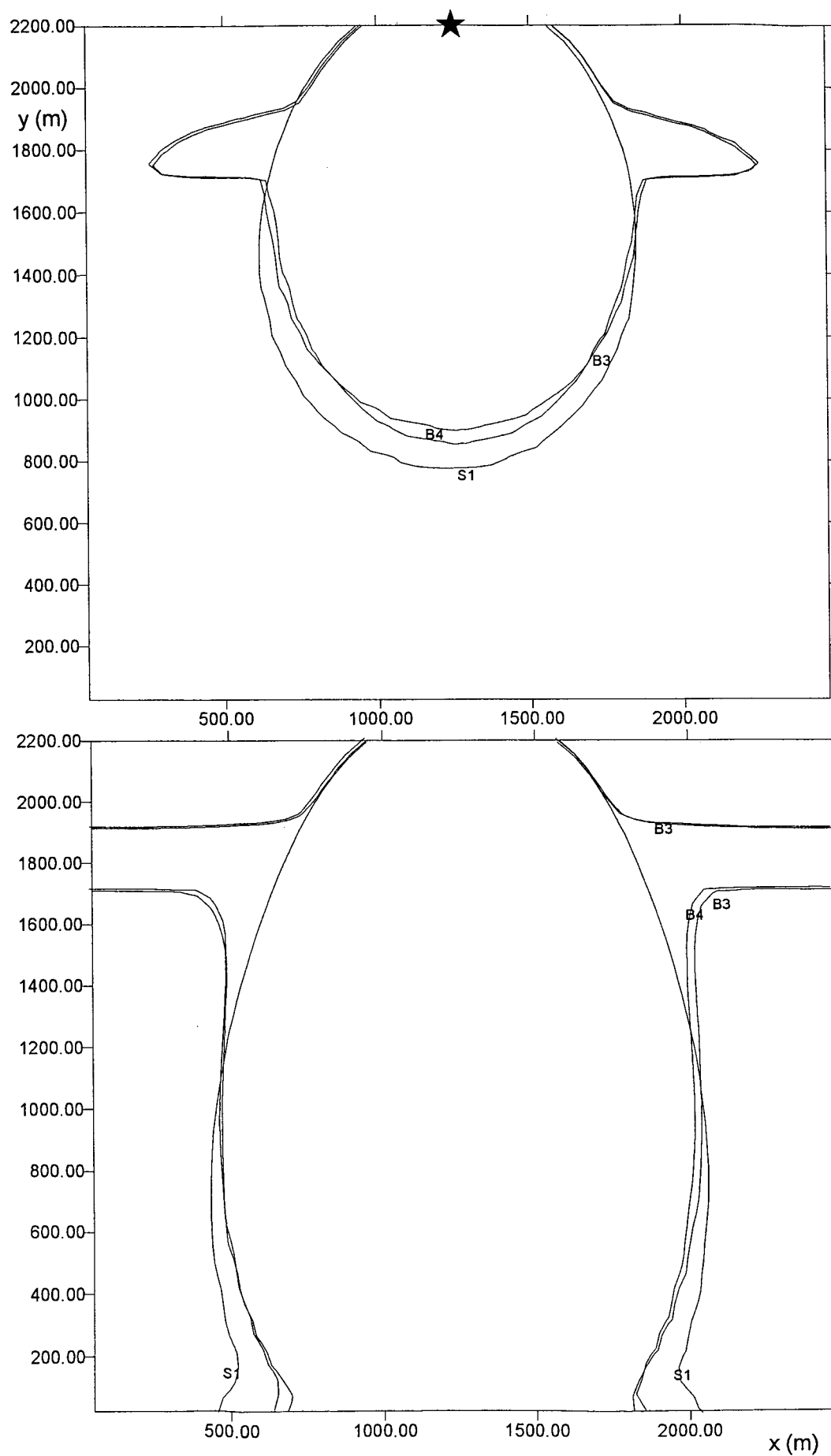


Fig.3.3.21 On the top: comparison between run B3, B4 and S1 for $t=1h$;
on the bottom: comparison between run B3, B4 and S1 for $t=2h$.

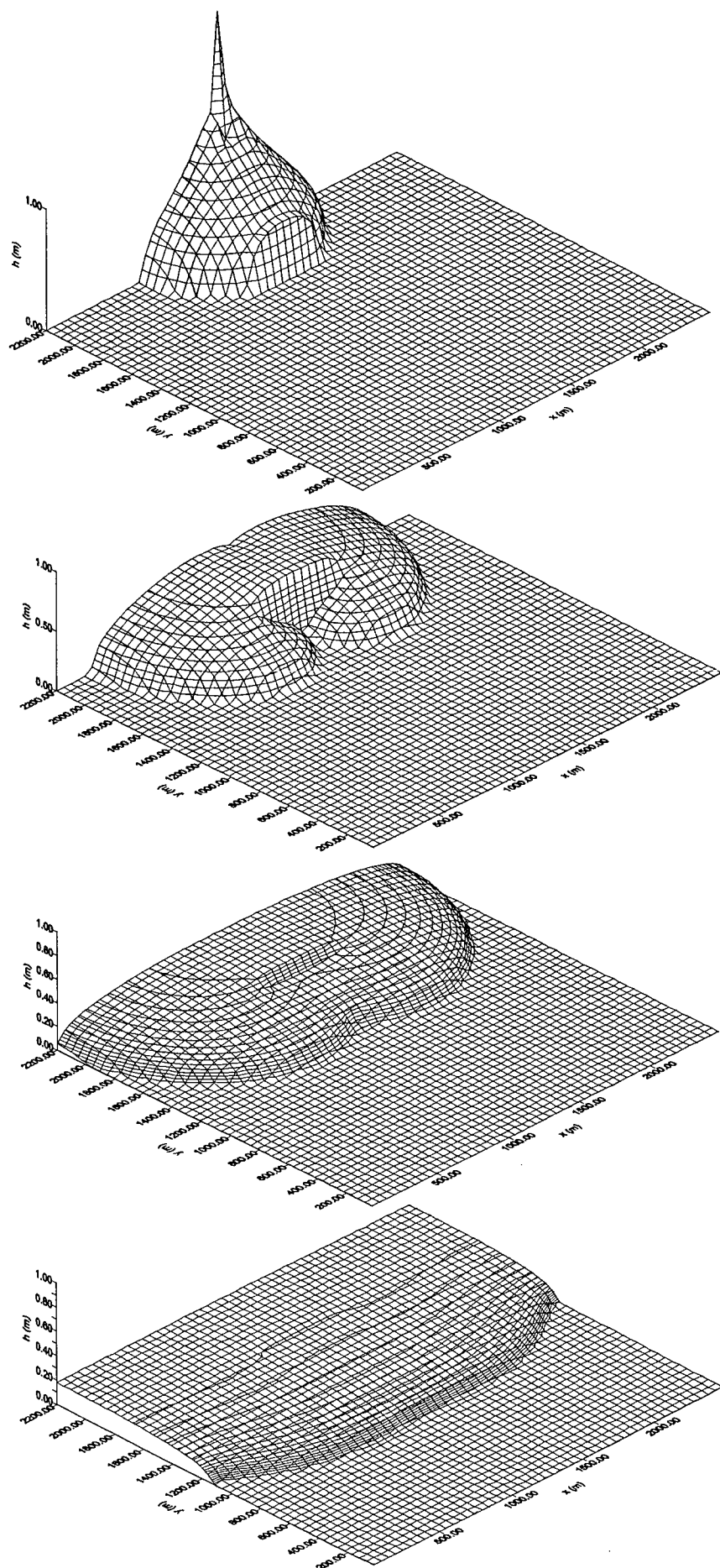


Fig.3.3.22 Surface plot for run B1T. From top to bottom: $t=20'$, $t=40'$, $t=1h$ and $t=2h$ (x , y and z scale in meters).

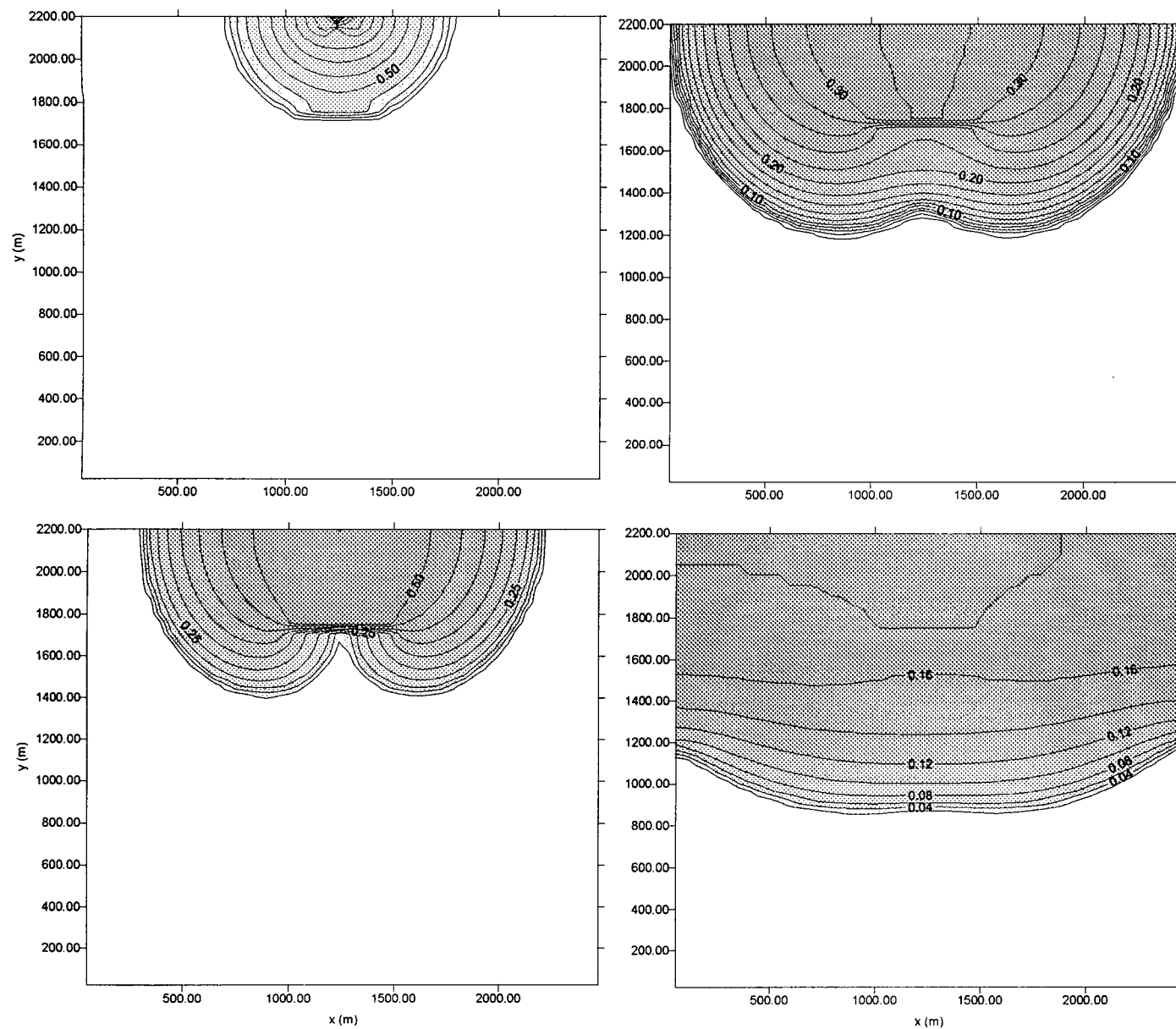


Fig.3.3.23 Contour plot for run B1T. On the left: top $t=20'$, bottom $t=40'$; on the right: top $t=1h$, bottom $t=2$ hours (scale in meter).

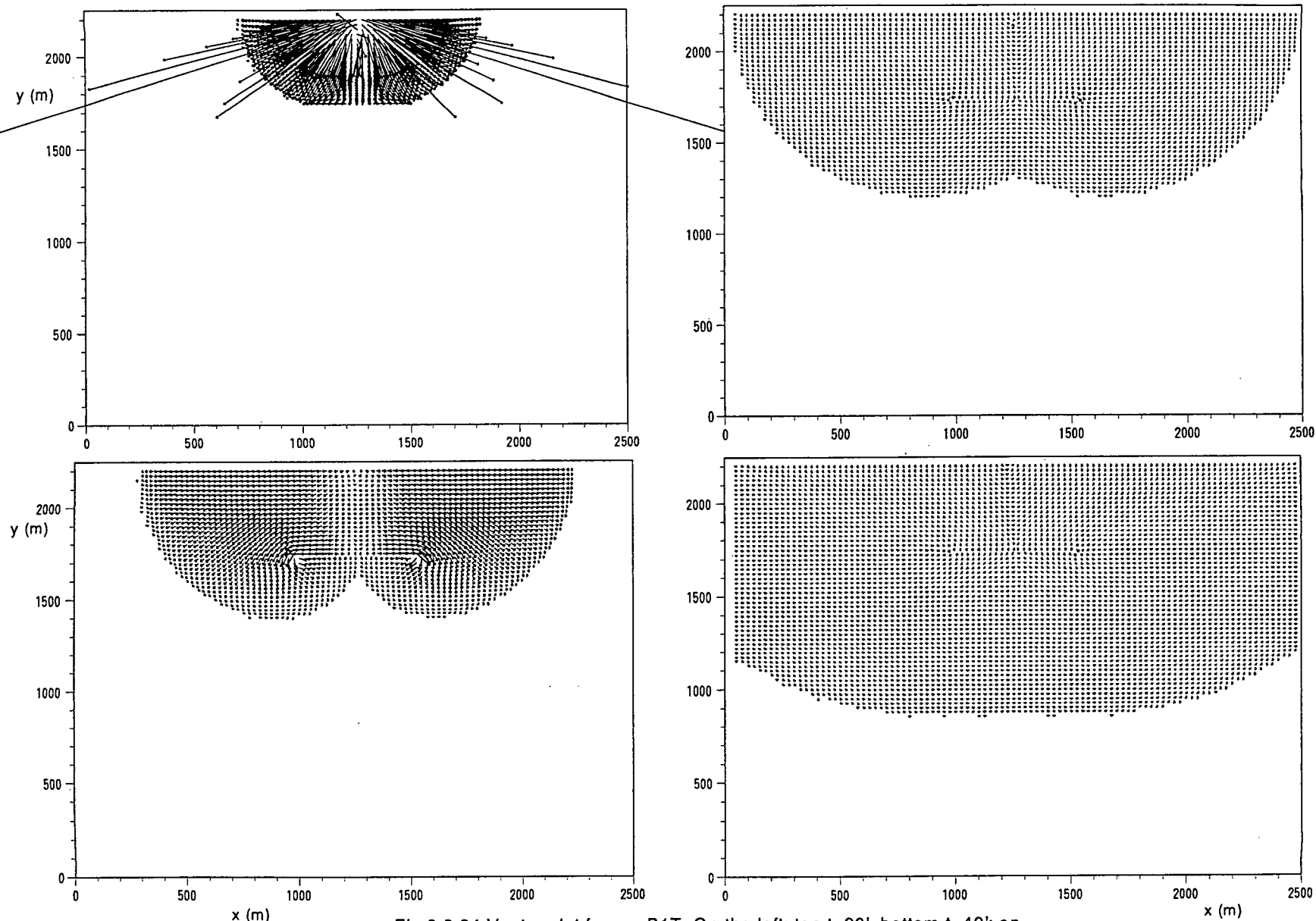


Fig.3.3.24 Vector plot for run B1T. On the left: top $t=20'$, bottom $t=40'$; on the right: top $t=1h$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 300 times the plot unit for $t=20'$, $t=40'$, $t=1h$ and 1000 for $t=2h$.

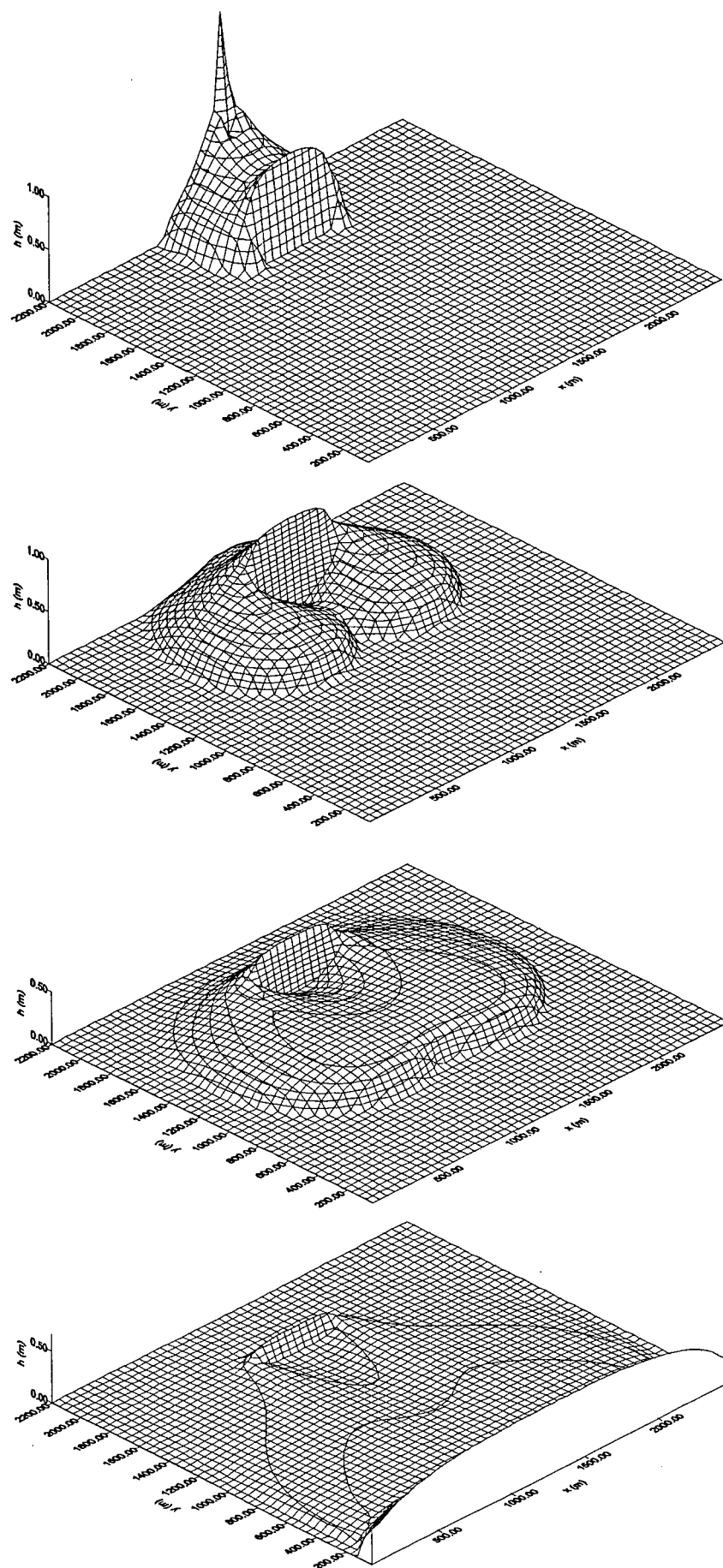


Fig.3.3.25 Surface plot for run B2T. From top to bottom: $t=20'$, $t=40'$, $t=1h$ and $t=2$ hours (x , y and z scale in meters).

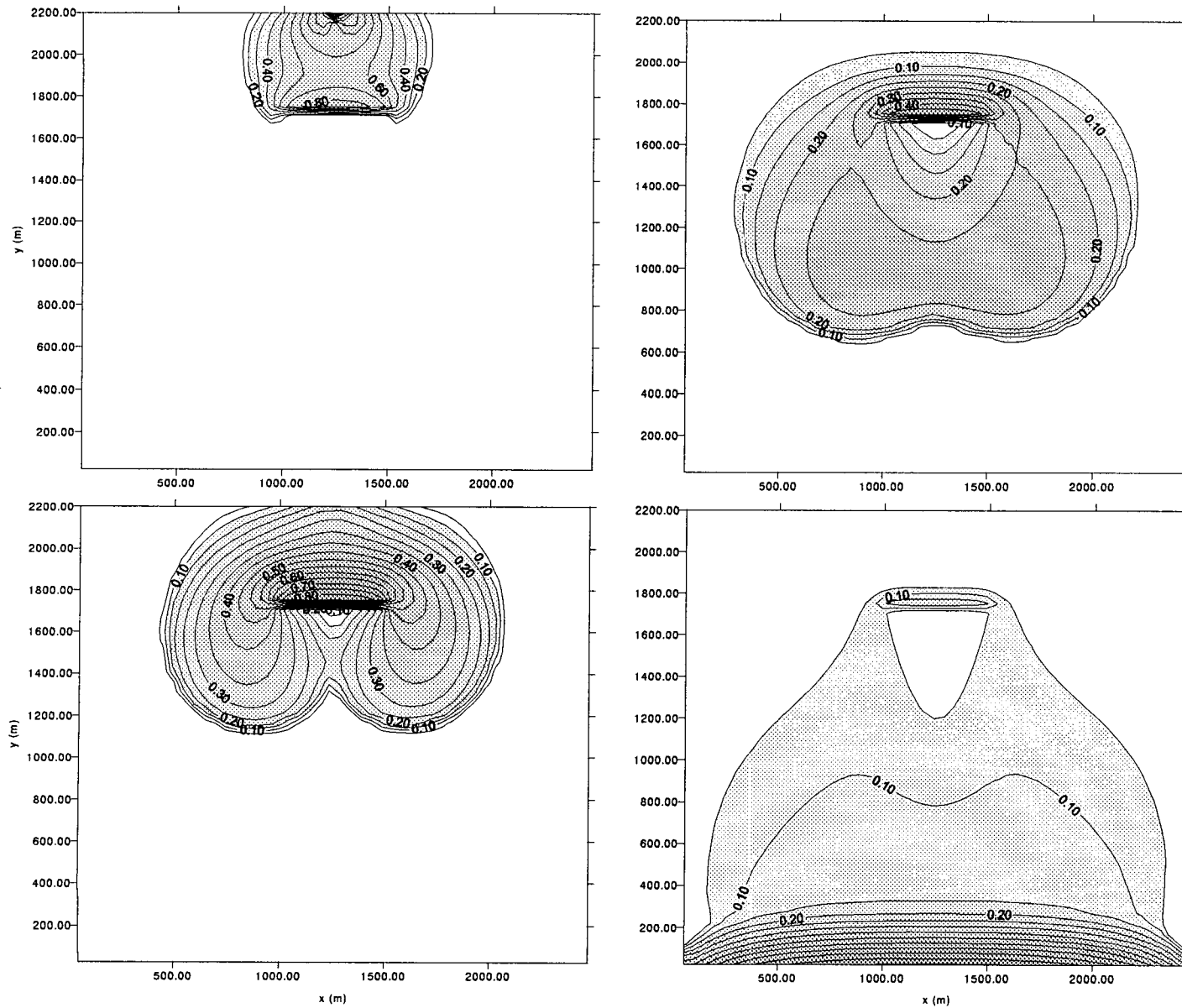


Fig.3.3.26 Contour plot for run B2T. On the left: top $t=20'$, bottom $t=40'$; on the right: top $t=1h$, bottom $t=2$ hours (scale in meter).

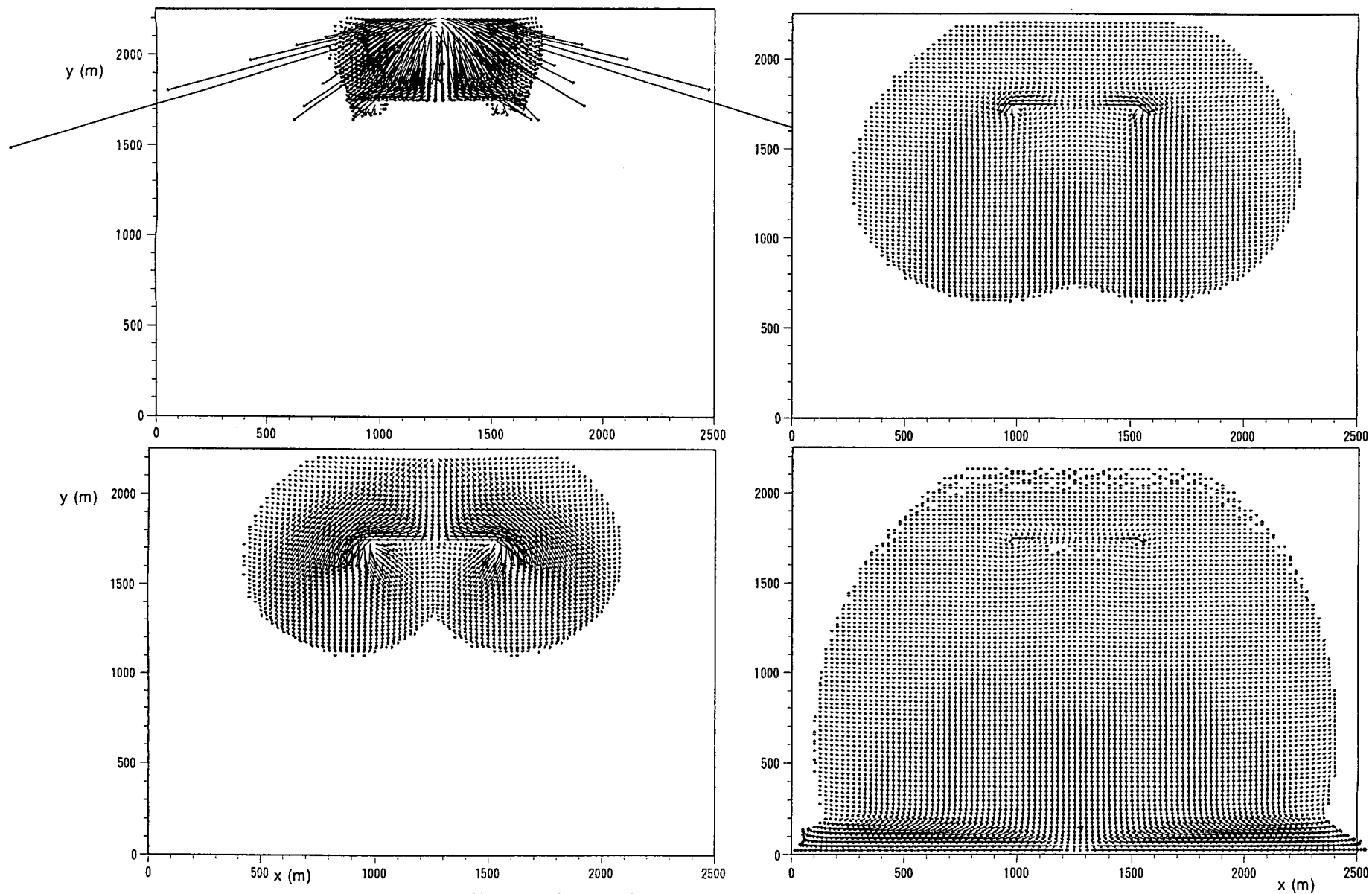


Fig.3.3.27 Vector plot for run B2T. On the left: top $t=20'$, bottom $t=40'$; on the right: top $t=1h$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 300 times the plot unit for $t=20'$, $t=40'$, $t=1h$ and 1000 for $t=2h$.

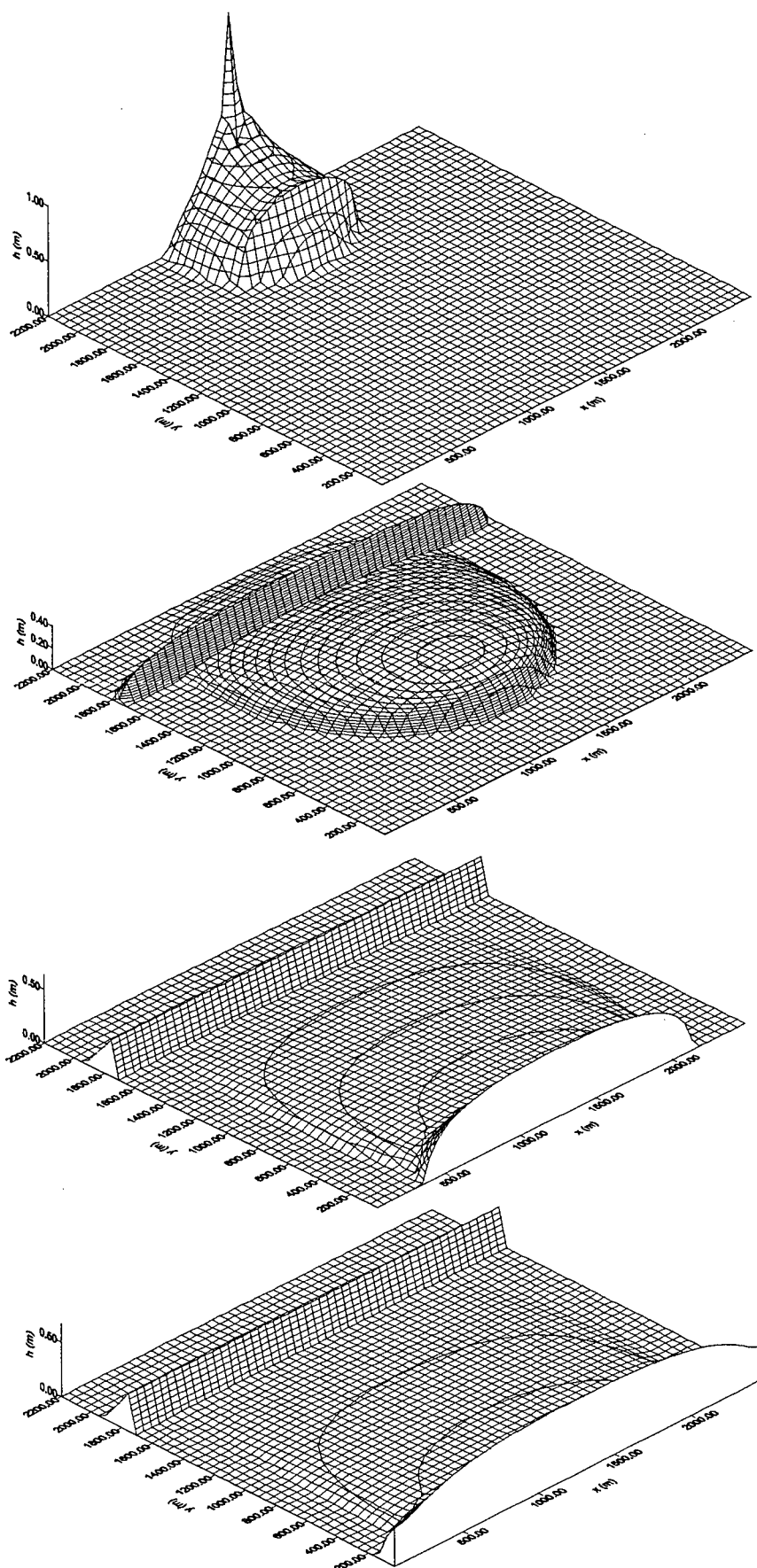


Fig.3.3.28 Surface plot for run B3T. From top to bottom: $t=20'$, $t=1\text{h}$, $t=1\text{h}40'$ and $t=2\text{ hours}$ (x , y and z scale in meters).

Fig.3.3.29 Contour plot for run B3T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

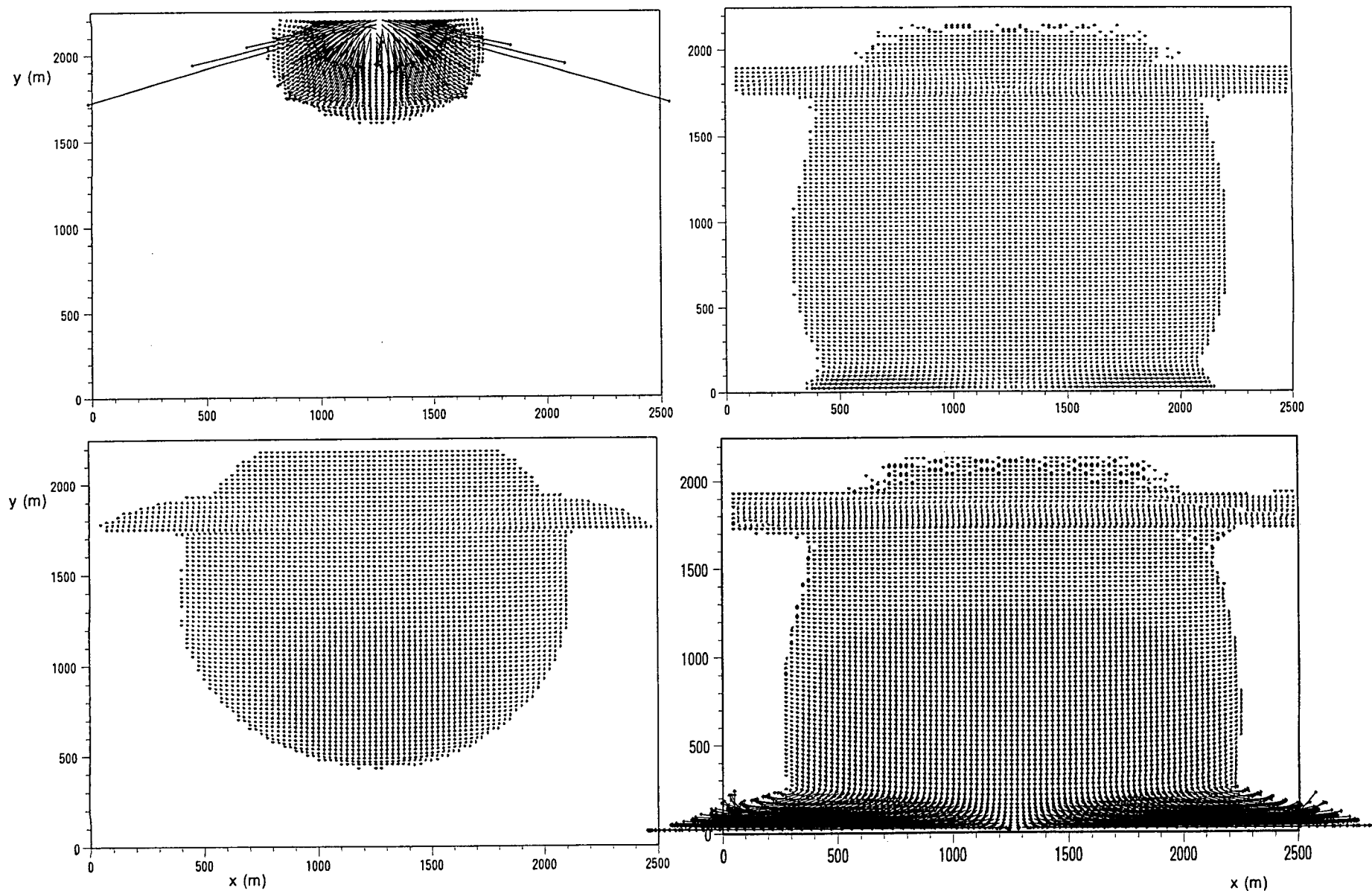


Fig.3.3.30 Vector plot for run B3T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 200 times the plot unit for $t=20'$, $t=1h$, $t=1h40'$ and 4000 for $t=2h$.

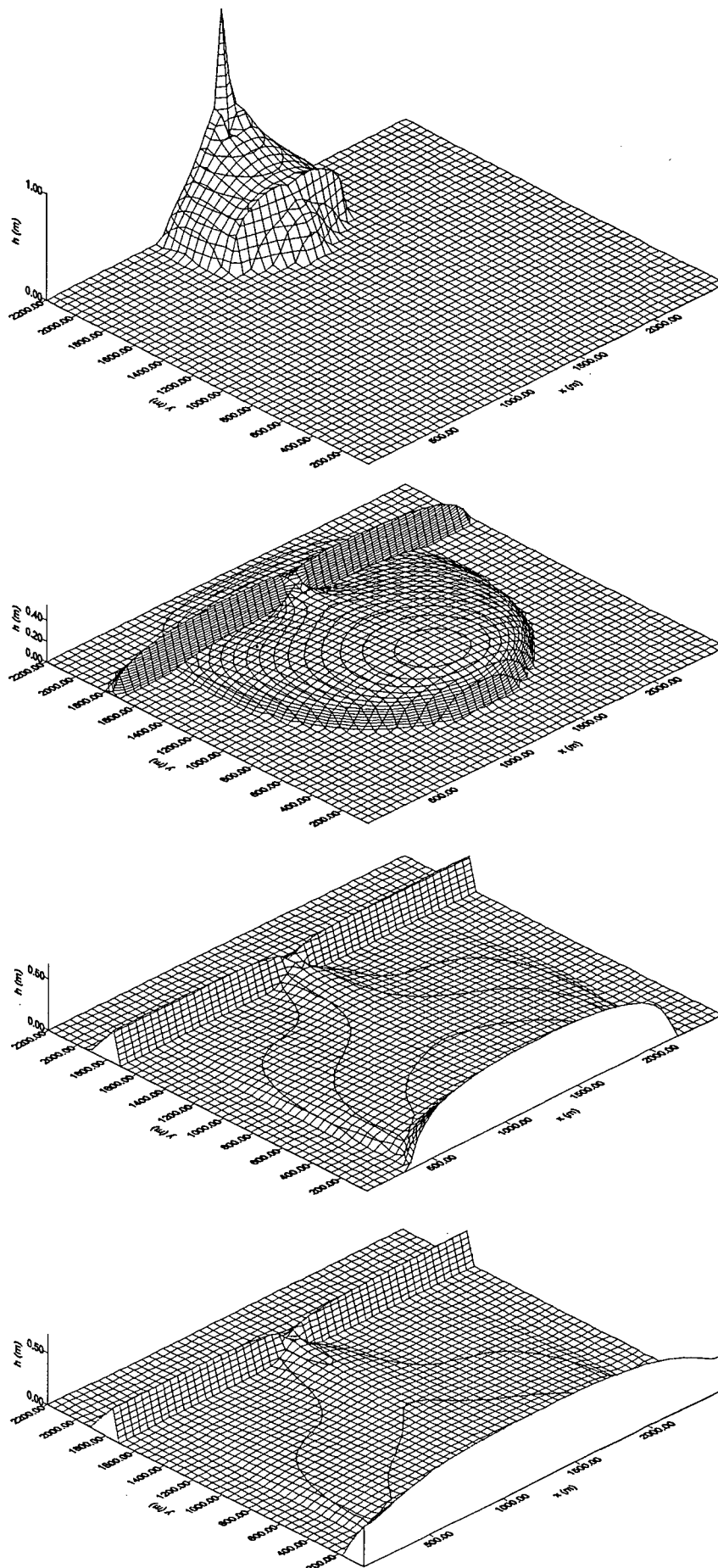


Fig.3.3.31 Surface plot for run B4T. From top to bottom: $t=20'$, $t=1h$, $t=1h40'$ and $t=2h$ (x , y and z scale in meters).

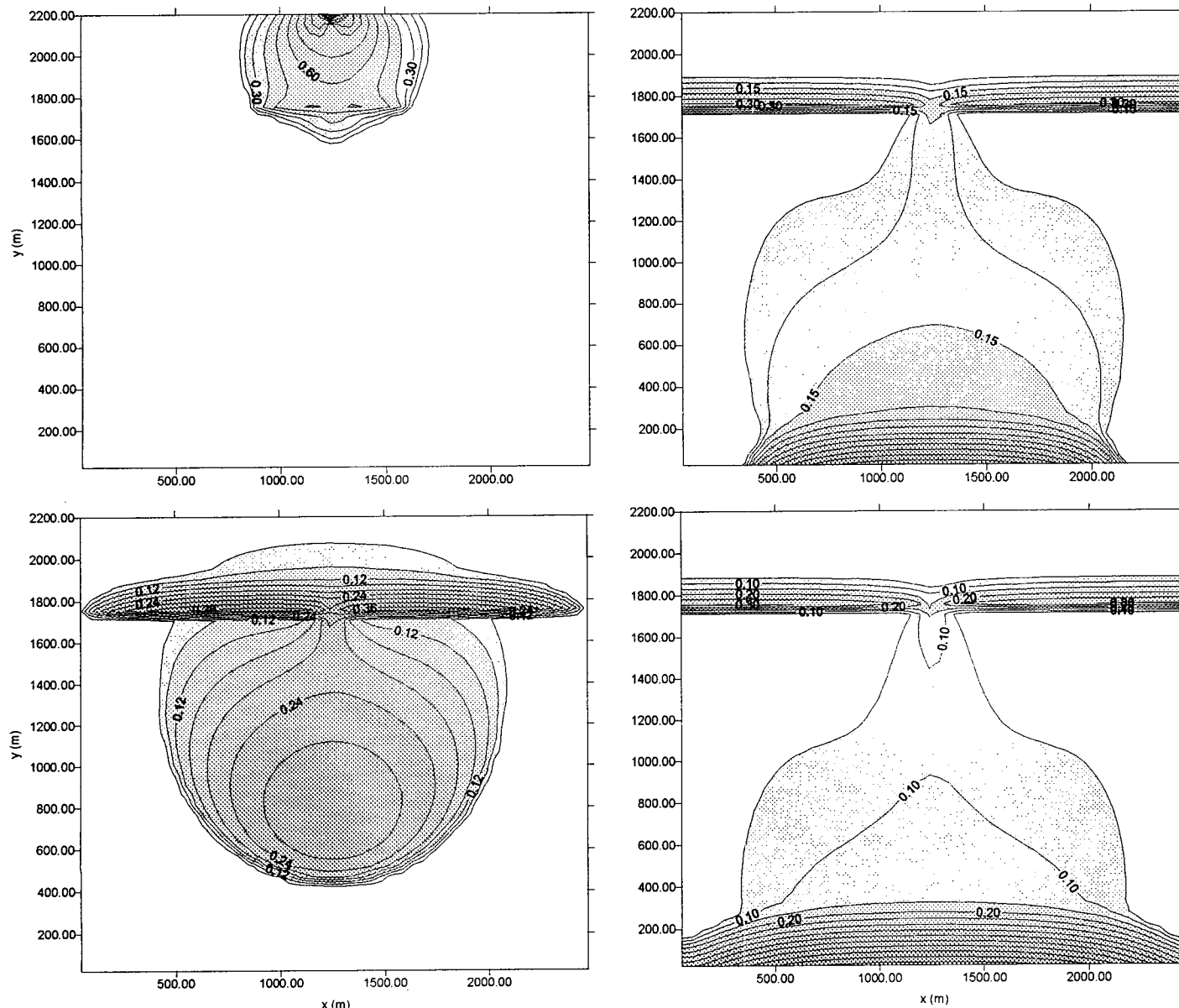


Fig.3.3.32 Contour plot for run B4T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

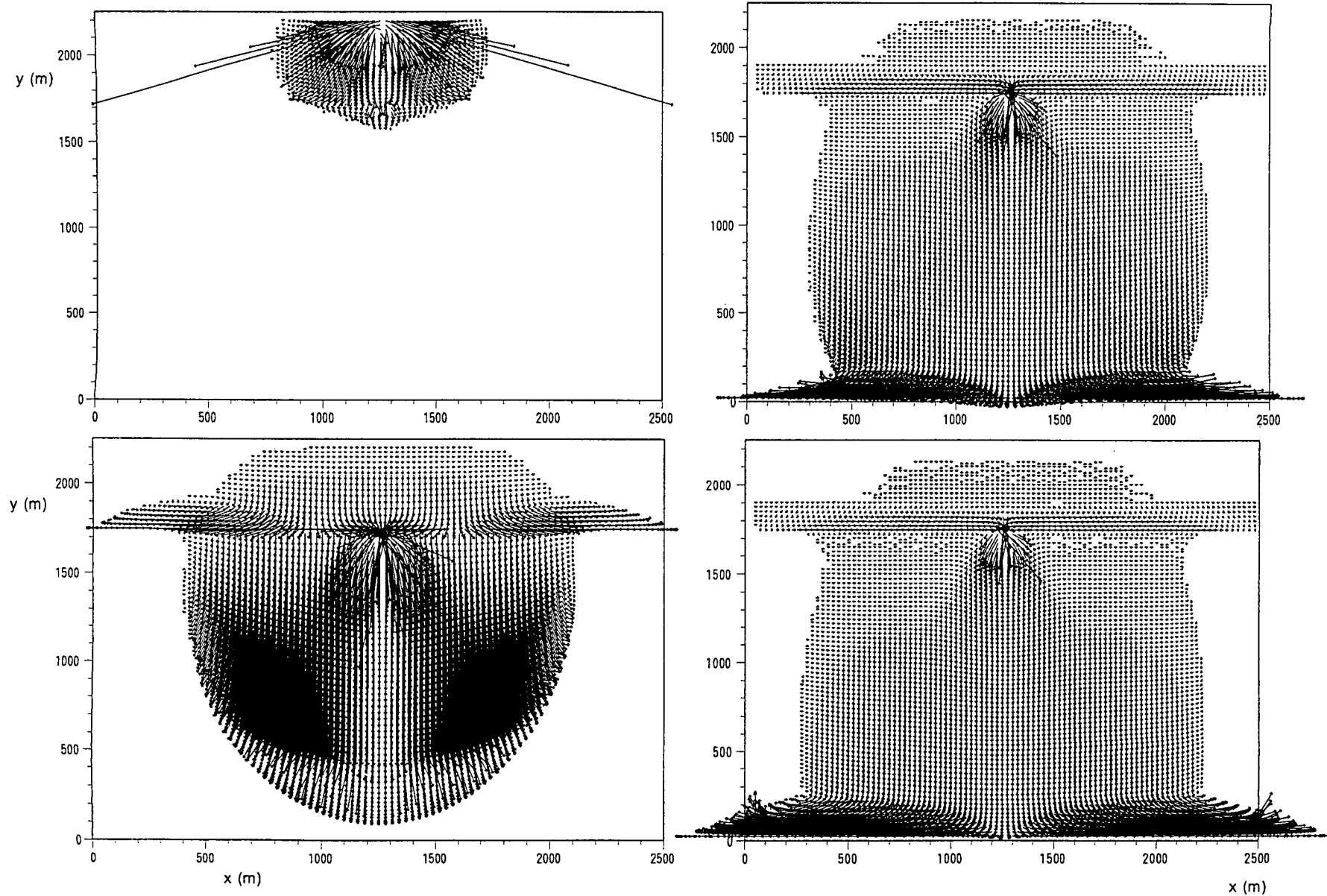


Fig.3.3.33 Vector plot for run B4T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 200 times the plot unit for $t=20'$ and 4000 for $t=1h$, $t=1h40'$, $t=2h$.

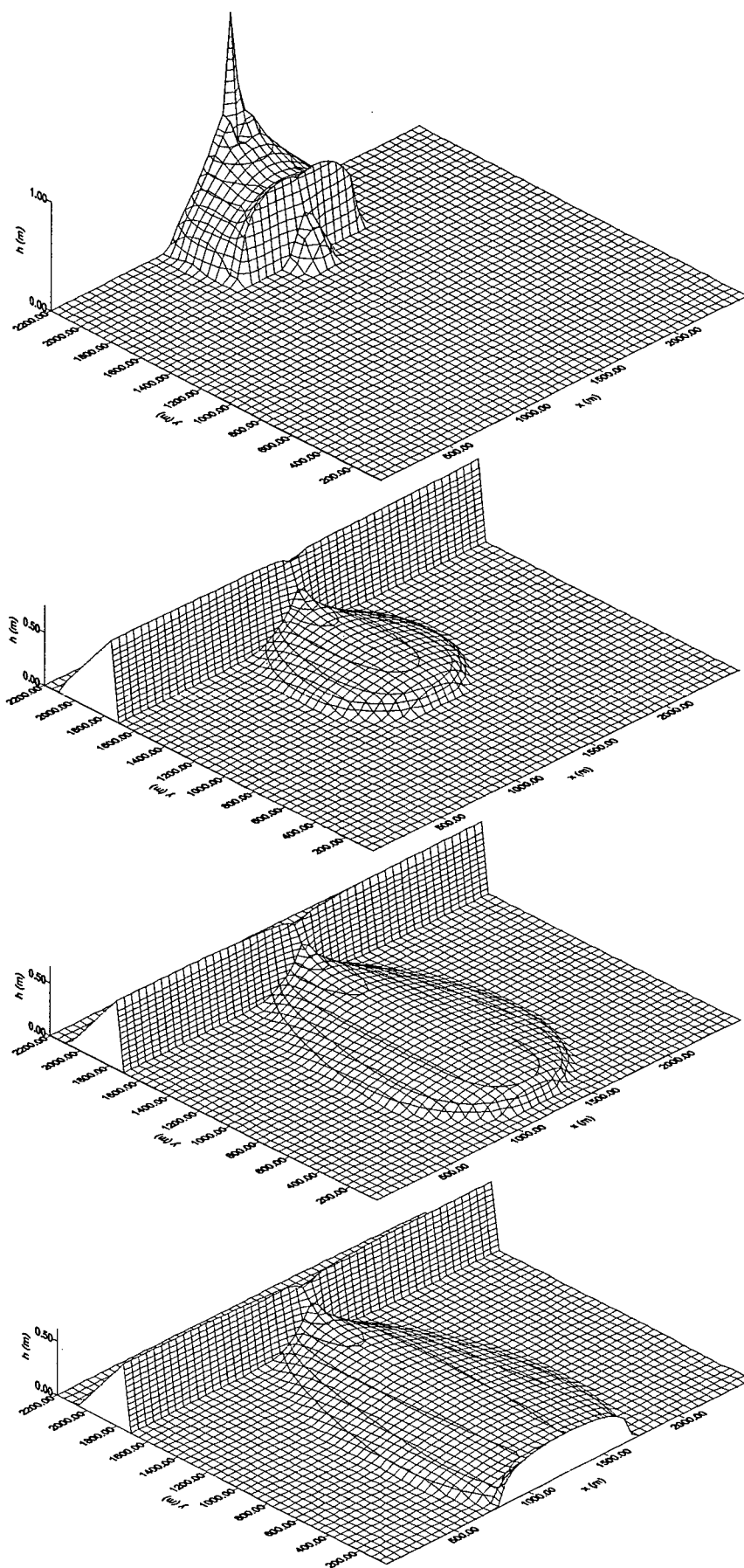


Fig.3.3.34 Surface plot for run B5T. From top to bottom: $t=20'$, $t=1h$, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

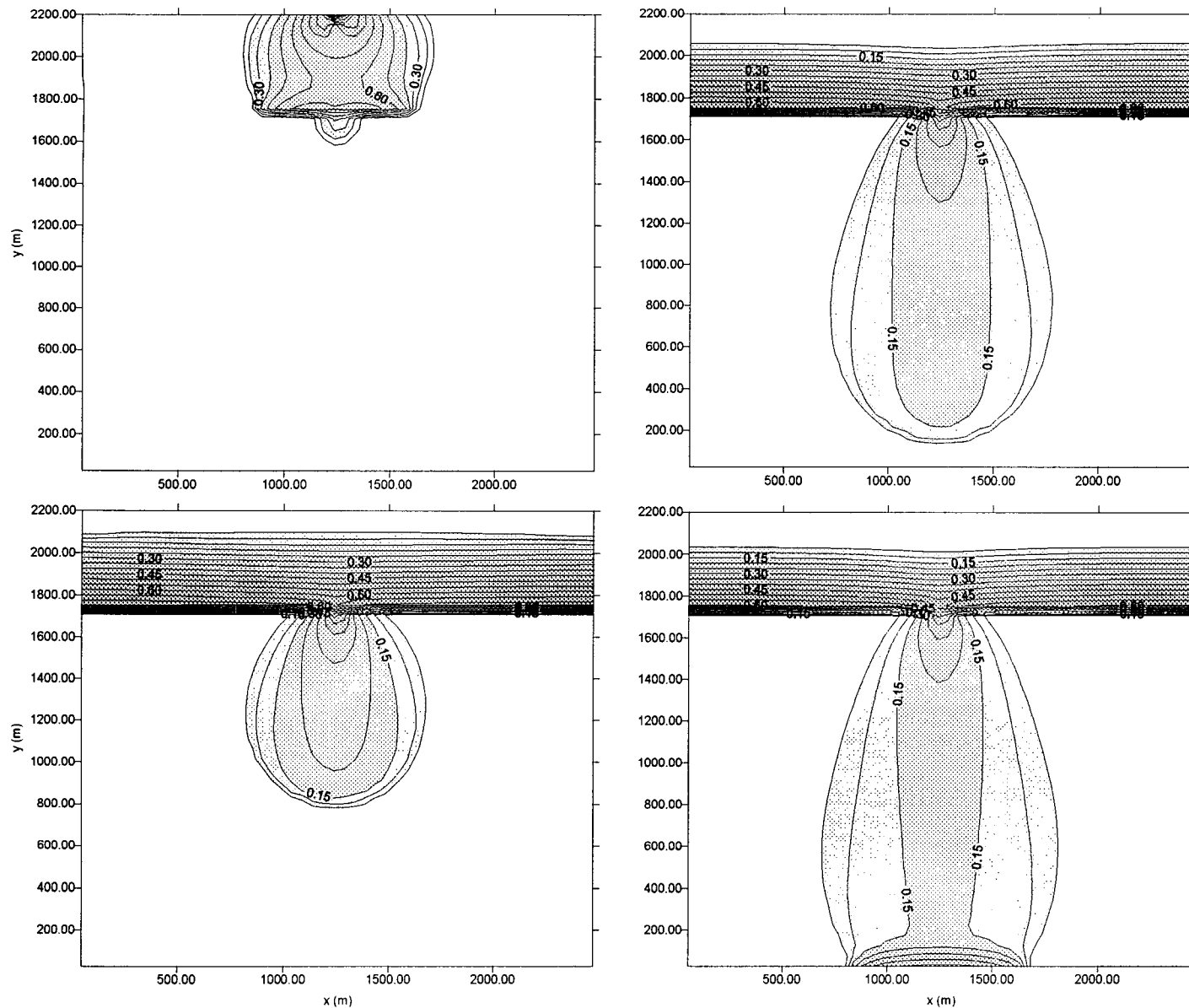


Fig.3.3.35 Contour plot for run B5T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

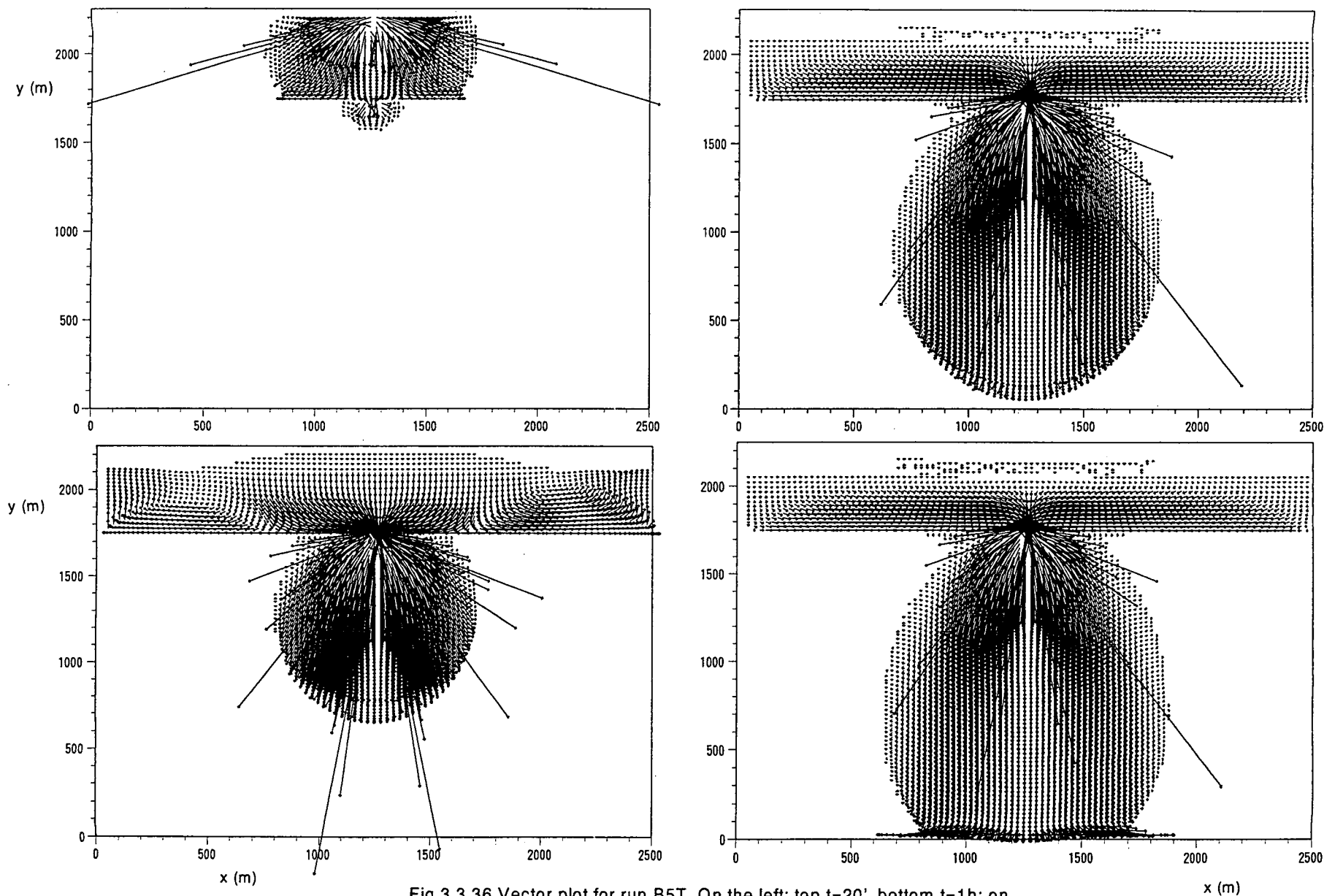


Fig.3.3.36 Vector plot for run B5T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 200 times the plot unit for $t=20'$ and 4000 for $t=1h$, $t=1h40'$, $t=2h$.

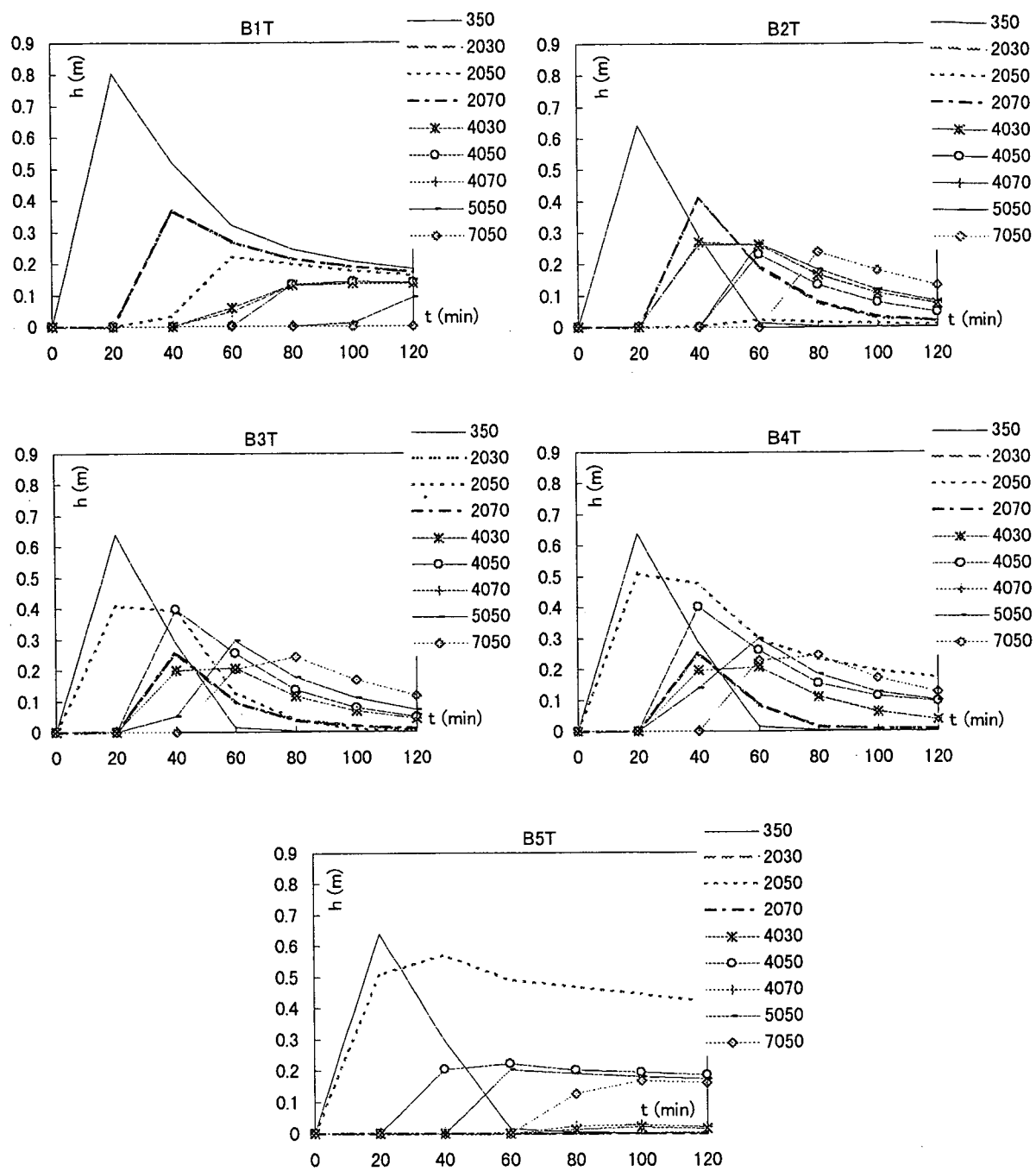


Fig.3.3.37 Water depth as a function of time for run B1T to B5T

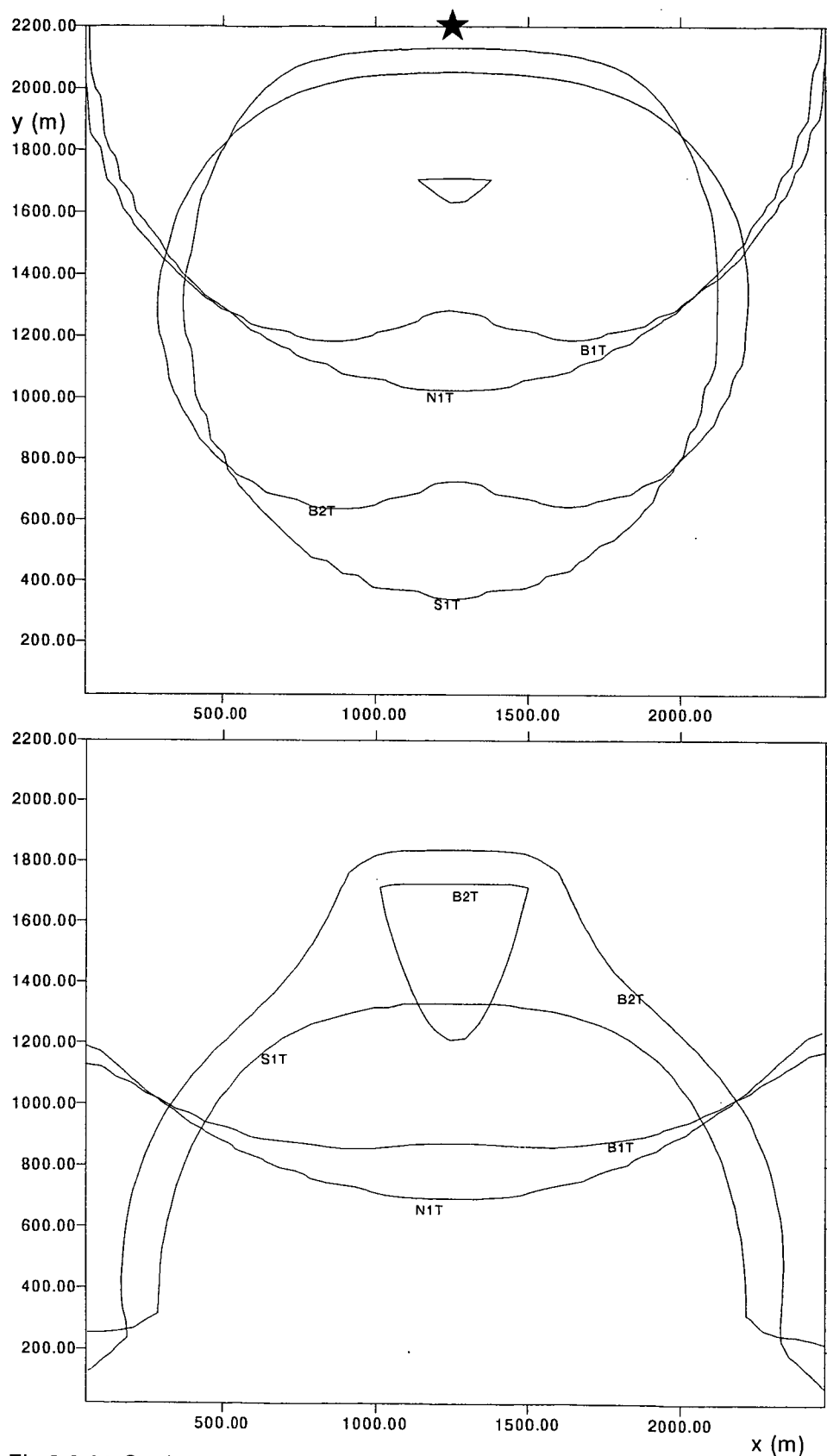


Fig.3.3.38 On the top: comparison between run B1T, N1T, B2T and S1T for $t=1h$; on the bottom: comparison between run B1T, B2T, N1T and S1T for $t=2h$.

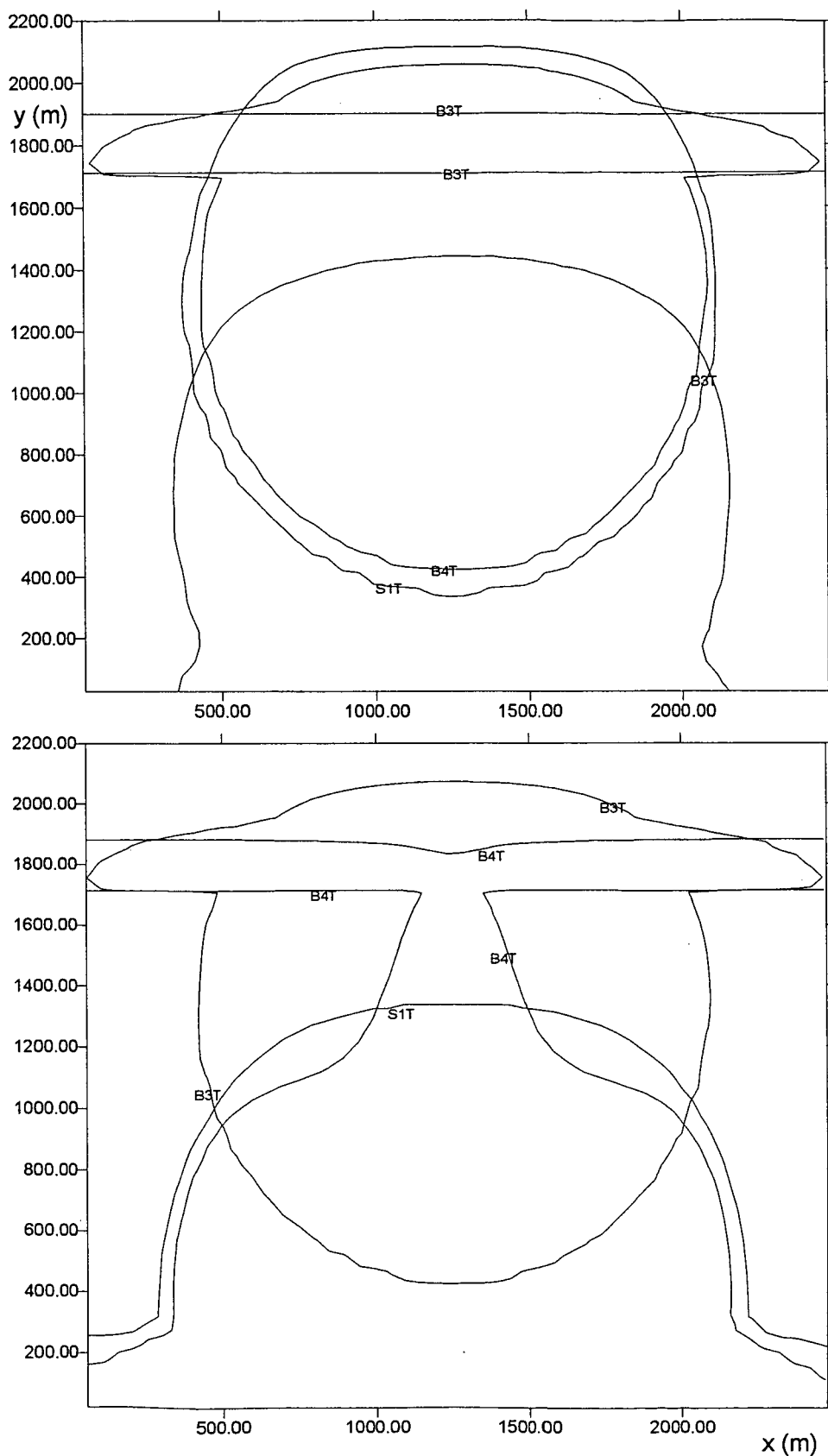


Fig.3.3.39 On the top: comparison between run B3T, B4T and S1T for t=1h; on the bottom: comparison between run B3T, B4T and S1T for t=2h.

3.4 EFFECT OF DRAINAGE CHANNELS

Drainage channels constitute the natural way to remove the excess of water. A floodplain with a good drainage capacity can considerably diminish the amount of damage during a flood inundation.

To evaluate the effect of channels in the floodplain, 10 numerical simulations has been done.

The layout of the plane with the drainage network is shown in Fig.3.4.1.

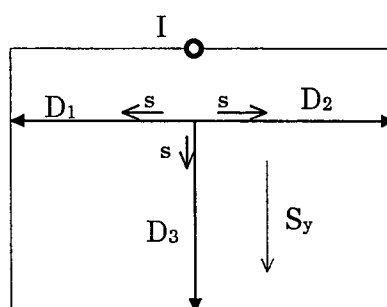


Fig.3.4.1 Layout for series C

In Fig.3.4.1 D_1 , D_2 and D_3 represent drainage channels while I represents the cell in which the discharge is introduced. Table 3.4.1 shows the details of the series.

Table 3.4.1 Summary for series C

Run	n_0	θ (%)	s_y	s_x	Input hydrograph	Bank and/or culvert element simulated
C1	0.05	0.0	0.0	0.0	H	D_1, D_2 $s=0.002$
C2	0.05	0.0	0.0	0.0	H	D_1, D_2 $s=0.004$
C3	0.05	0.0	0.0	0.0	H	D_3 $s=0.002$
C4	0.05	0.0	0.0	0.0	H	D_1, D_2, D_3 $s=0.002$
CT1	0.05	0.0	0.0	0.0	T	D_1, D_2 $s=0.002$
CT2	0.05	0.0	0.0	0.0	T	D_1, D_2 $s=0.004$
CT3	0.05	0.0	0.0	0.0	T	D_3 $s=0.002$
CT4	0.05	0.0	0.0	0.0	T	D_1, D_2, D_3 $s=0.002$

In the table, s represent the slopes of the drainage channels. The channels have a width equal to the cell dimension (25 m), a depth equal to 0.5m and a slope s as indicated in table 3.4.1. At the end of the channel is located a pump that drain the water out of the mesh. The roughness coefficient of the channel has been set the same as the one relative to the plane.

The results are reported in Figg. 3.4.2 to 3.4.13 for the runs from C1 to C4 relative to time $t=20'$, 1^h , $1^h40'$ and 2^h . Figg. 3.4.2-3.4.4 show the case of channel D1 and D2 with a slope of 0.002. Not all the water is drained by the channels. Figg. 3.4.5-3.4.7 shows the same channels D1 and D2 but with a slope of 0.004; in this case all the water is drained and the downstream part of the plan is dry. Figg.3.4.8-3.4.10 illustrate the case of a channel that flows in the same direction of the slope of the plan; in this case the water drained is less due to the ineffectiveness of the configuration. Figg.3.4.11-3.4.13 show the case in which all the channels are present.

Fig.3.4.14 reports the water depth as a function of time for the usual points considered. We need to remarks that the highest values are due to points that are inside a channel.

Fig.3.4.15 shows a comparison between runs C1, C2, C3 and N1. Some considerations can be pointed out. The most effective channel is the one that is perpendicular to the front of the flow (D1 and D2 in this particular case). In the case of the prove C4 all the three channels together avoid the flooding of the downstream part of the plane. The differences among the runs C3 and N1 (with no drainage) are small also if, they depend, of course, on the importance of the channel capacity in comparison with the input hydrograph.

Fig.3.4.16 to 3.4.27 illustrates the results for the runs CT1-CT4.

Fig. 3.4.28 shows the depth as a function of time for selected points. The points relative to the cells 2030, 2050, 2070 for the runs C1T and C2T, 2050, 4050, 5050 and 7050 for the run C3T and 2030, 2050, 2070, 4050, 5050 and 7050 for the run C4T are located inside the drainage network.

Fig.3.4.29 shows a comparison between runs C1T, C3T, C4T and N1T (without drainage). It is interesting to note that in this case, in the prove CT4, all the three channels together cannot preserve the flooding of the downstream portion of the plain; all this considering that the volume of this flood is less than the one due to the uniform hydrograph relative to the prove B4. This is due to the shape of the inflow hydrograph that is such that for a certain amount of time creates a discharge exceeding the carrying capacity of the channels; instead, in the case of prove B4, the carrying capacity of the drainage network is never exceeded also if the total amount of water is bigger.

Further results regarding the effect of the drainage network on a flood plain are reported by Kuriki et Al. (1997).

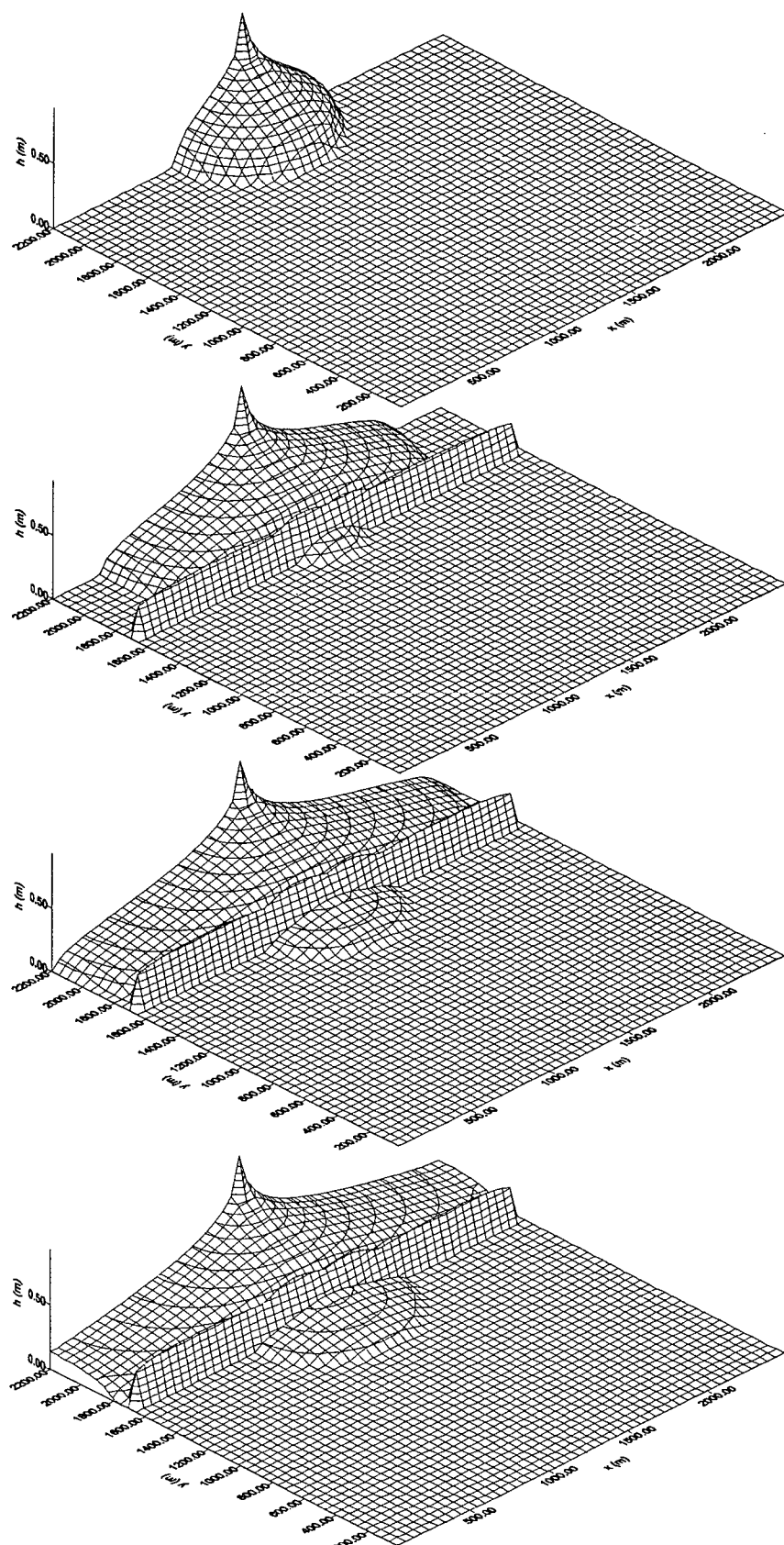


Fig.3.4.2 Surface plot for run C1. From top to bottom: $t=20'$, $t=1h$, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

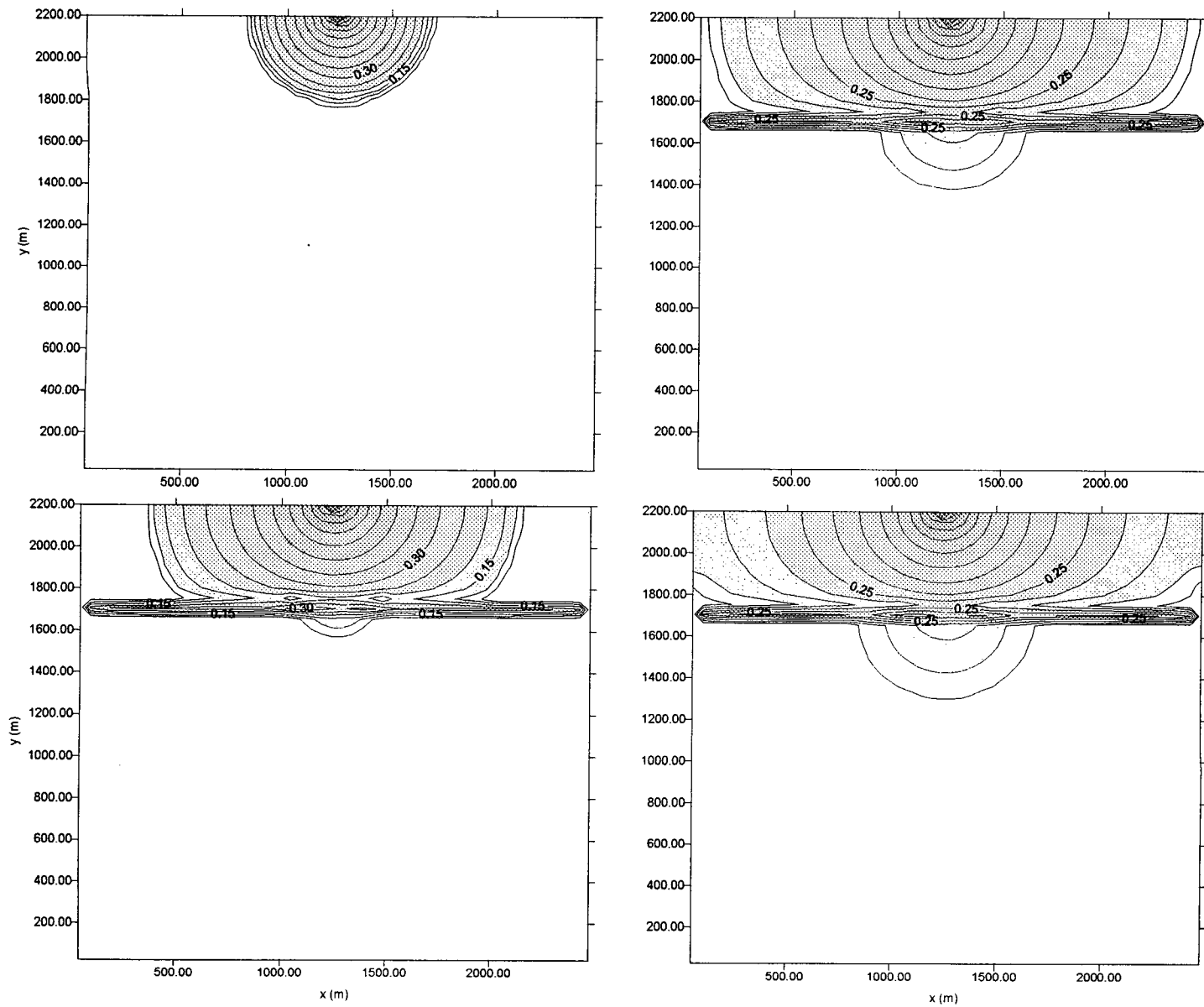


Fig.3.4.3 Contour plot for run C1. On the left: top $t=20'$, bottom $t=1\text{h}$; on the right: top $t=1\text{h}40'$, bottom $t=2\text{ hours}$ (scale in meter).

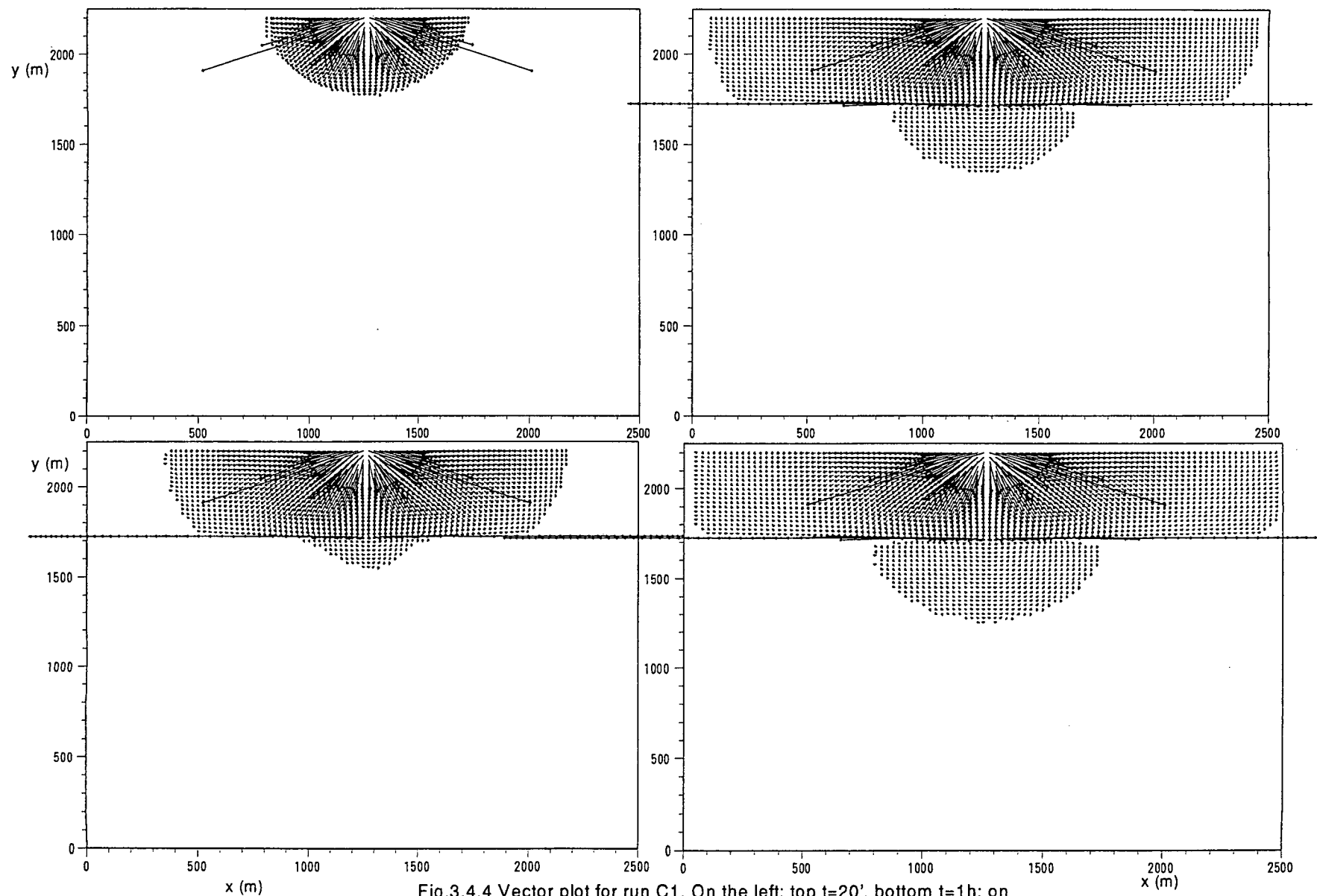


Fig.3.4.4 Vector plot for run C1. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m²/s) is 500 times the plot unit.

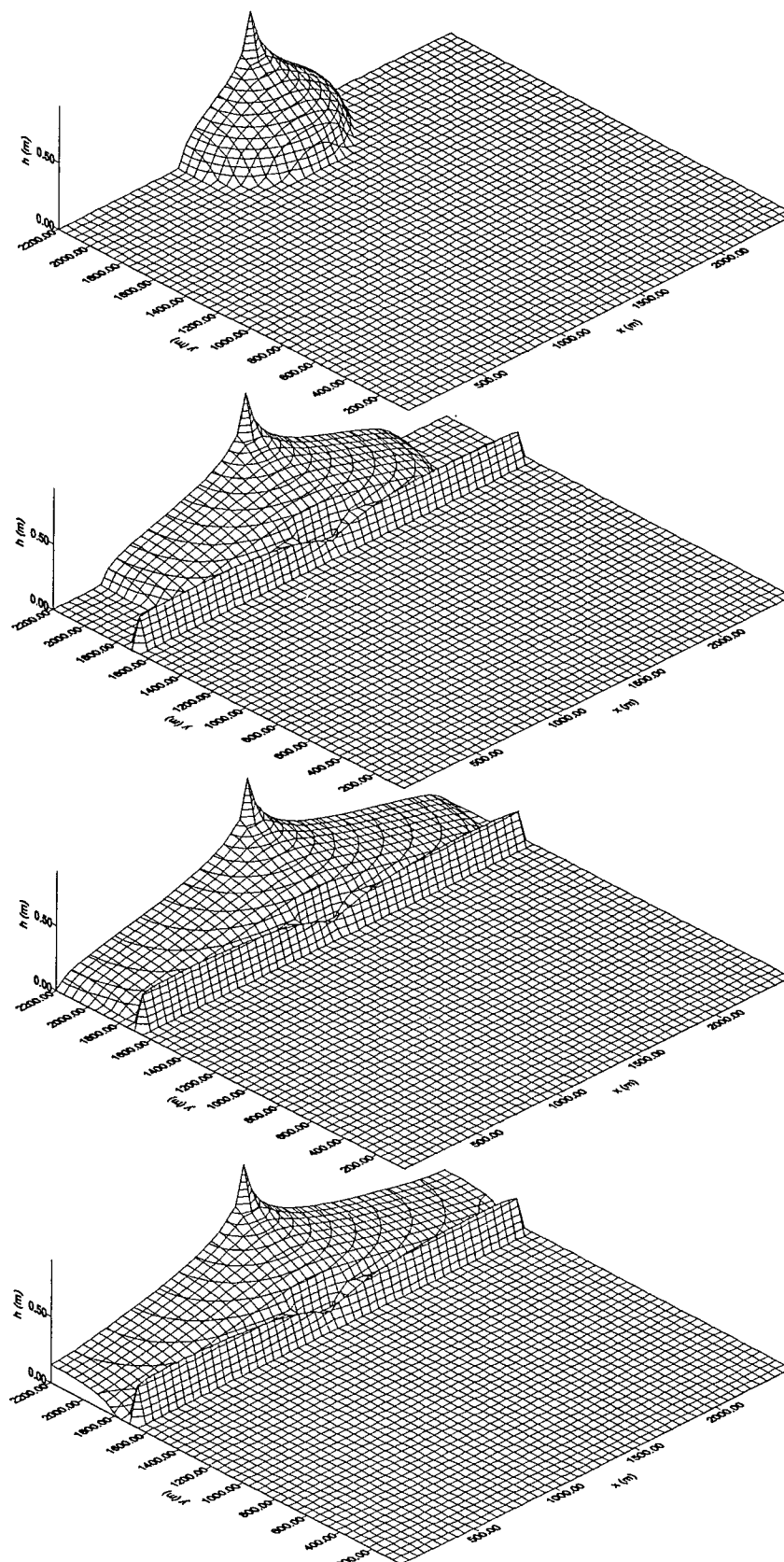


Fig.3.4.5 Surface plot for run C2. From top to bottom: $t=20'$, $t=1h$, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

Fig.3.4.6 Contour plot for run C2. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

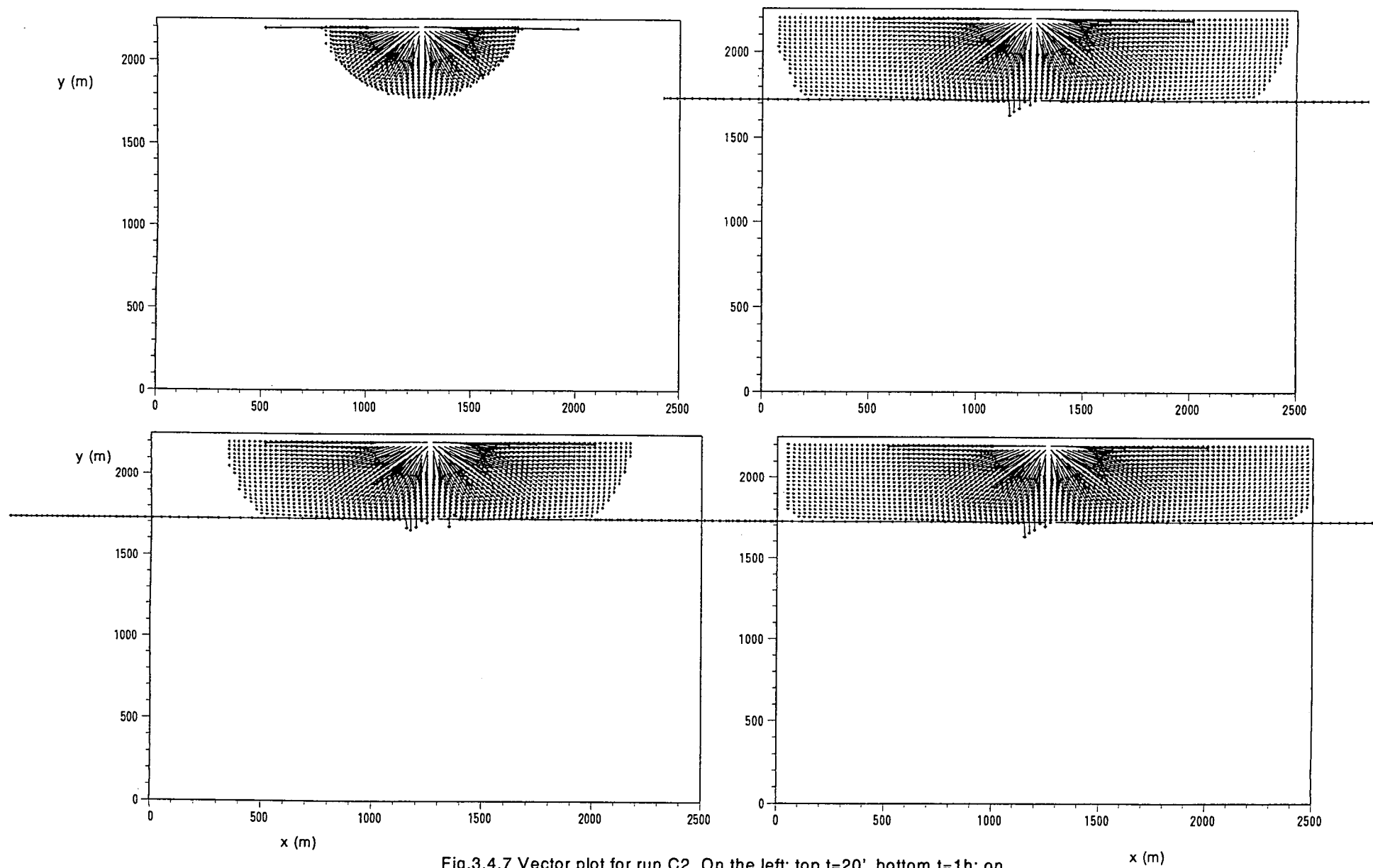


Fig.3.4.7 Vector plot for run C2. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 500 times the plot unit.

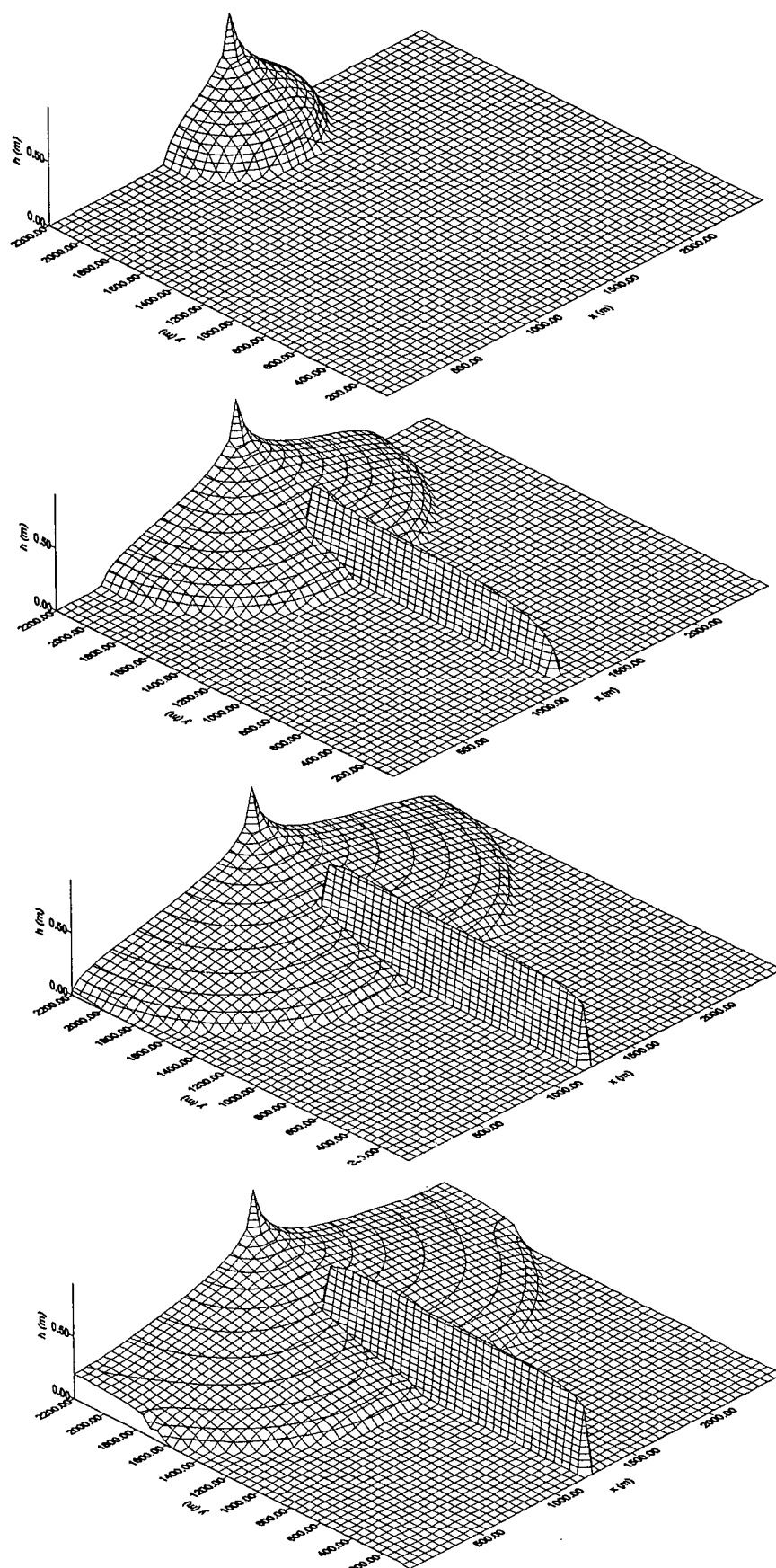


Fig.3.4.8 Surface plot for run C3. From top to bottom: $t=20'$, $t=1h$, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

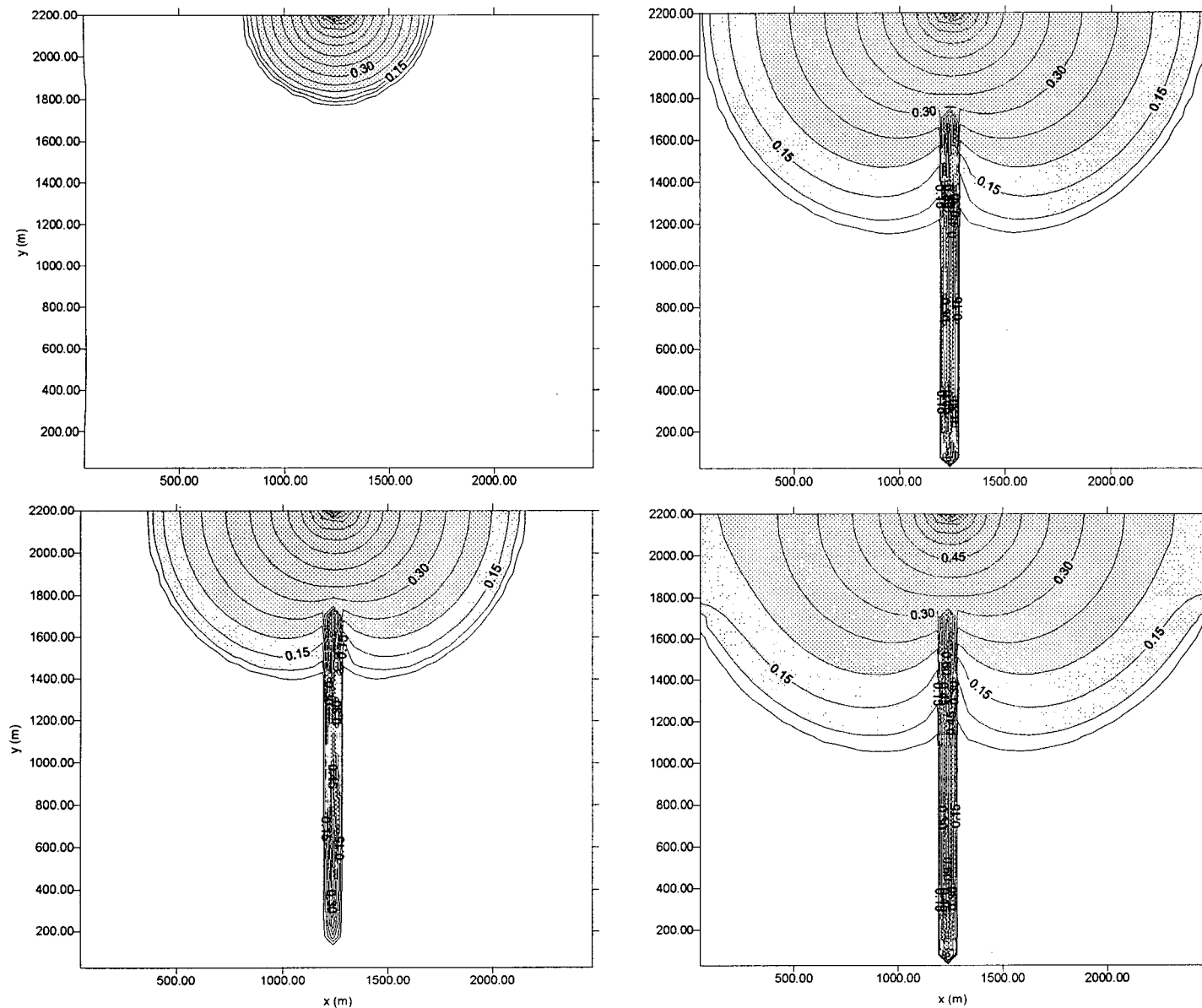


Fig.3.4.9 Contour plot for run C3. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

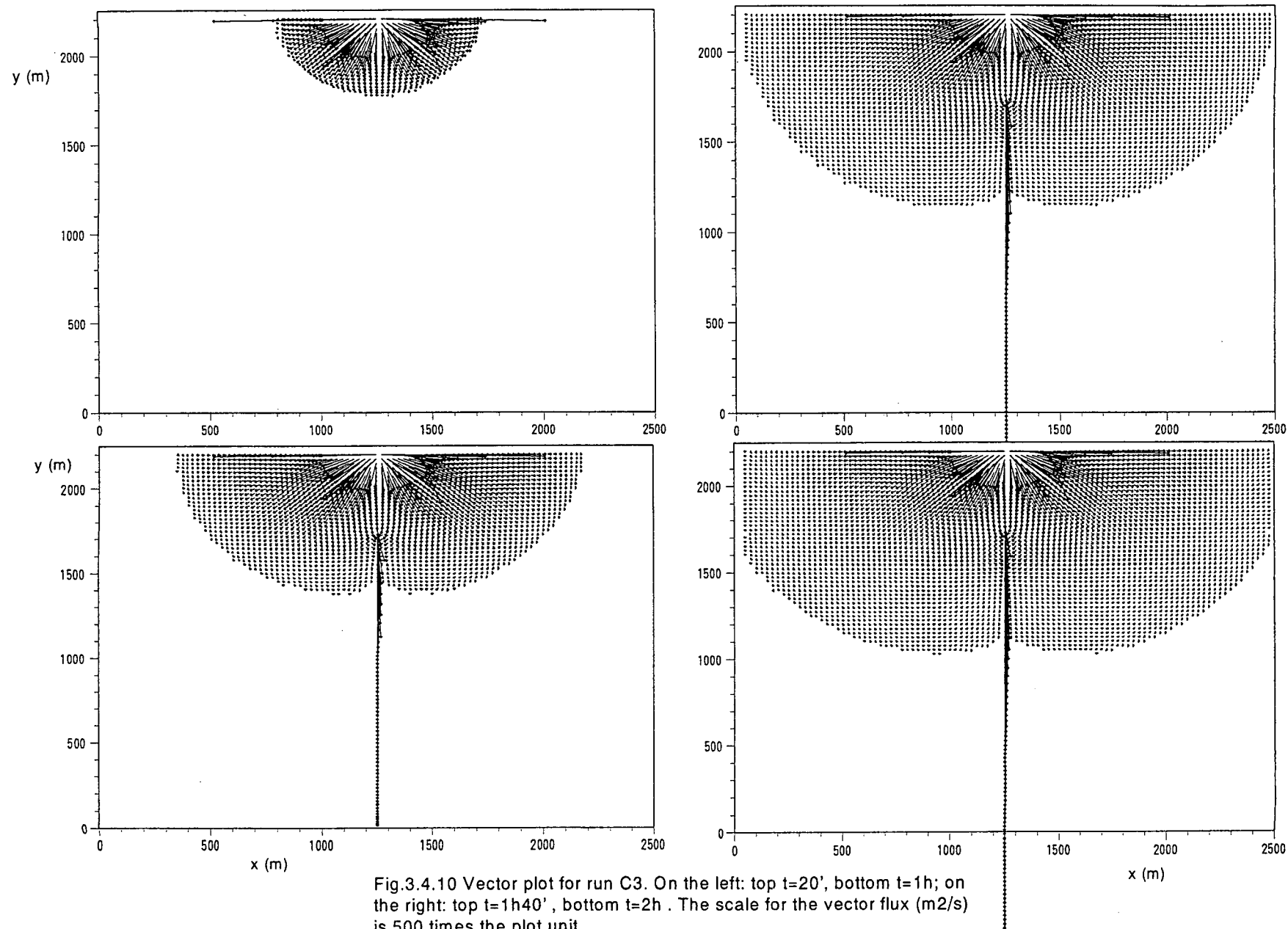


Fig.3.4.10 Vector plot for run C3. On the left: top $t=20'$, bottom $t=1\text{h}$; on the right: top $t=1\text{h}40'$, bottom $t=2\text{h}$. The scale for the vector flux (m^2/s) is 500 times the plot unit.

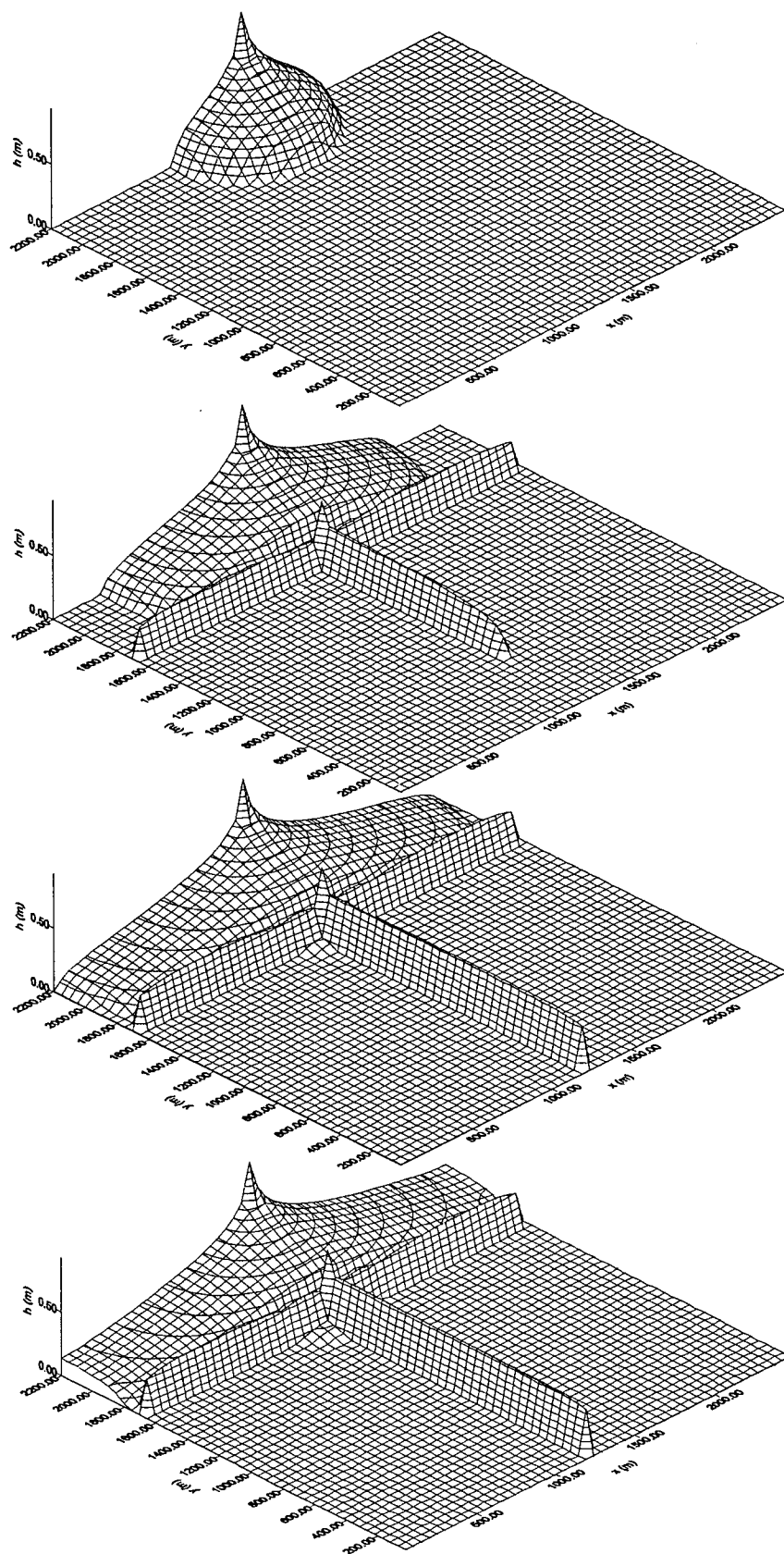


Fig.3.4.11 Surface plot for run C4. From top to bottom: $t=20'$, $t=1h$, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

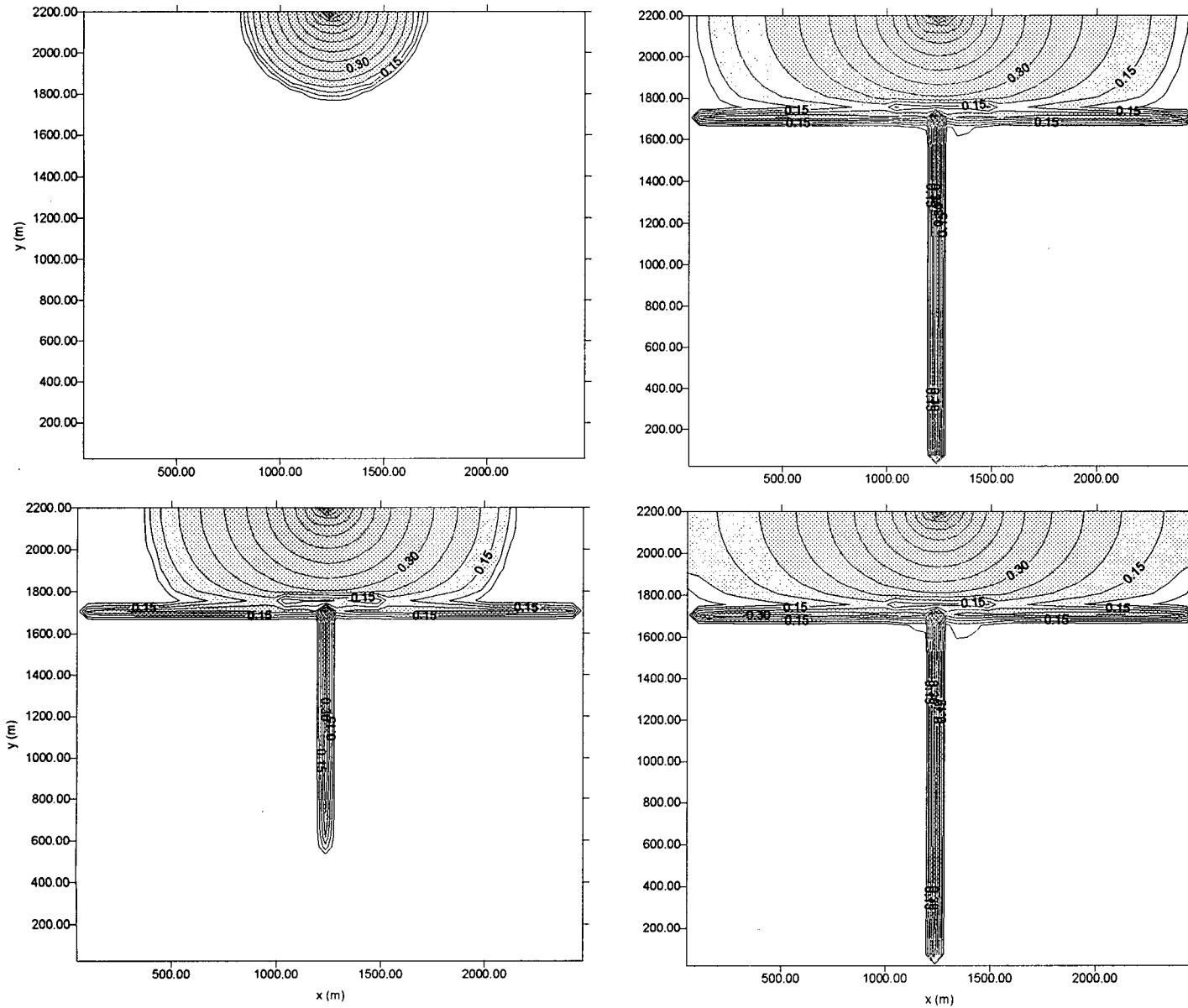


Fig.3.4.12 Contour plot for run C4. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

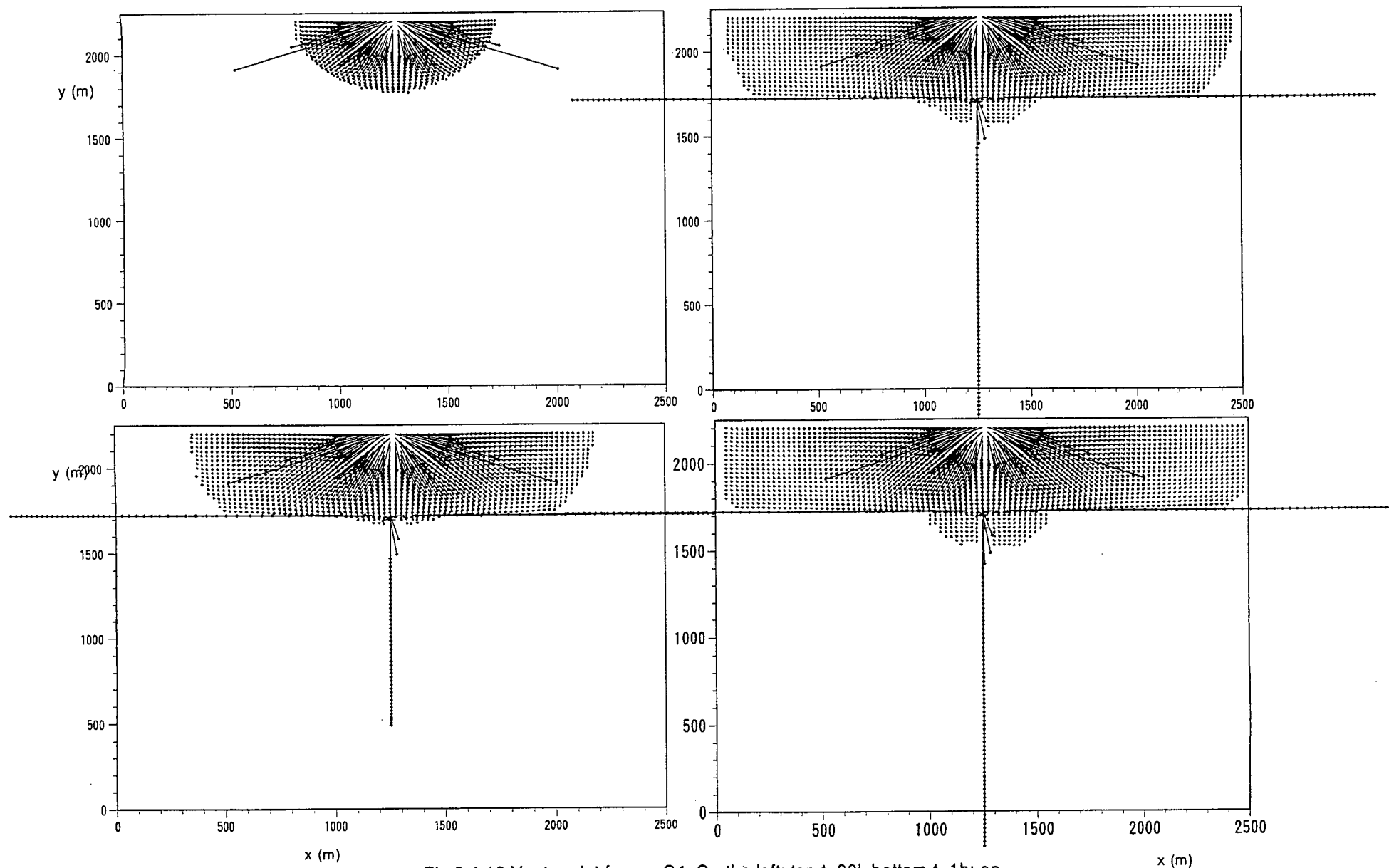


Fig.3.4.13 Vector plot for run C4. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 500 times the plot unit.

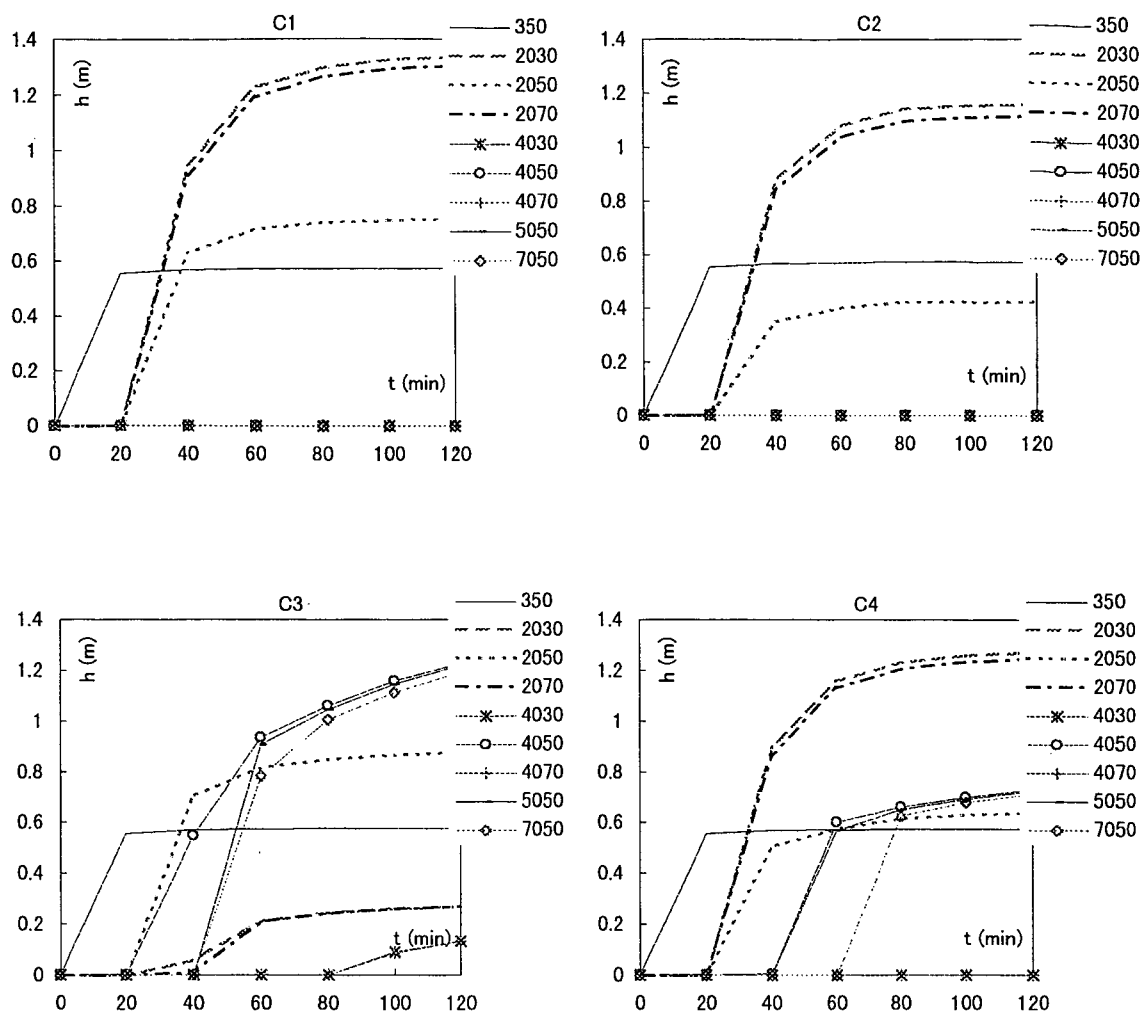


Fig.3.4.14 Water depth as a function of time for run C1 to C4

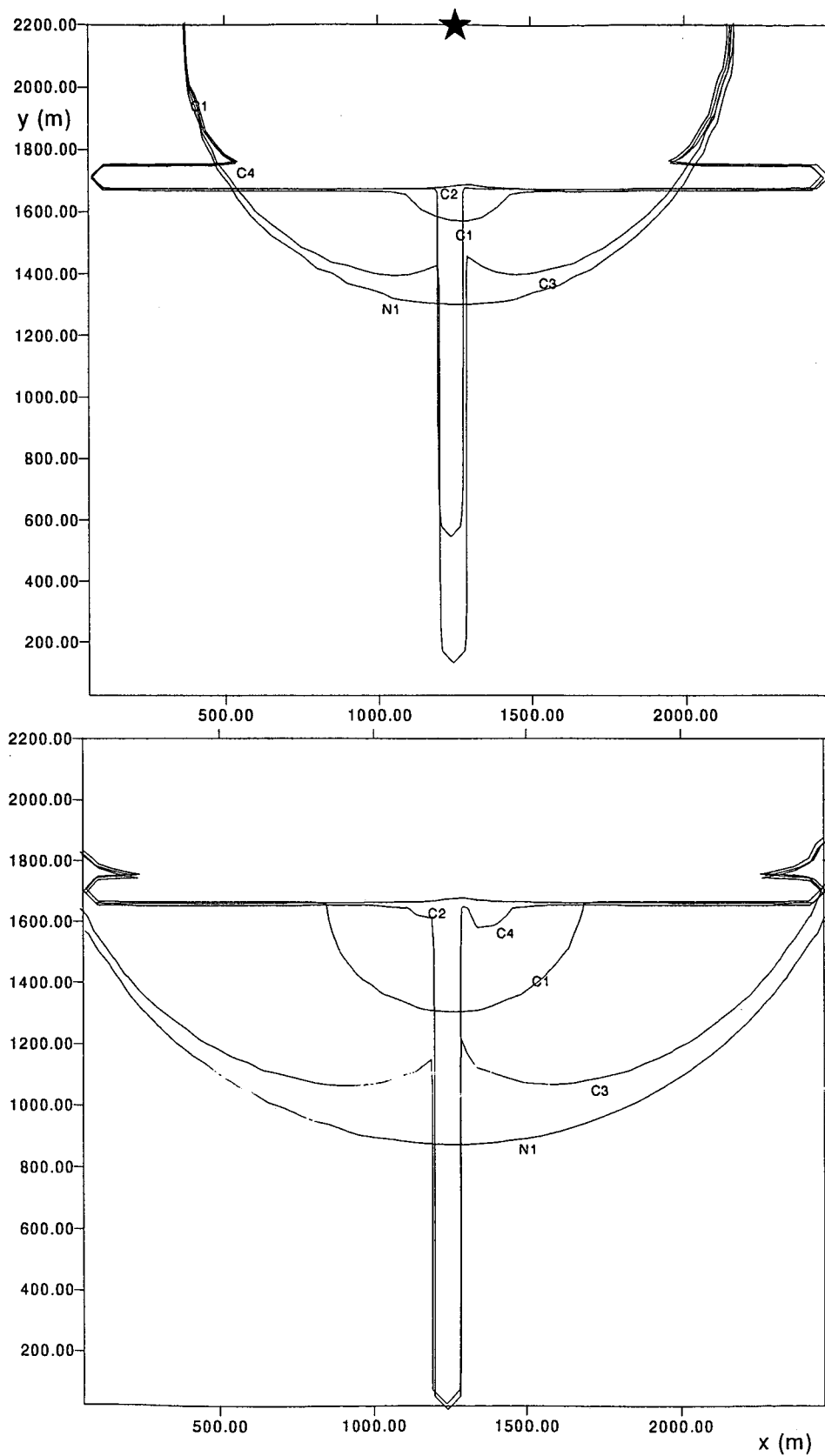


Fig.3.4.15 On the top: comparison between water fronts for run N1, C1, C2, C3 and C4 for $t=1h$; on the bottom: comparison between water fronts run N1, C1, C2, C3 and C4 for $t=2h$.

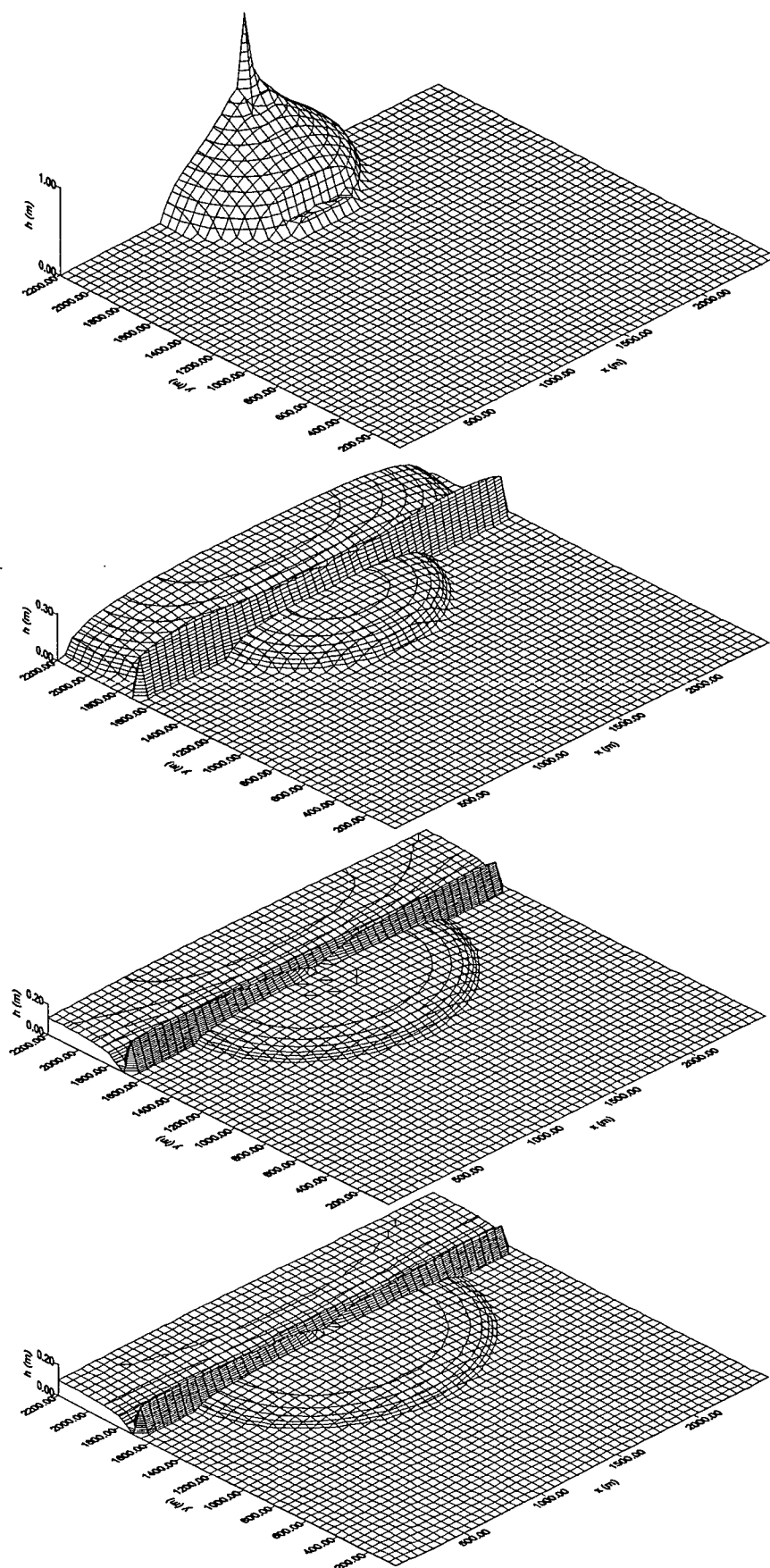
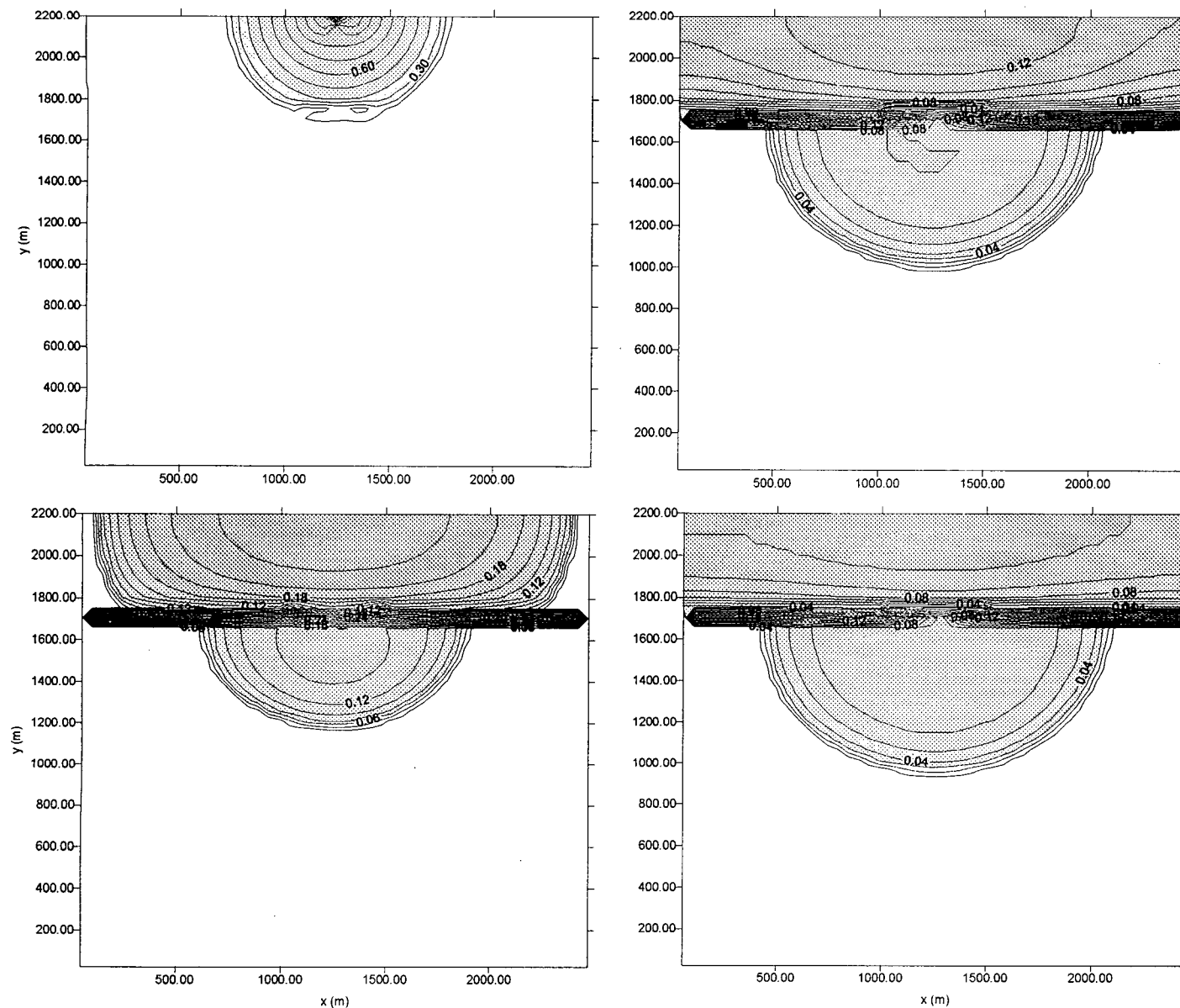


Fig.3.4.16 Surface plot for run C1T. From top to bottom: $t=20'$, $t=1h$, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).



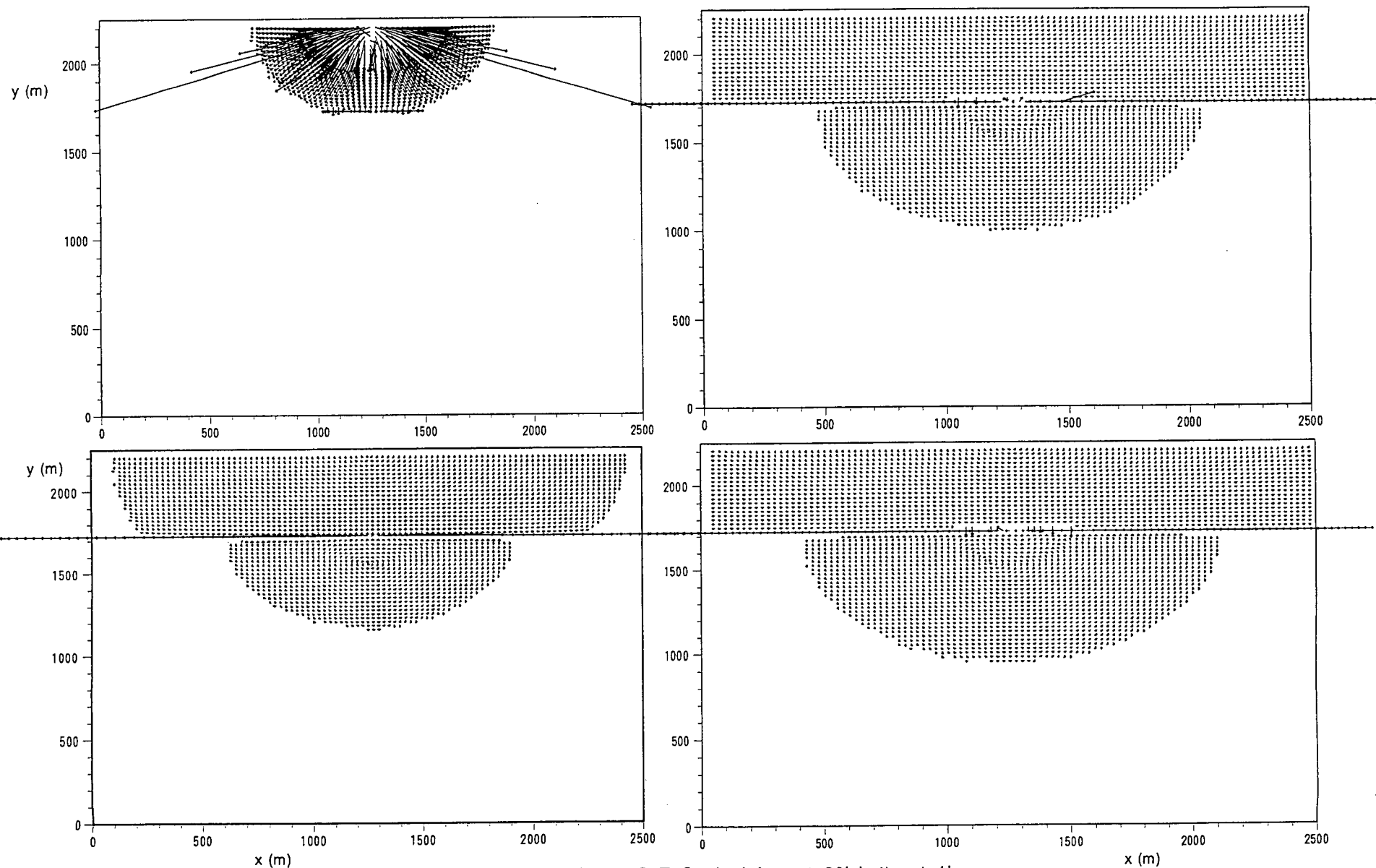


Fig.3.4.18 Vector plot for run C1T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 200 times the plot unit for $t=20'$ and 500 for $t=1h$, $1h40'$ and $2h$.

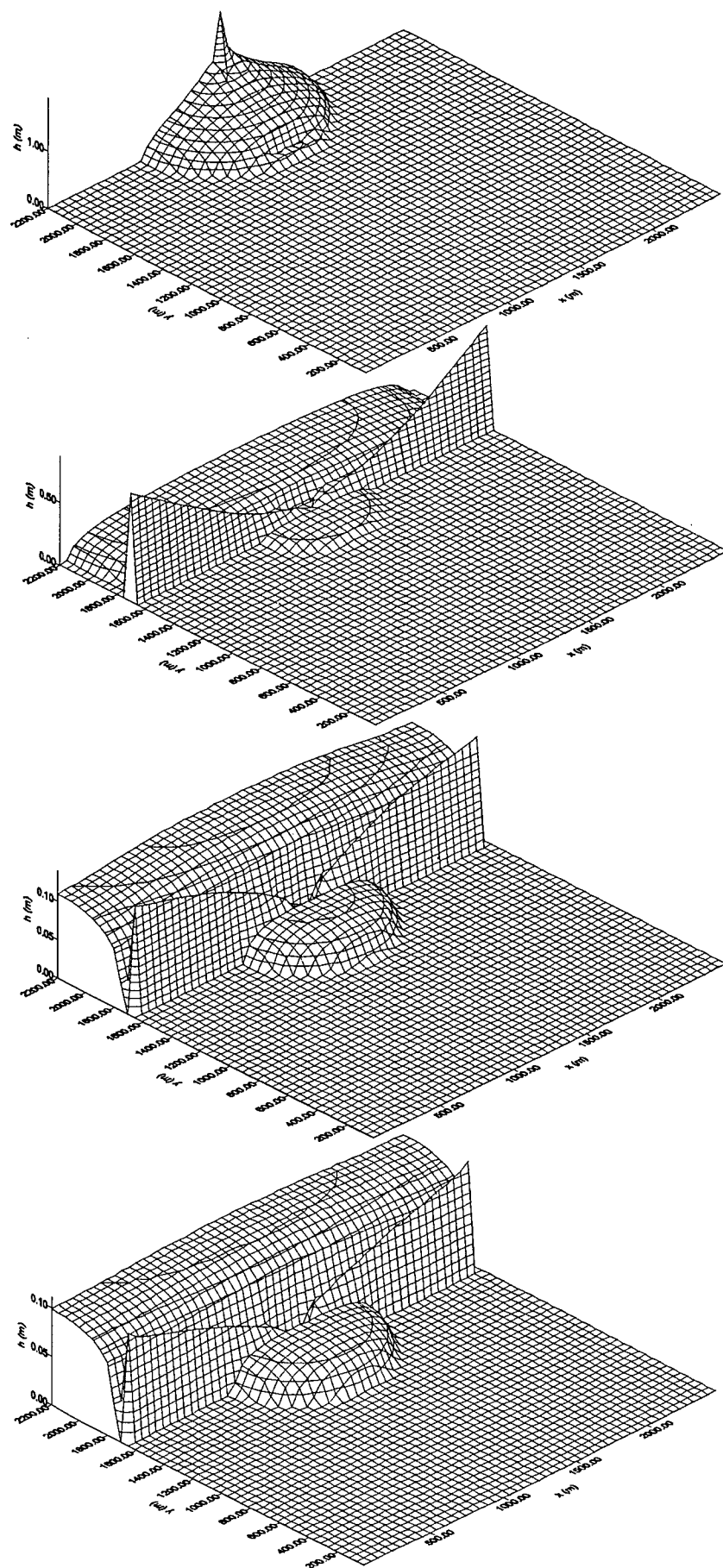


Fig.3.4.19 Surface plot for run C2T. From top to bottom: $t=20'$, $t=1h$, $t=1h40'$ and $t=2$ hours (x , y and z scale in meters).

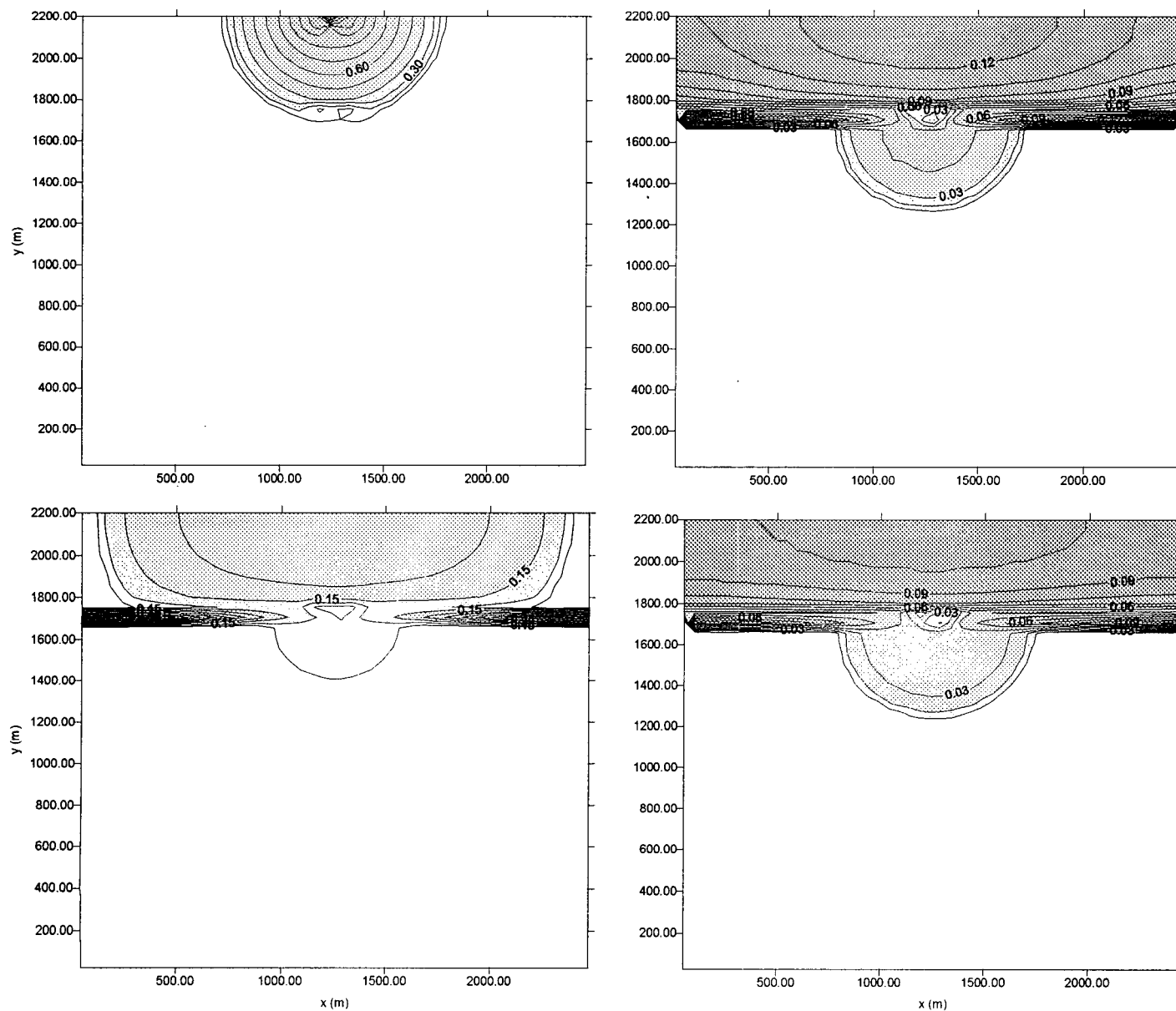


Fig.3.4.20 Contour plot for run C2T. On the left: top t=20', bottom t=1h; on the right: top t=1h40', bottom t= 2 hours (scale in meter).

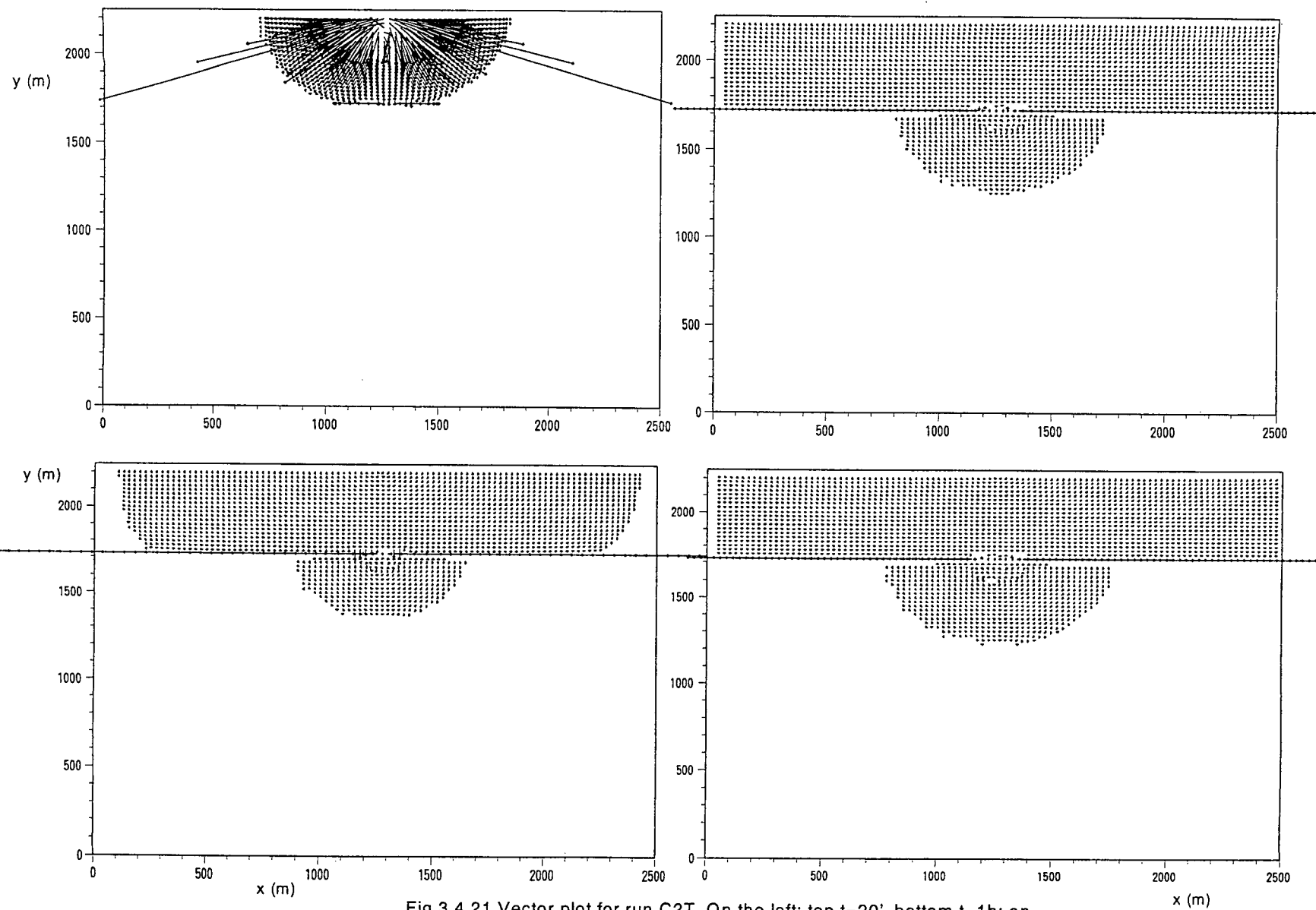


Fig.3.4.21 Vector plot for run C2T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 200 times the plot unit for $t=20'$ and 500 for $t=1h$, $1h40'$ and $2h$.

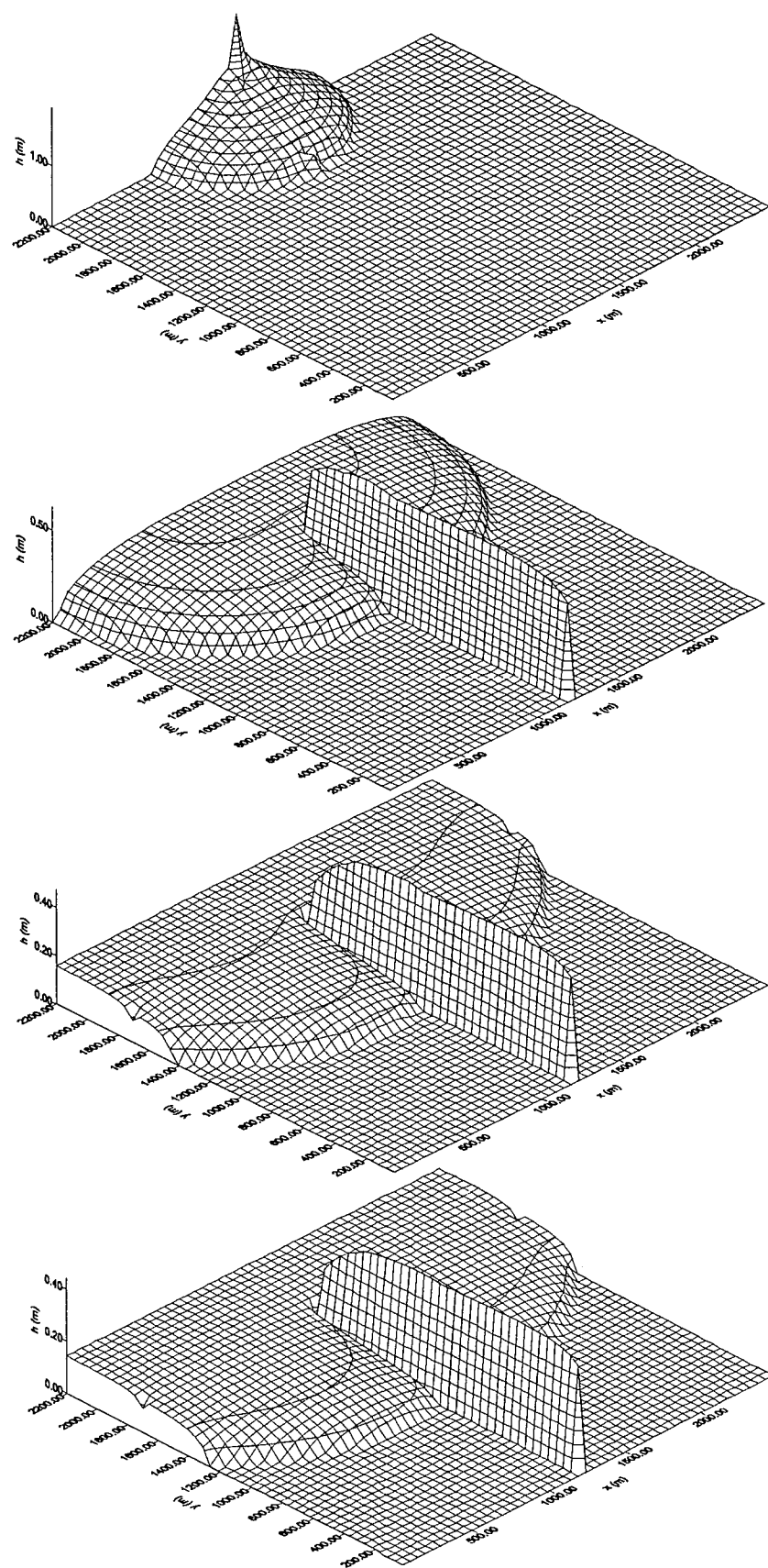


Fig.3.4.22 Surface plot for run C3T. From top to bottom: $t=20'$, $t=1\text{h}$, $t=1\text{h}40'$ and $t=2$ hours (x , y and z scale in meters).

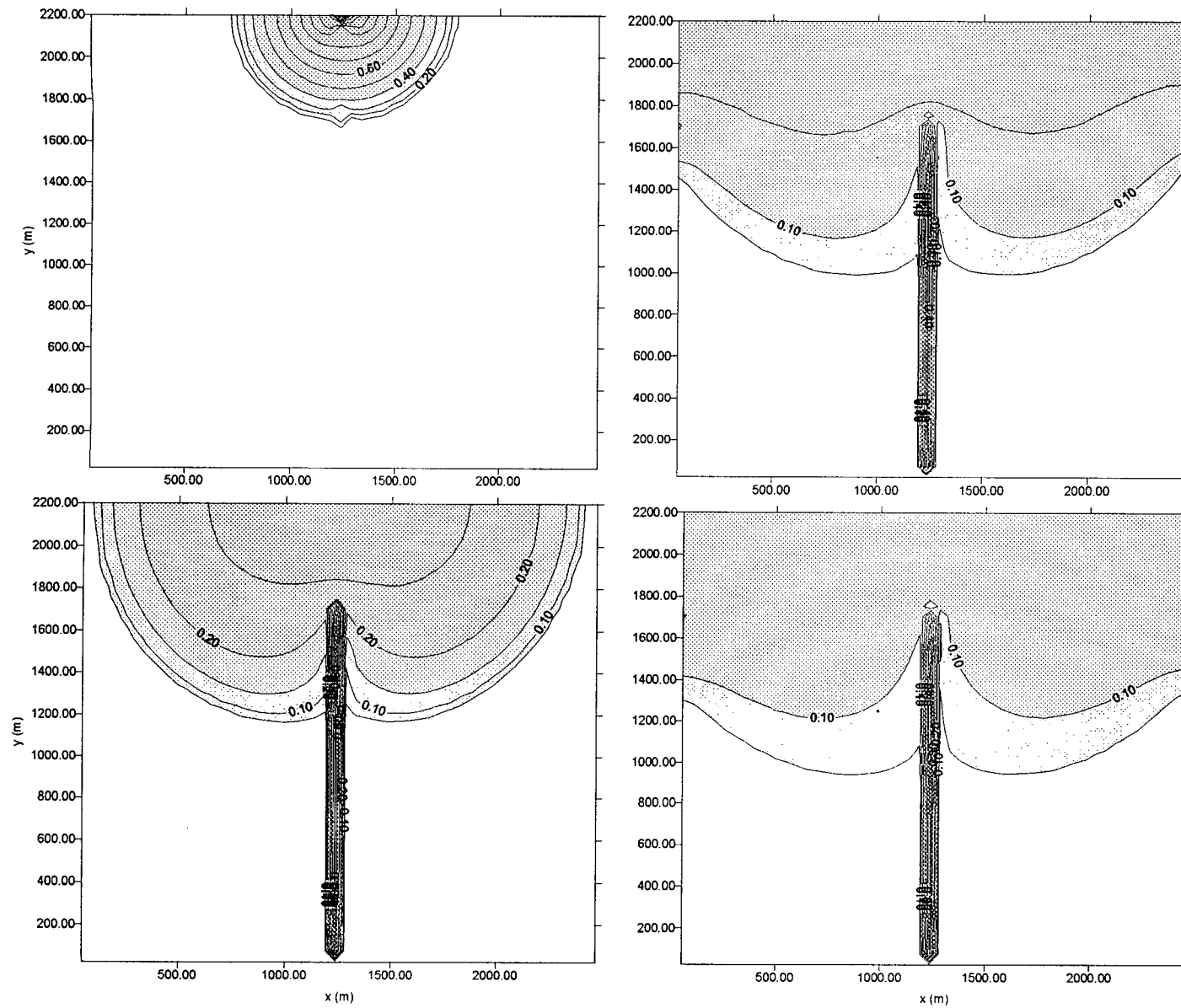


Fig.3.4.23 Contour plot for run C3T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

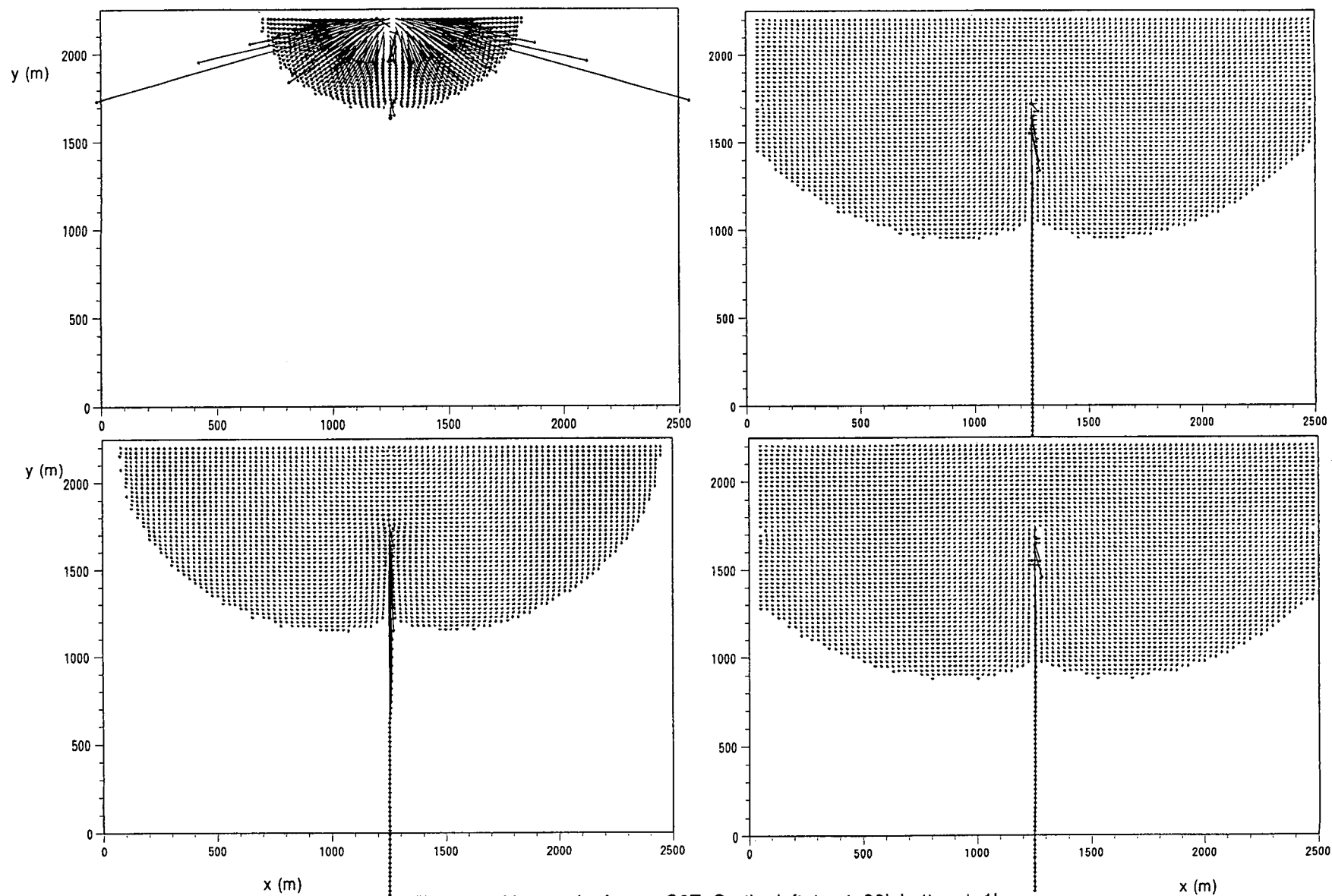


Fig.3.4.24 Vector plot for run C3T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 200 times the plot unit for $t=20'$ and 500 for $t=1h$, $1h40'$ and $2h$.

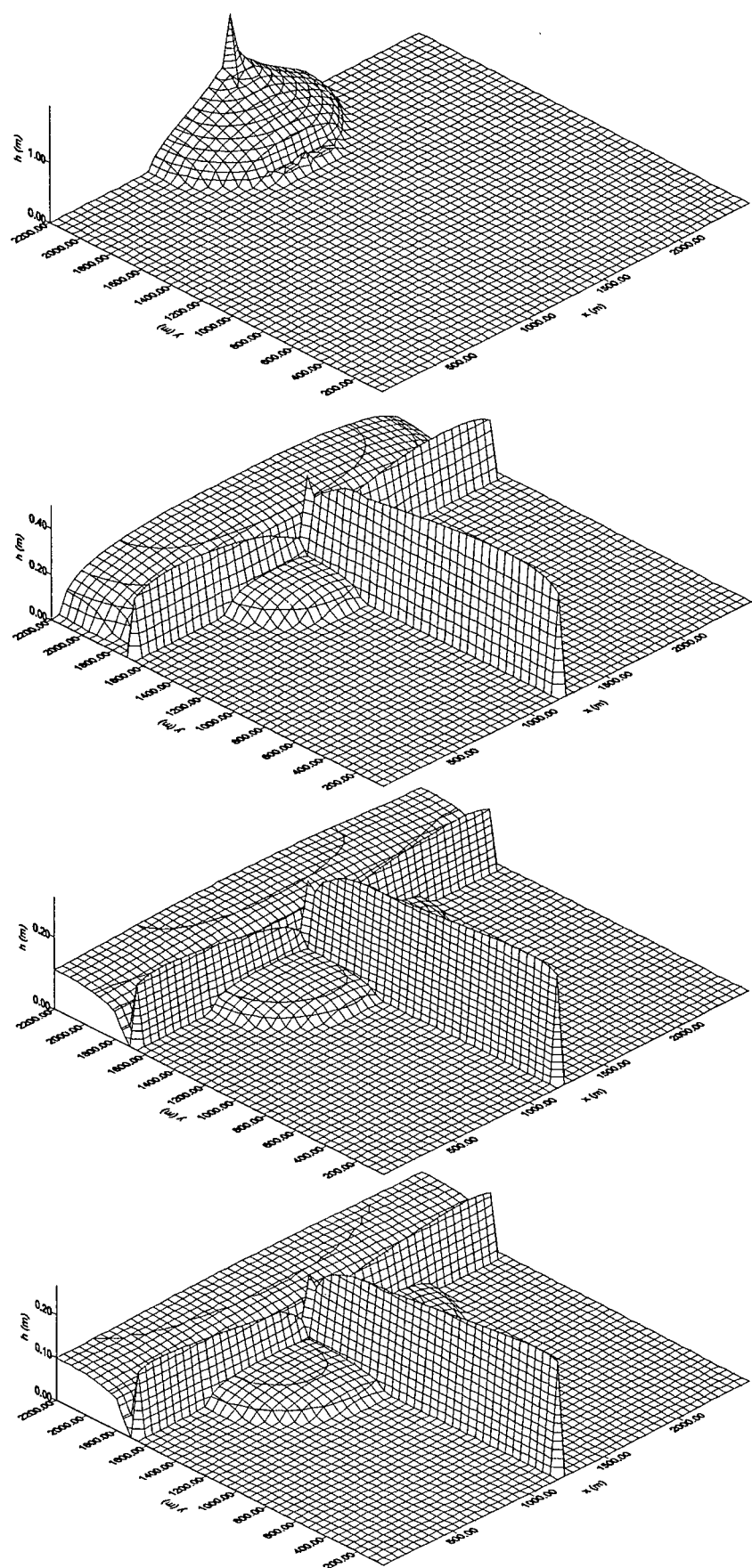


Fig.3.4.25 Surface plot for run C4T. From top to bottom: $t=20'$, $t=1\text{h}$, $t=1\text{h}40'$ and $t=2\text{ hours}$ (x , y and z scale in meters).

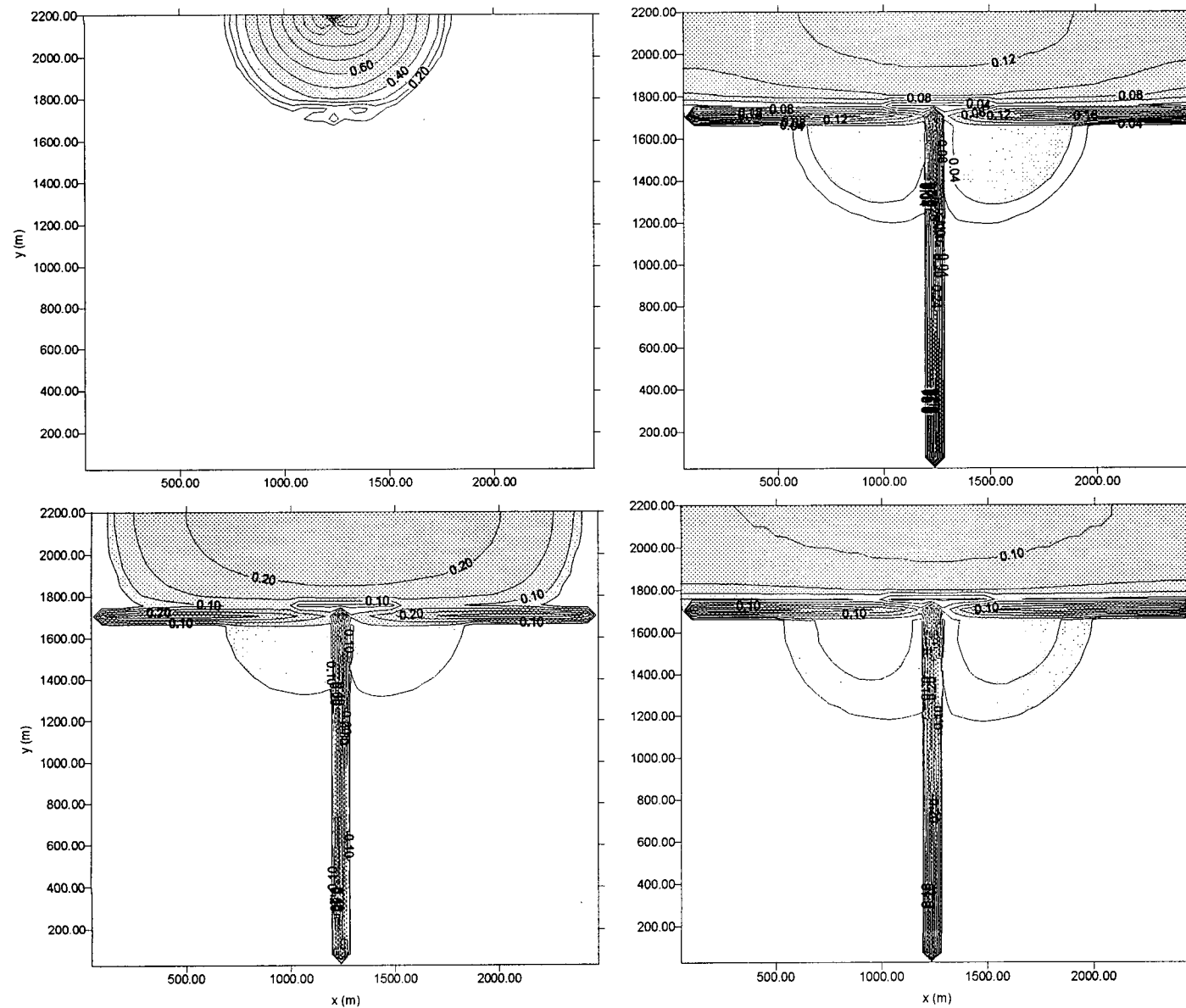


Fig.3.4.26 Contour plot for run C4T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2$ hours (scale in meter).

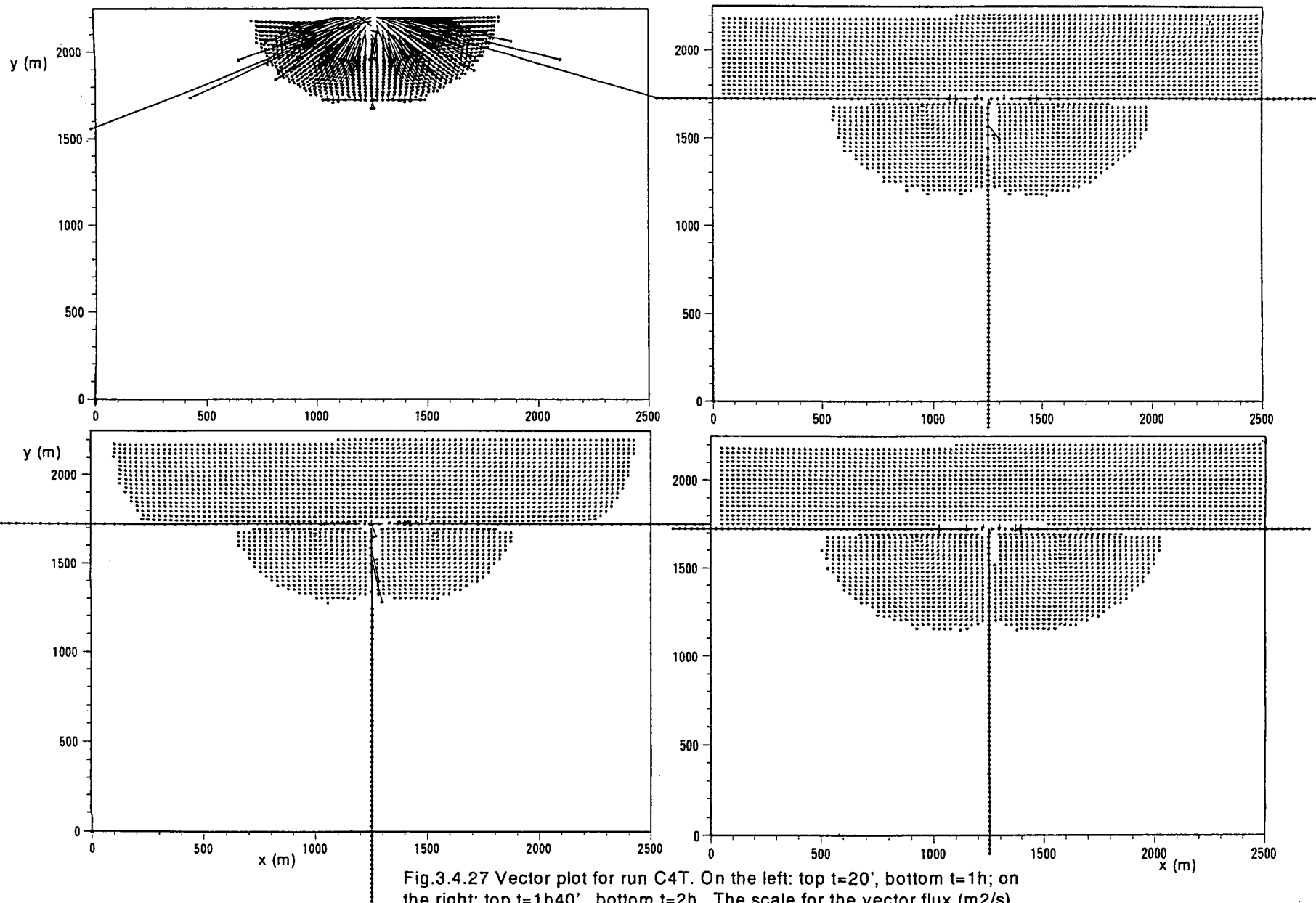


Fig.3.4.27 Vector plot for run C4T. On the left: top $t=20'$, bottom $t=1h$; on the right: top $t=1h40'$, bottom $t=2h$. The scale for the vector flux (m^2/s) is 500 times the plot unit.

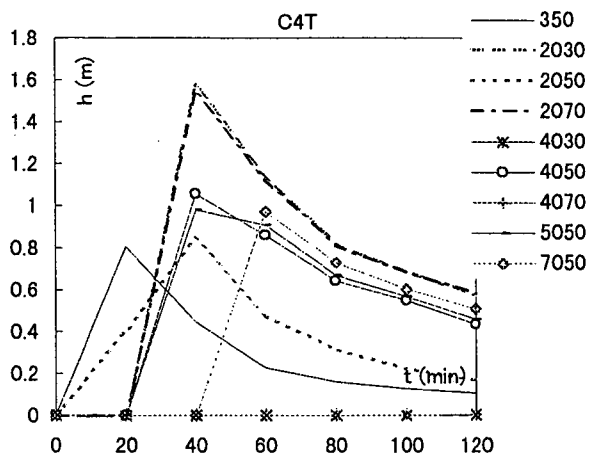
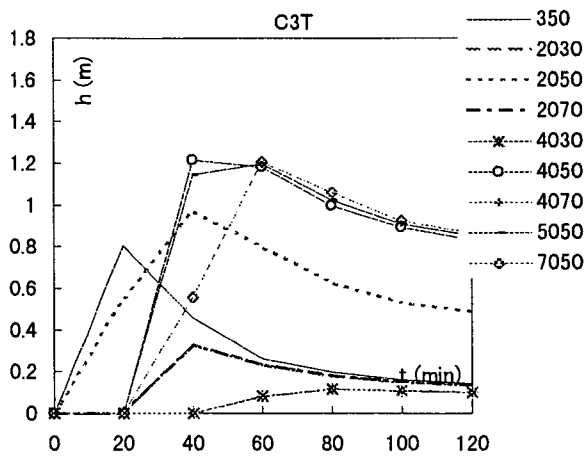
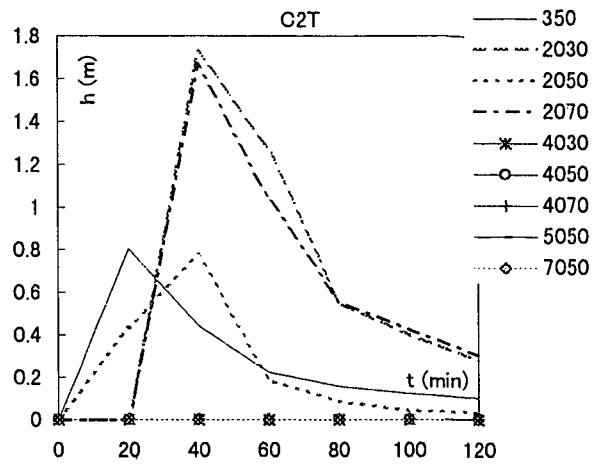
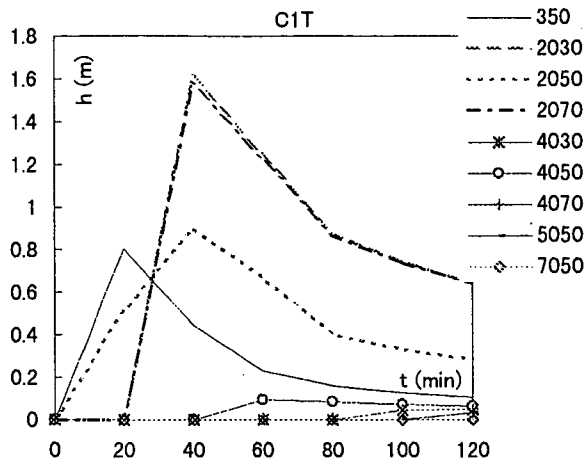


Fig.3.4.28 Water depth as a function of time for run C1T to C4T

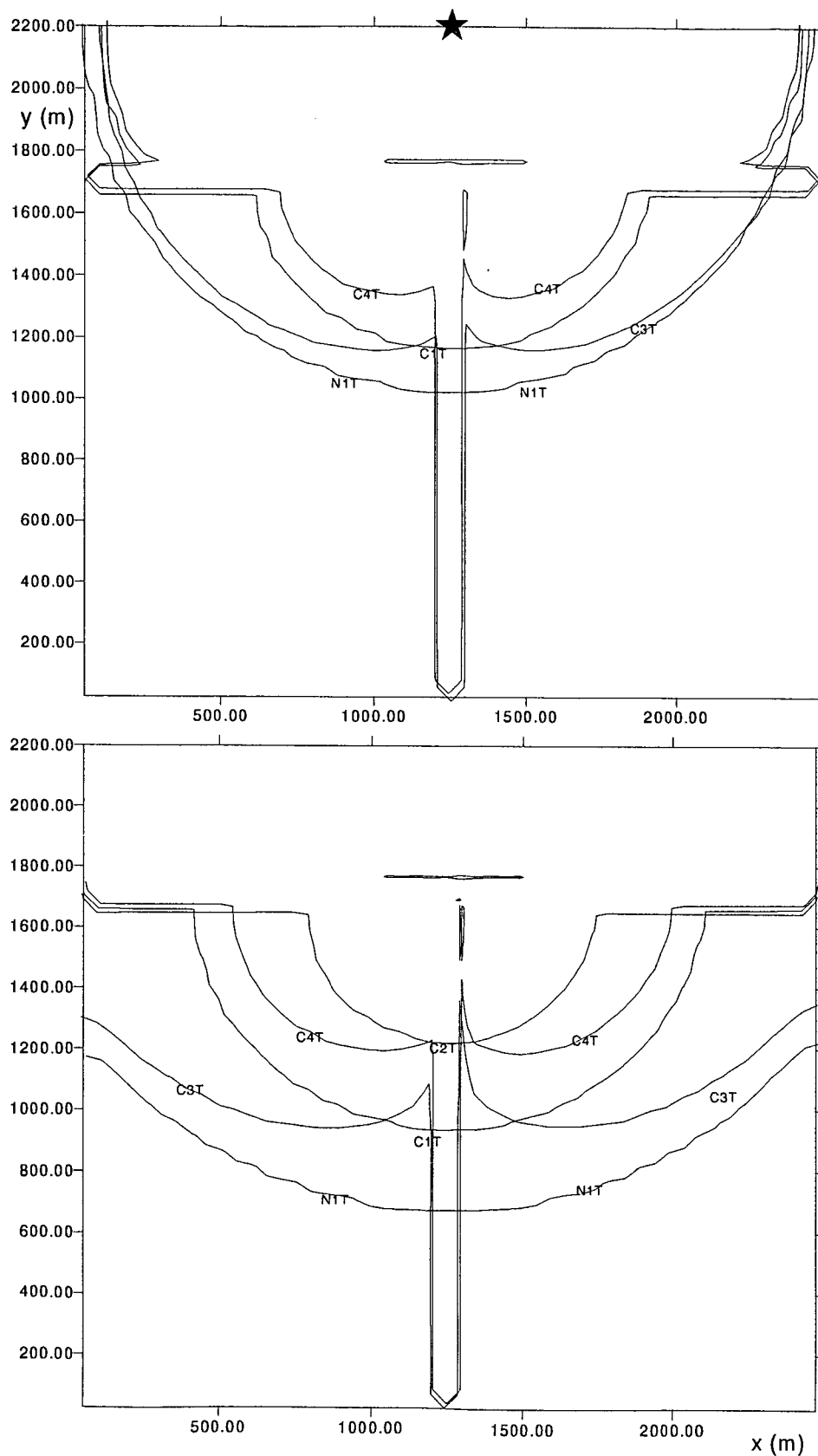


Fig.3.4.29 On the top: comparison between run C1T, N1T, C3T and C4T for $t=1h$; on the bottom: comparison between run N1T, C1T, C2T, C3T and C4T for $t=2h$.

3.5 EFFECT OF MESH SIZE

The effect of mesh size has been tested to check the validity of the simulations varying the scale of the problem. Three dimensions of cells have been tested, that are 25x25m for the run M1, 50x50m for the run M2 and 100x100m for the run M3.

Table 3.5.1 Summary for series M

Run	n_0	θ (%)	s_y	s_x	Input hydrograph	Mesh dimension
M1	0.05	0.0	0.001	0.0	H	92x104
M2	0.05	0.0	0.001	0.0	H	46x52
M3	0.05	0.0	0.001	0.0	H	24x26

Figg.3.5.1 to 3.5.6 show the results for the three runs at time $t=1$ and $t=2^h$. Figg. 3.5.7 illustrates the surface plots at time $t=2^h$ for comparison. Fig.3.5.8 shows the contour plots for time $t=1$ and 2^h ; there is a good agreement between the three runs with practical no differences in the water level. This result allows to use bigger dimensions of the cells where possible, with considerable saving of calculation time. Of course, the presence of channels, road and other minor structures can oblige the modeller to use a finer mesh in order to follow more closely their path.

Finally Fig.3.5.9. illustrates the depth as a function of time for two points located in the cells No.2130 and 4210 in the mesh relative to the dimension 25x25m; no appreciable differences are present between the various curves.

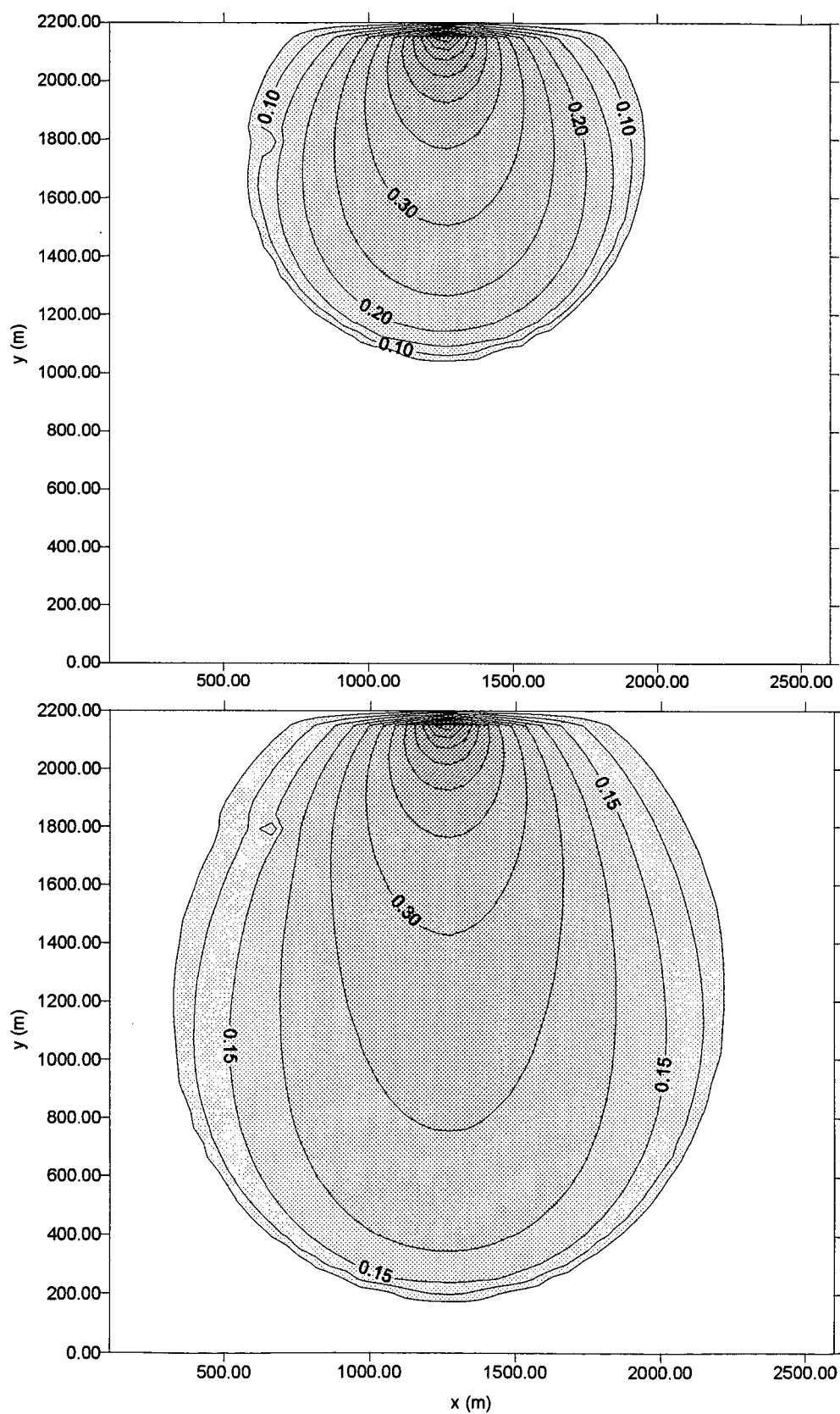


Fig.3.5.1 Contour plot for run M1. On the top $t=1\text{h}$; on the bottom $t=2\text{ hours}$ (scale in meter).

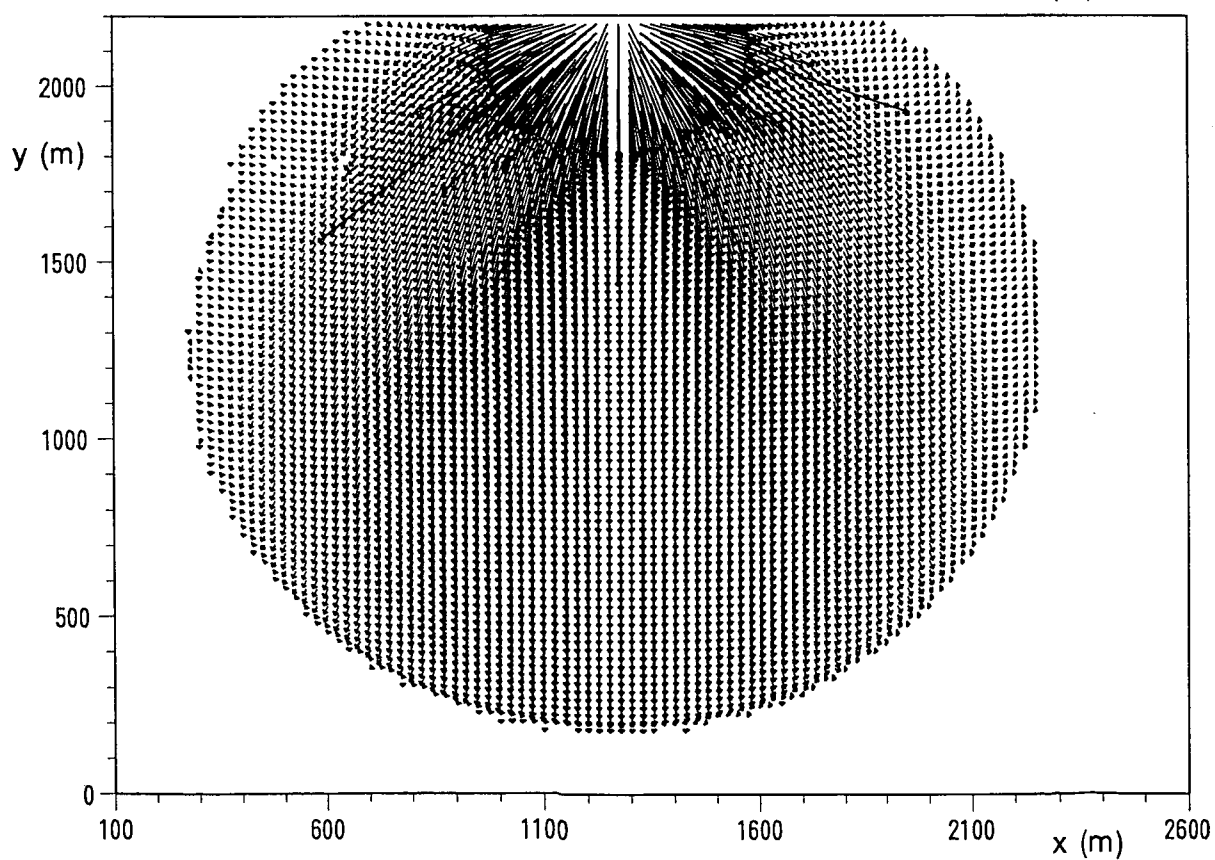
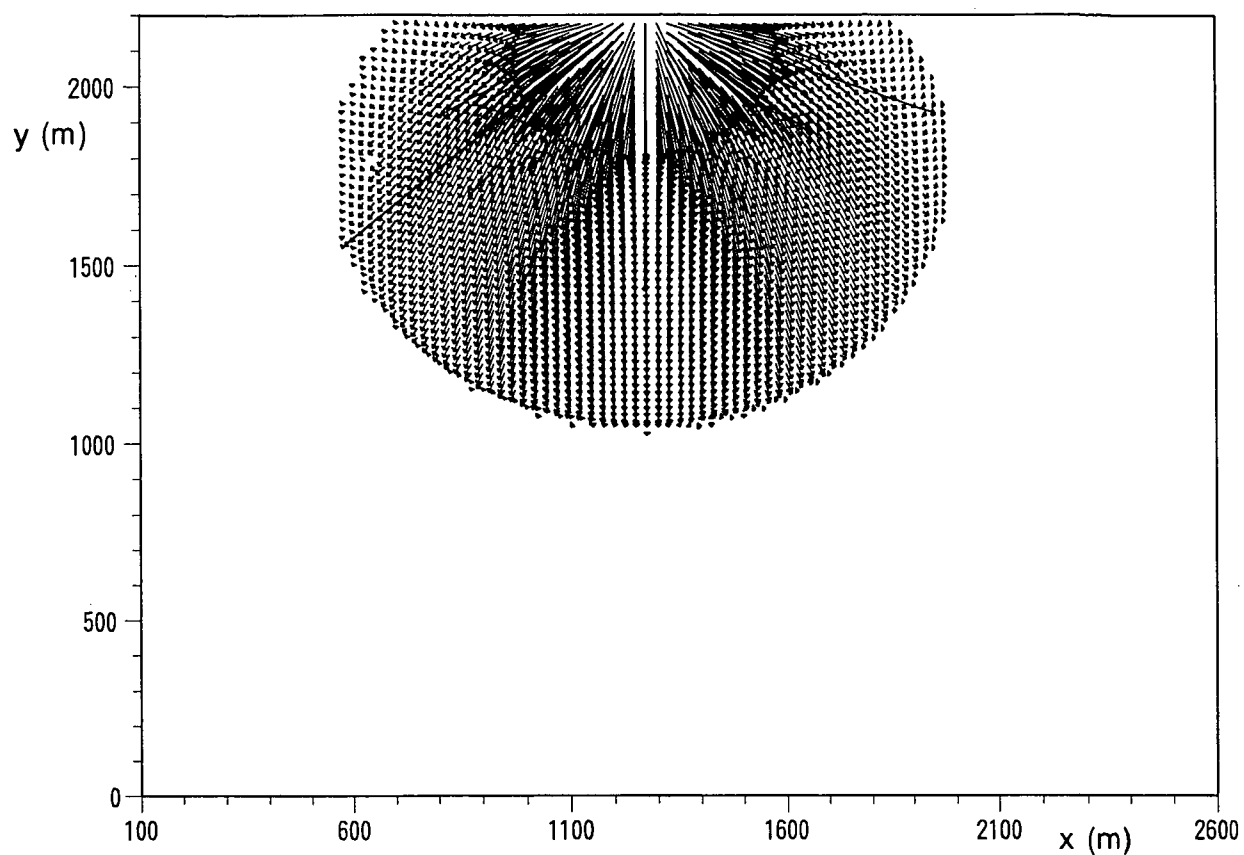


Fig.3.5.2 Vector plot for run M1. On the top $t=1h$; on the bottom $t=2h$.
The scale for the vector flux (m^2/s) is 1000 times the plot unit.

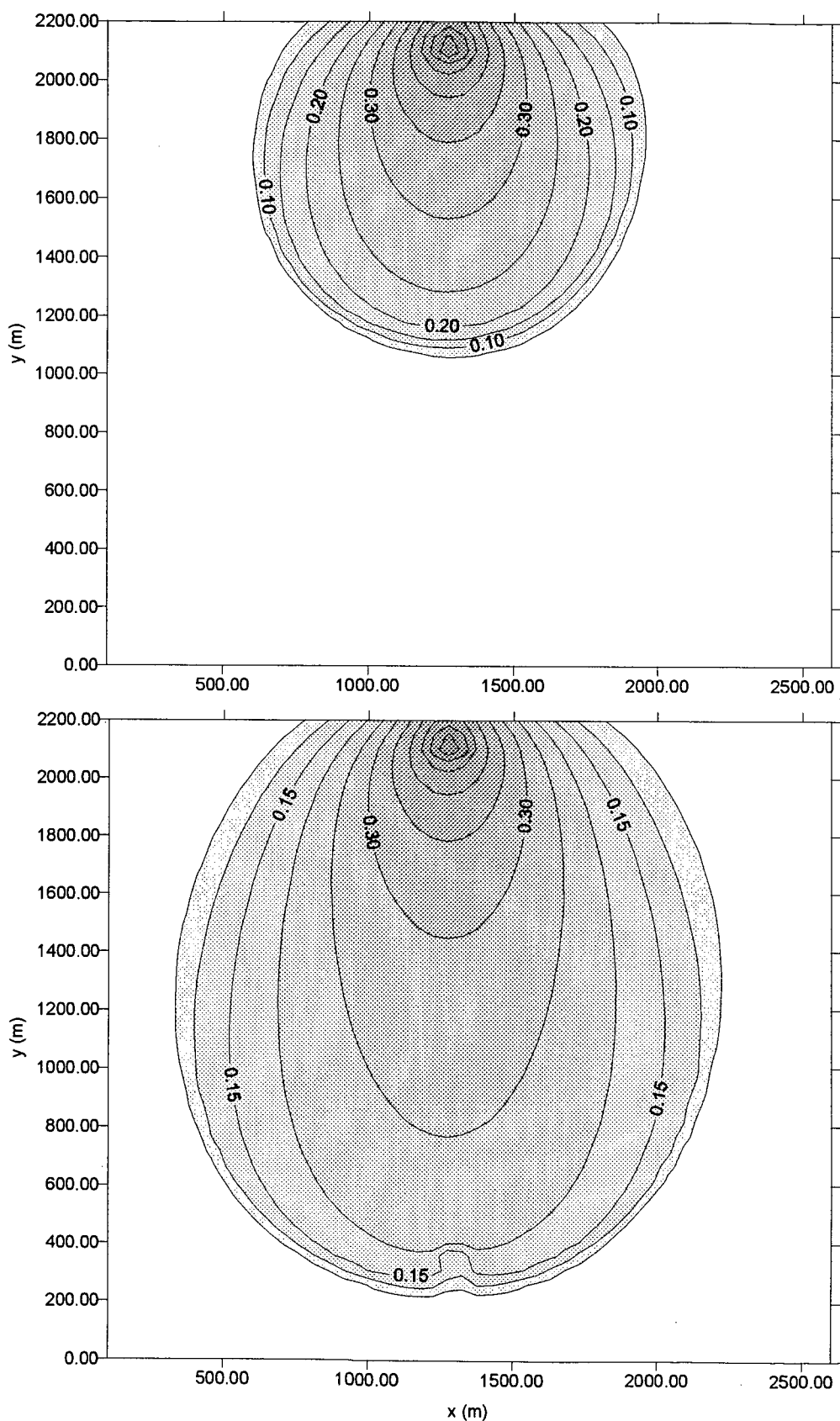


Fig.3.5.3 Contour plot for run M2. On the top $t=1\text{h}$; on the bottom $t=2\text{ hours}$ (scale in meter).

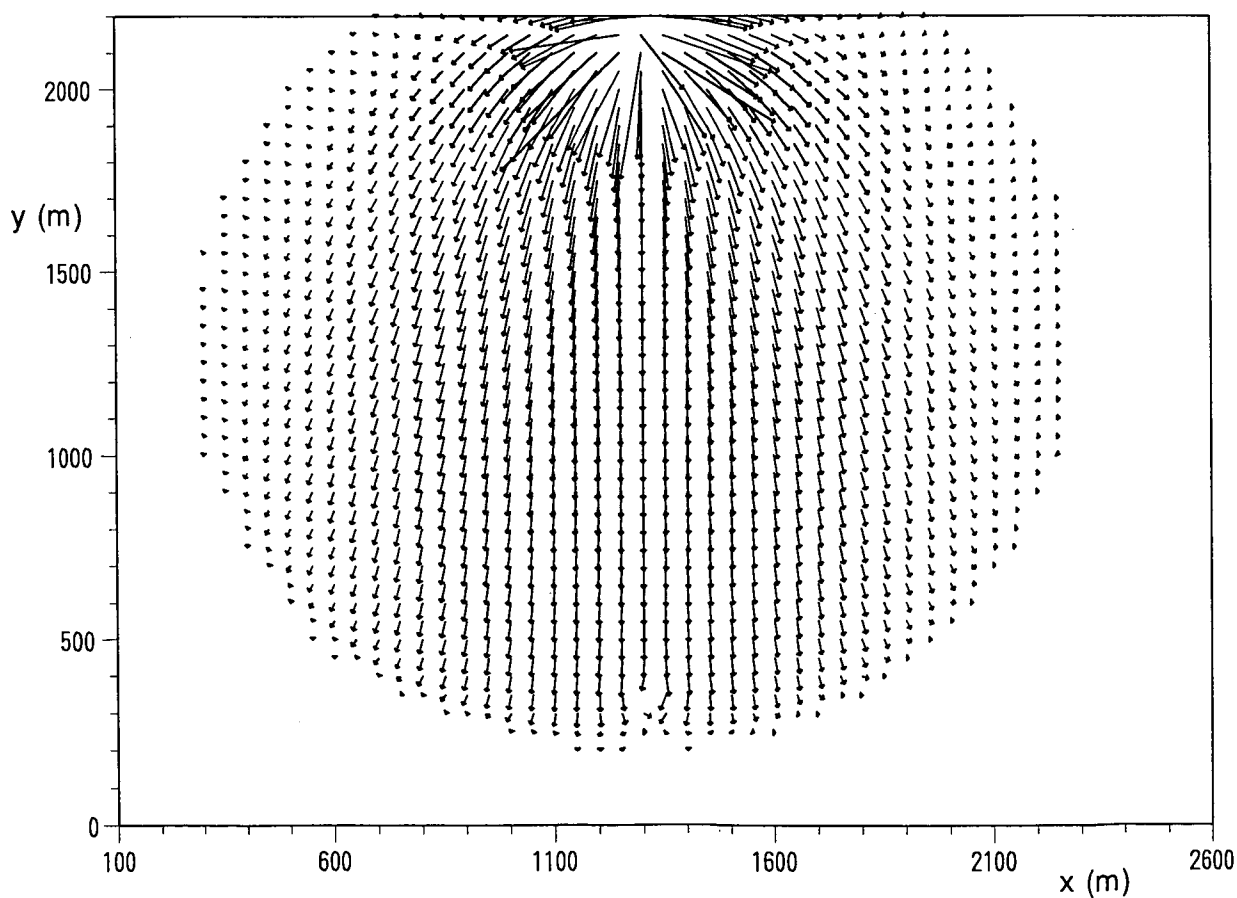
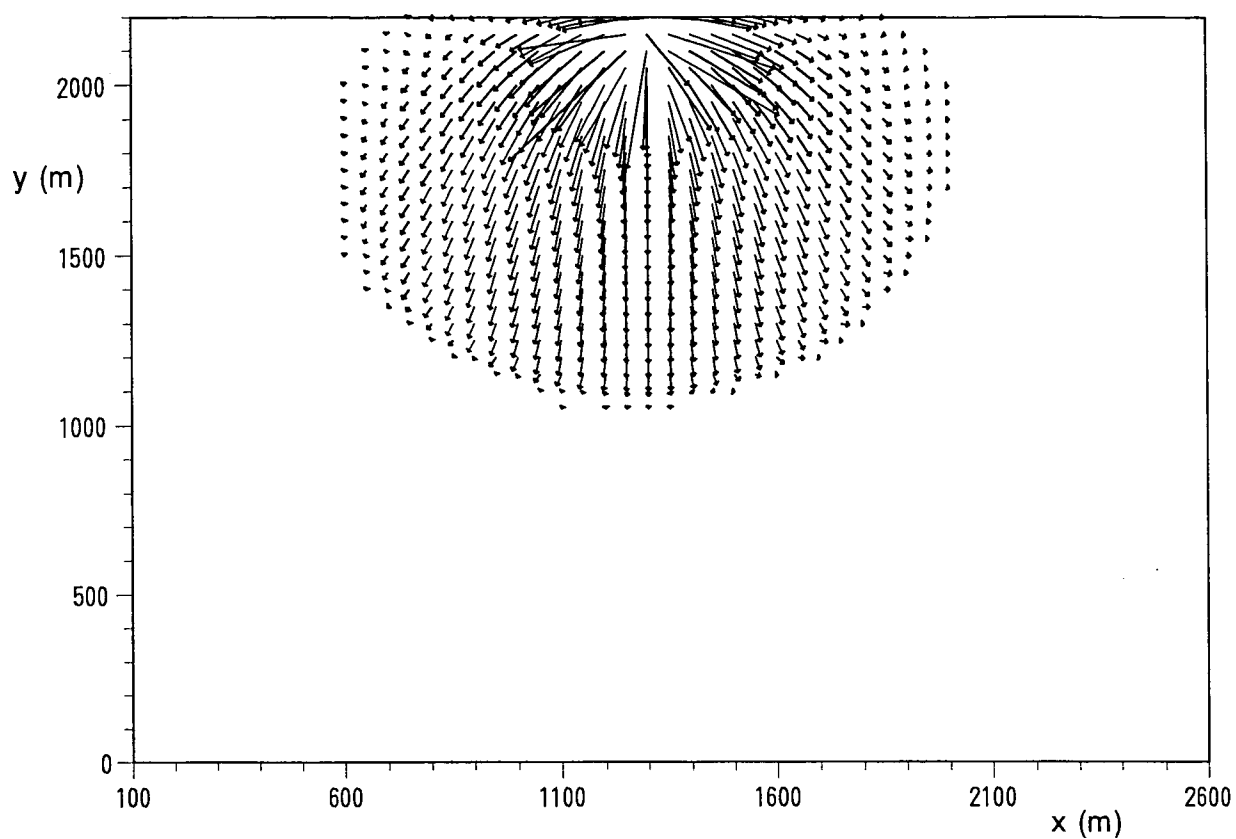


Fig.3.5.4 Vector plot for run M2. On the top $t=1h$; on the bottom $t=2h$.
The scale for the vector flux (m^2/s) is 1000 times the plot unit.

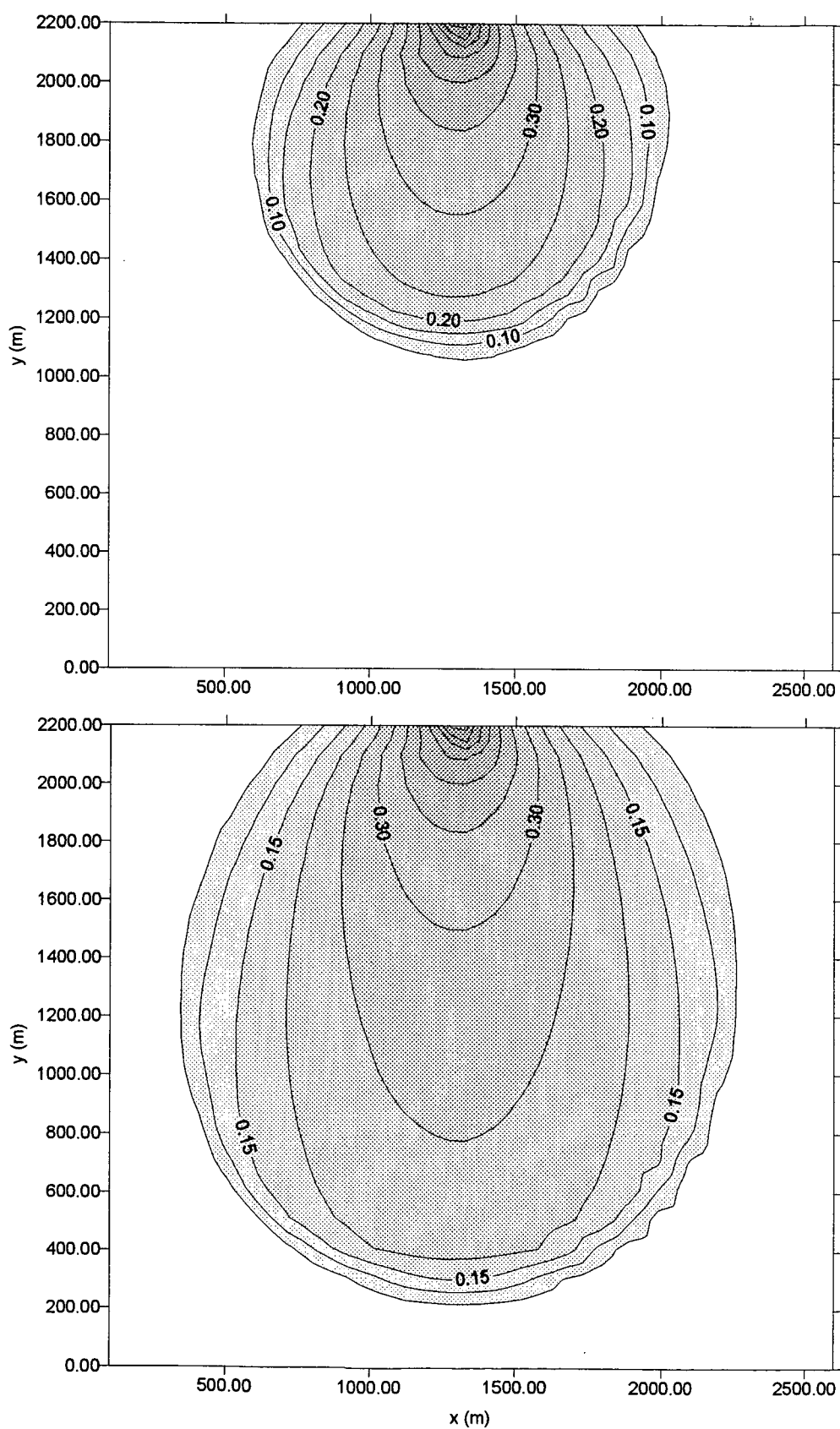


Fig.3.5.5 Contour plot for run M3. On the top $t=1\text{h}$; on the bottom $t=2\text{h}$ (scale in meter).

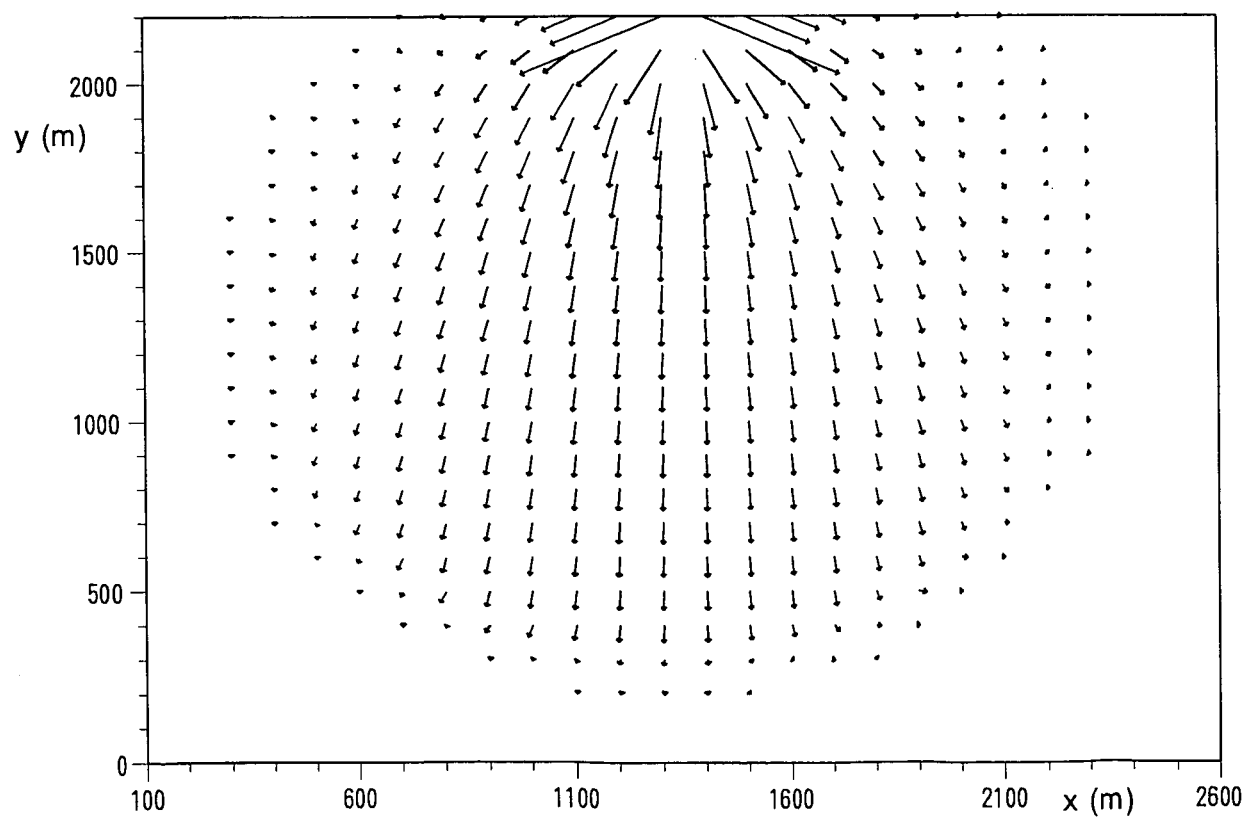
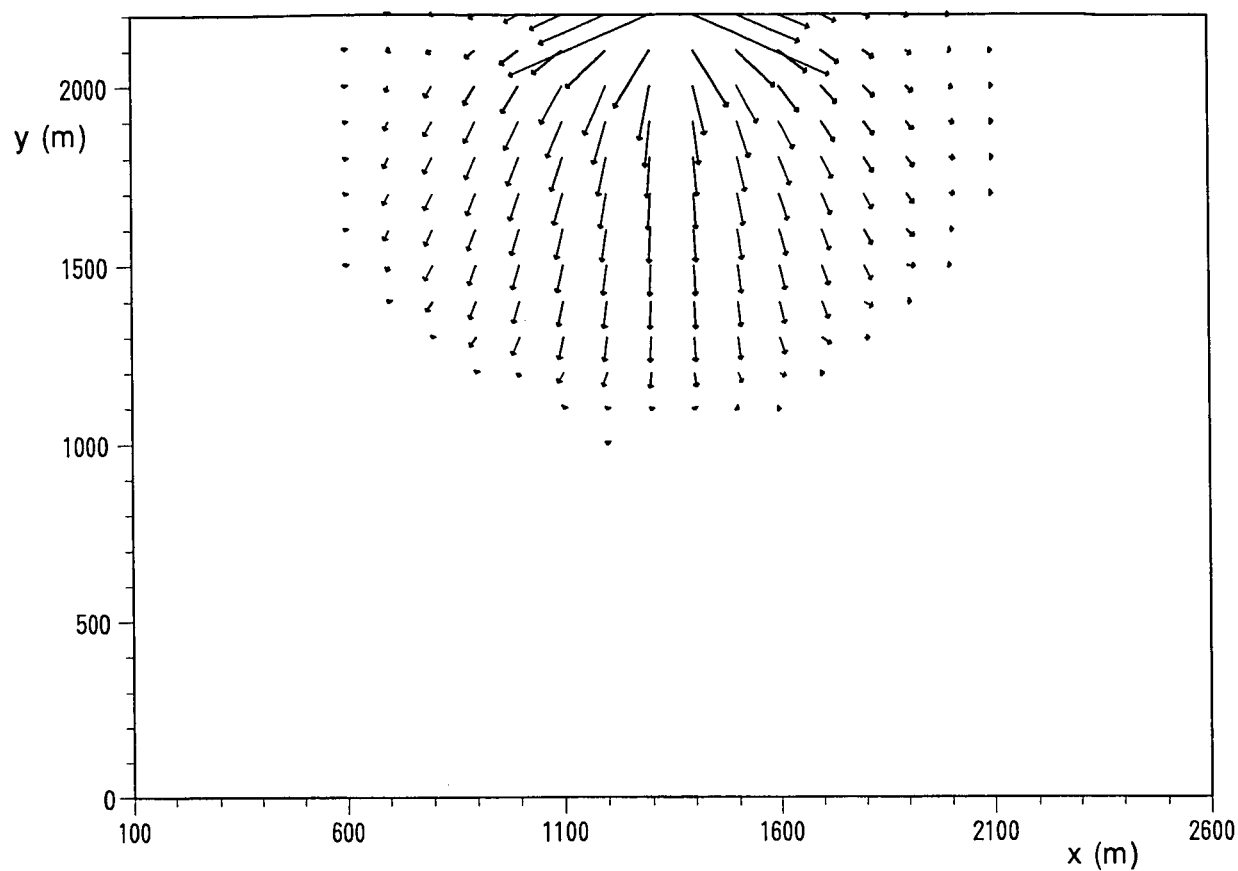


Fig.3.5.6 Vector plot for run M3. On the top $t=1h$; on the bottom $t=2h$.
The scale for the vector flux (m^2/s) is 1000 times the plot unit.

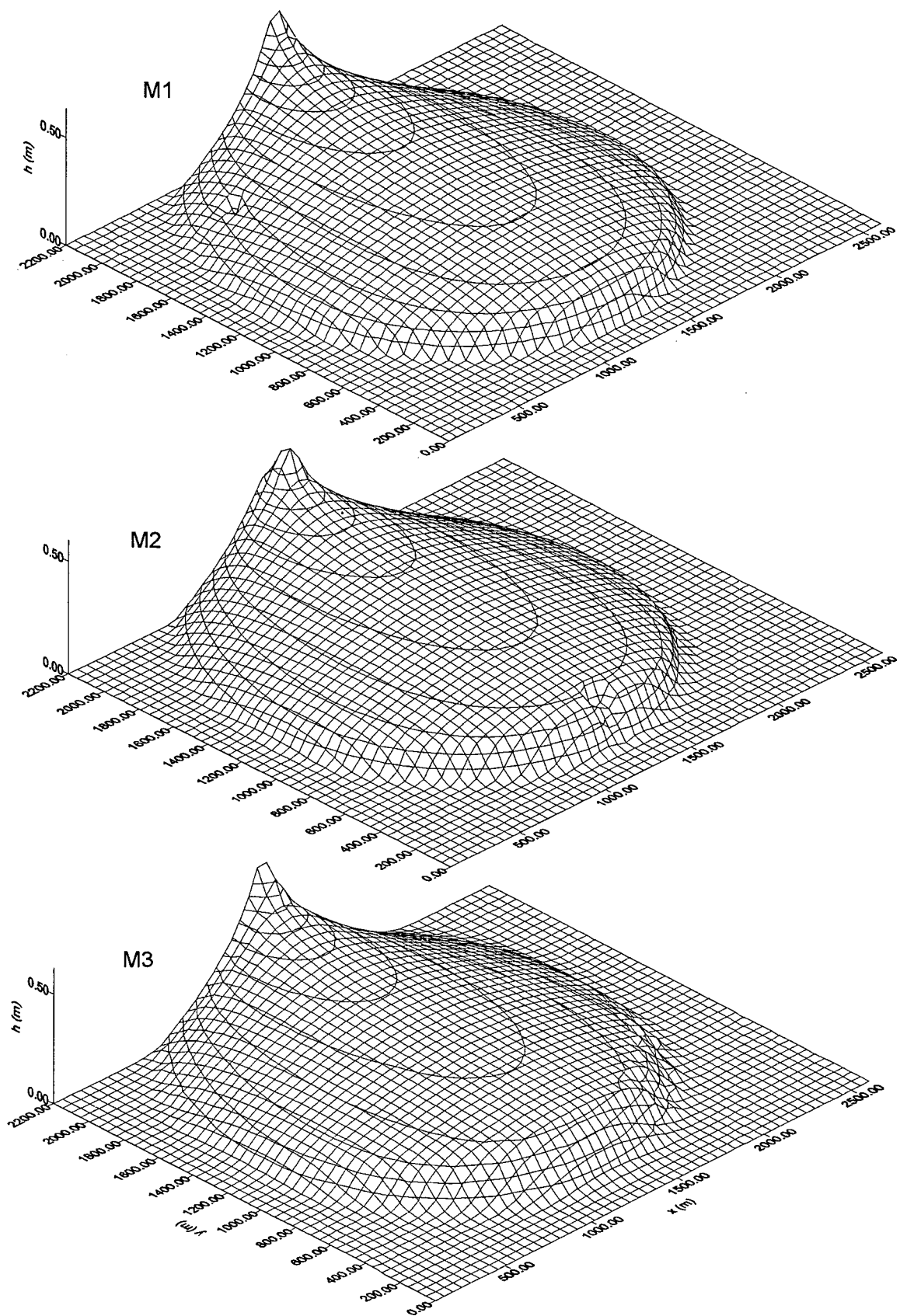


Fig.3.5.7 Surface plots for run M1, M2 and M3 for $t=2h$

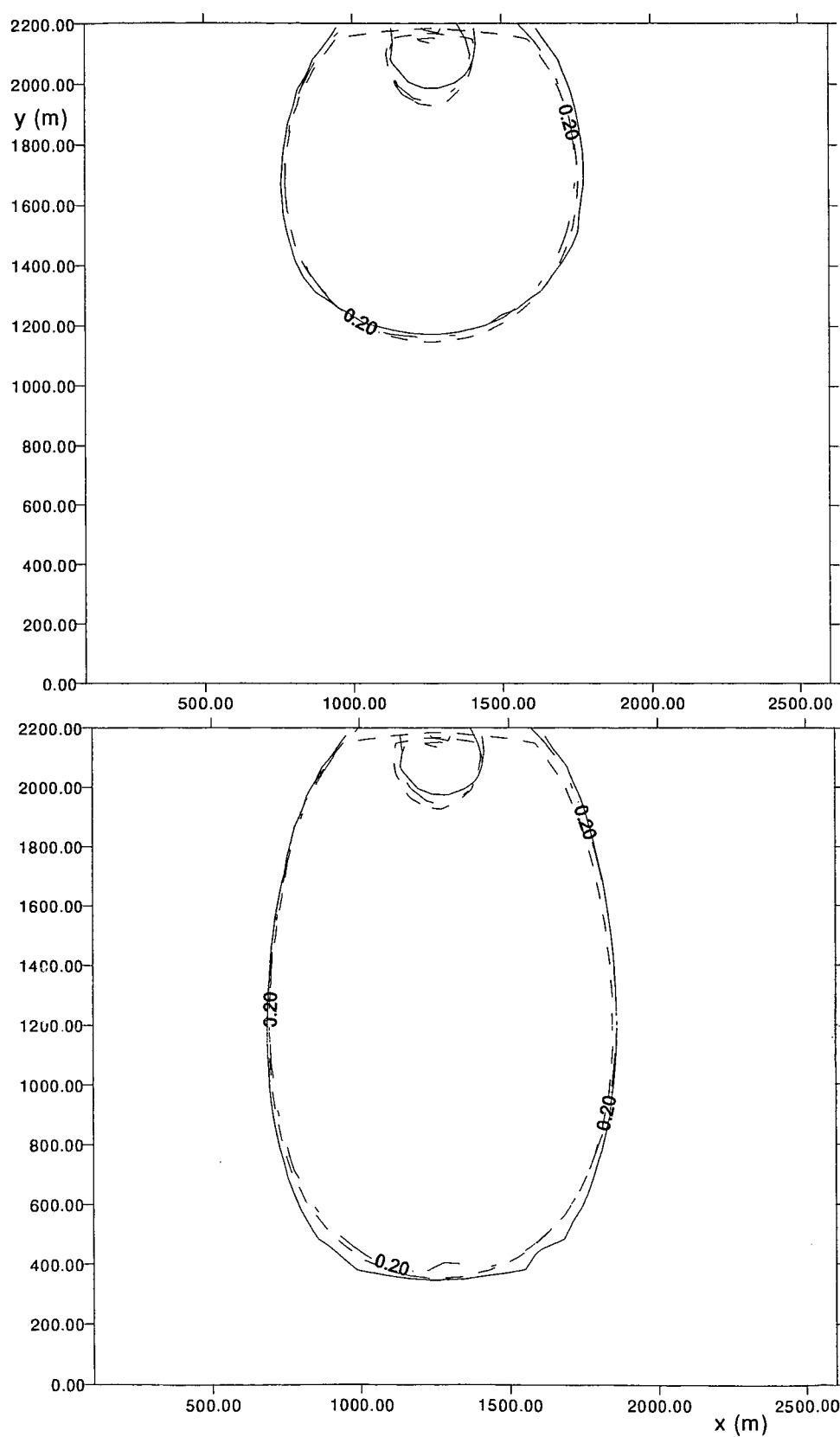


Fig.3.5.8 Comparison between run M1, M2 and M3. On the top: $t=1\text{h}$; on the bottom: $t=2\text{h}$ (the curves are relative to a water level expressed in meter).

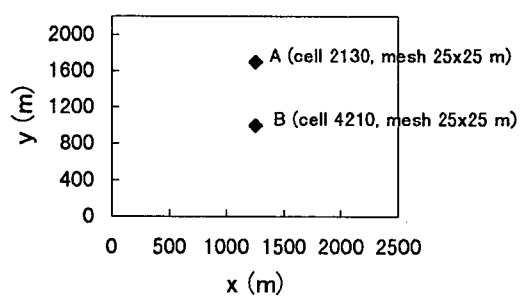
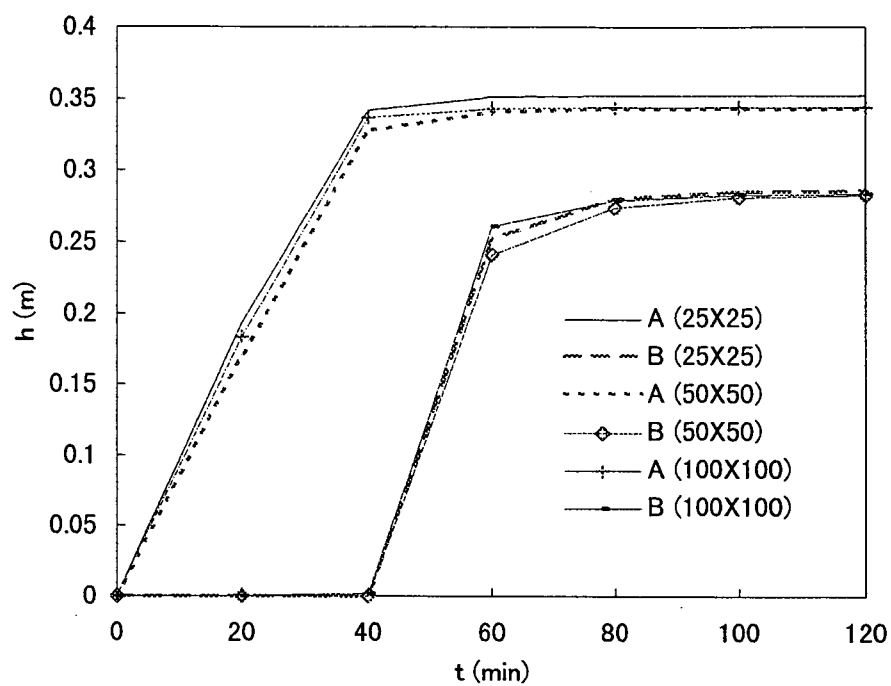


Fig.3.5.9 Water depth as a function of time for the points A and B of run M1, M2 and M3

3.6 INTERACTION BETWEEN RIVER AND FLOODPLAIN

Till now, in all the runs, an hydrograph of uniform or triangular shape has been superimposed in one cell of the mesh. In this part we will consider the interaction between the river and the floodplain simulating the levee break and the possibility of submergence.

For this purpose, a river has been simulated with the model and a given hydrograph has been routed.

Three different situations has been numerically investigated. The first simulation (R1) considers a case in which there is a levee break when the water level in the river reaches the fixed value of +5.00 m and where, after the break, the final level of the broken levee is situated at +3.5 m; in this case the velocity of breaking along the levee has been fixed in 0.5 m/s and the final width of the break in 100 m. For this run the inundated plan was at a level of +0.0 m so that, no submergence conditions can be achieved.

The second simulation (R2), is equal to the first one except for the level of the inundated plan that has been fixed at +3.5 m. This cause a reduction in the discharge from the river to the floodplain due to submergence conditions.

The third simulation (R3) is equal to the first one except for the fact that the levee is now overtopped without breaking. So the level of the levee remains fixed at +5.00 m.

For this series, the dimensions of each cell are 100x100m and the mesh size is 90x100. Table 3.6.1 reports a summary of the numerical simulations.

Table 3.6.1 Summary for run simulations R

Prove	n_0	θ (%)	s_y	s_x	Inundation volume (m ³)	Level of overtopping (m)
R1	0.05	0.0	0.0	0.0	5540000	+5.00
R2	0.05	0.0	0.0	0.0	5060000	+5.00
R3	0.05	0.0	0.0	0.0	1125000	+5.00

The equation for the discharge from the river to the plan and viceversa are the same of those for the bank (i.e. the levee is considered as a broad crested weir).

Fig. 3.6.1 shows the scheme of the simulation.

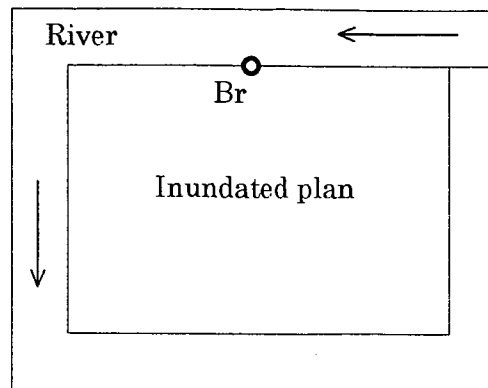


Fig.3.6.1 Scheme for series R

In the figure, Br represents the levee break point.

Figg. 3.6.2 to 3.6.10 show the results of the simulations for time $t=4, 6, 8$ and 12 hours. Fig.3.6.11 shows the hydrograph in the river and the one that enters in the floodplain. In Fig.3.6.12 are illustrated, for the three runs, the depths of the water for some cells. There is a little difference between the runs R1 and R2. The depths for the case R3 are much less due to the fact that the levee has been only overtopped.

Fig.3.6.13 reports the comparison between the water-front at time $t=6$ and 12^h . The value for the run R2 are slightly less than those regarding the run R1 due to the submerged functioning of the break as a consequence of the elevation of the inundated plain. The prove R3 shows the logical evidence that a simple overtopping of a levee, without any break, comports considerably less damage.

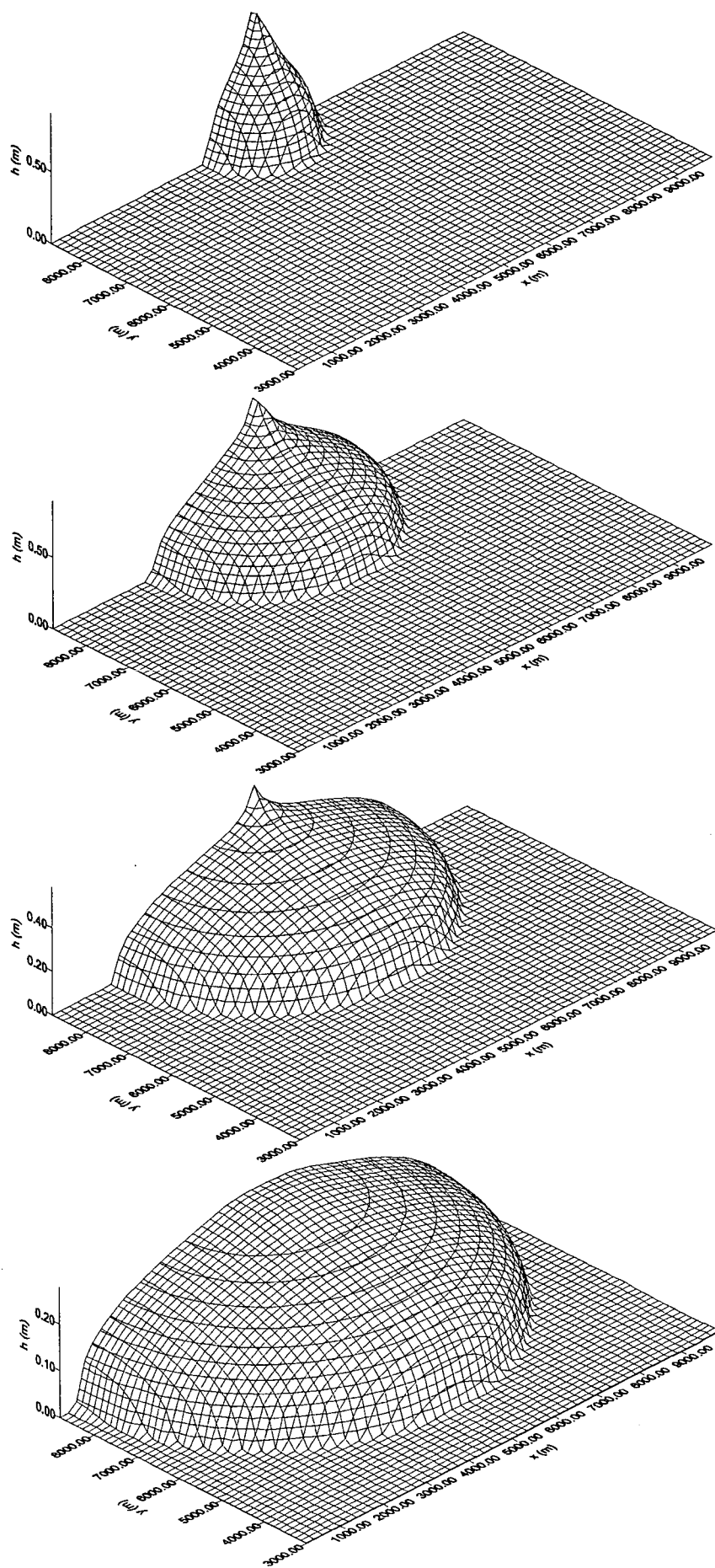


Fig.3.6.2 Surface plot for run R1. From top to bottom: $t=4h$, $t=6h$, $t=8h$ and $t=12$ hours (x , y and z scale in meters).

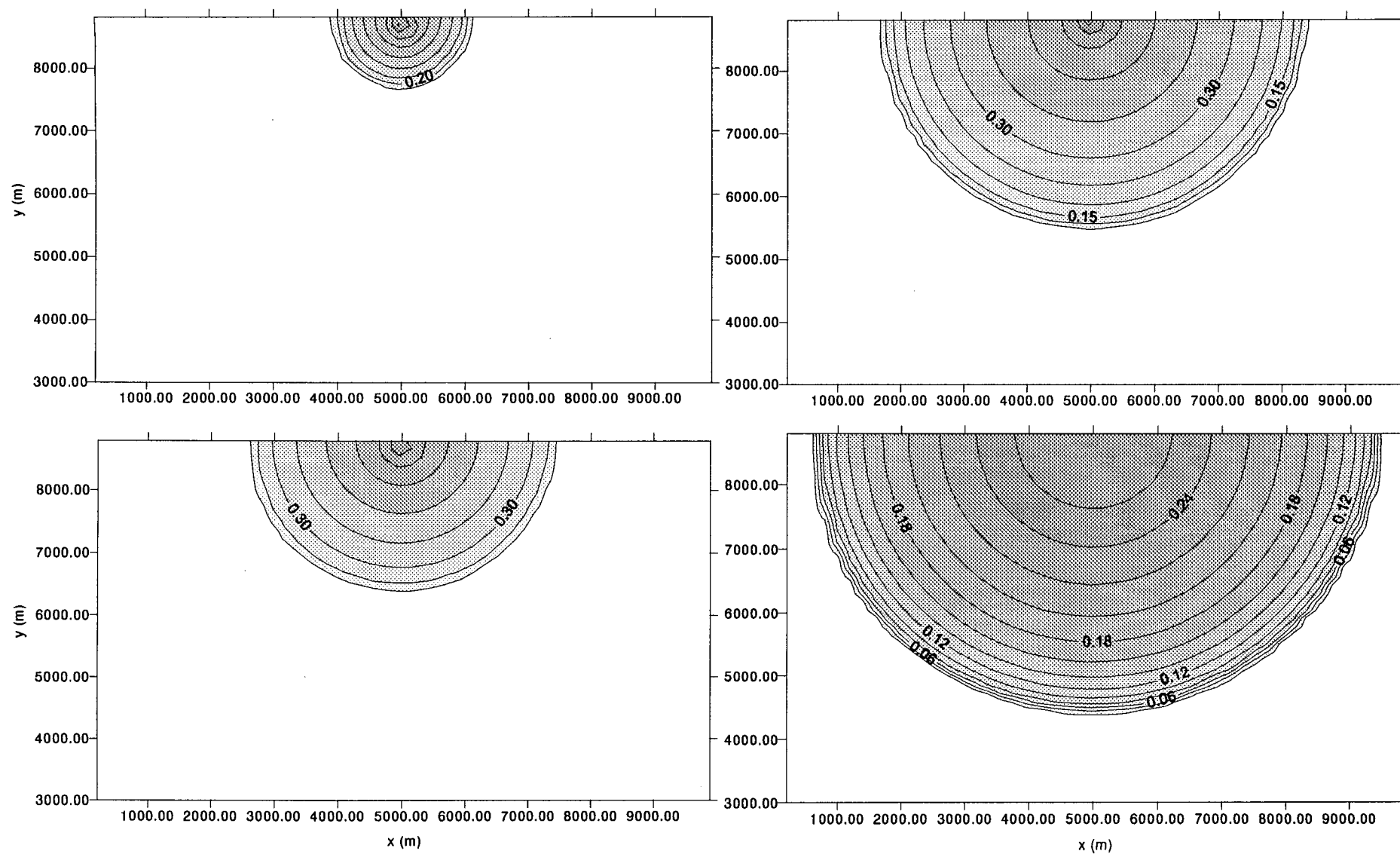


Fig.3.6.3 Contour plot for run R1. On the left: top t=4h, bottom t=6h; on the right: top t=8h, bottom t= 12 hours (scale in meter).

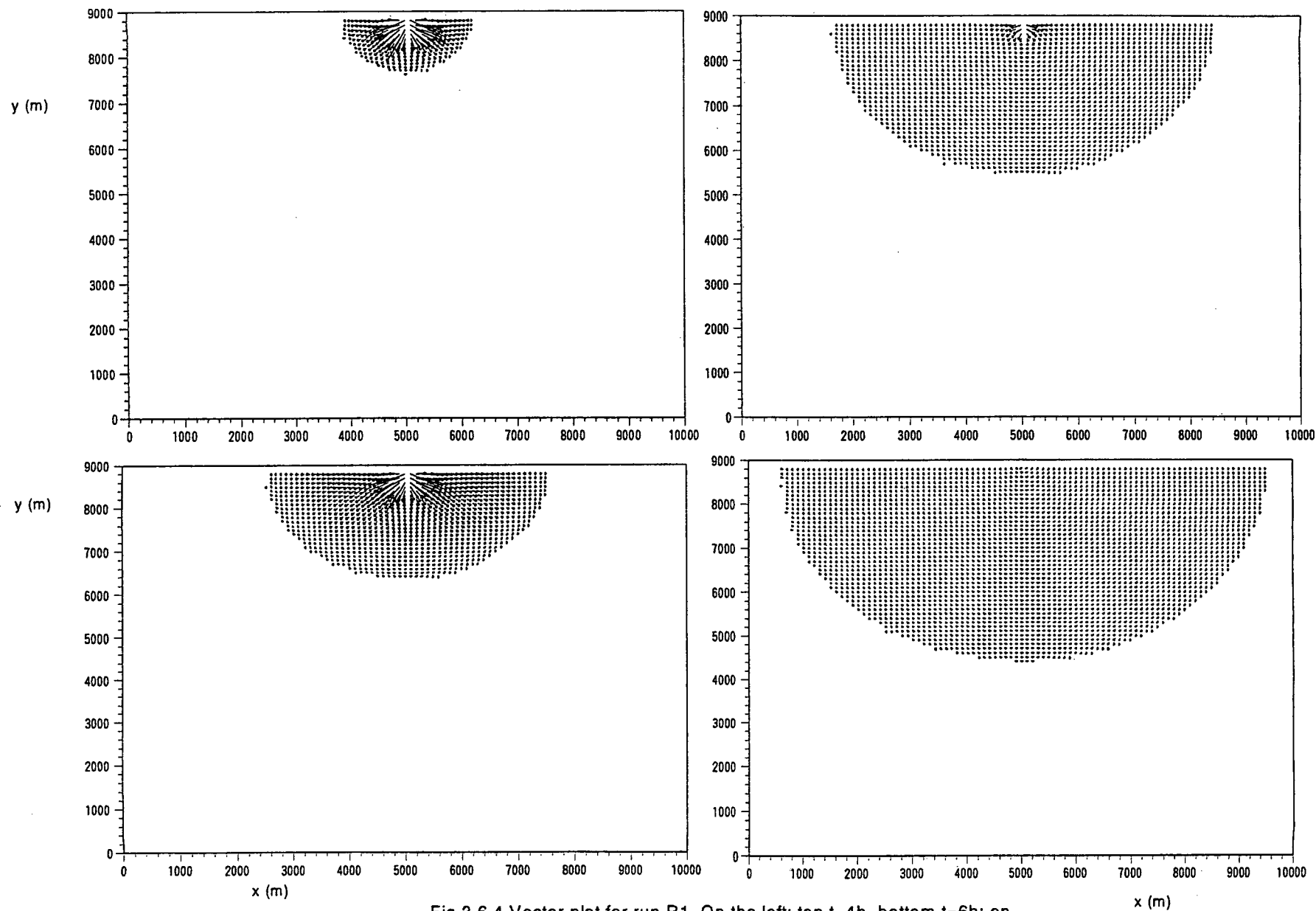


Fig.3.6.4 Vector plot for run R1. On the left: top $t=4h$, bottom $t=6h$; on the right: top $t=8h$, bottom $t=12h$. The scale for the vector flux (m^2/s) is 1000 times the plot unit.

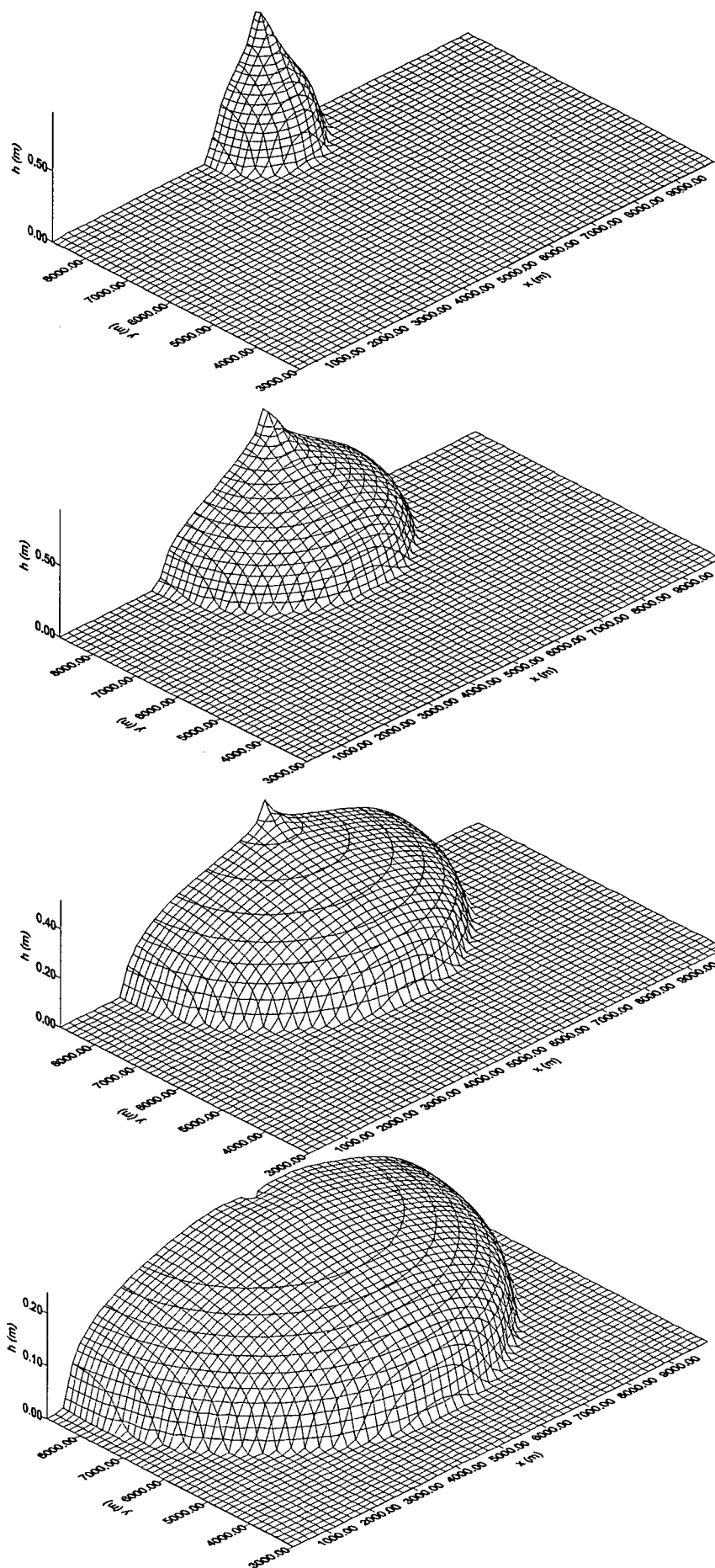


Fig.3.6.5 Surface plot for run R2. From top to bottom: $t=4h$, $t=6h$, $t=8h$ and $t=12$ hours (x , y and z scale in meters).

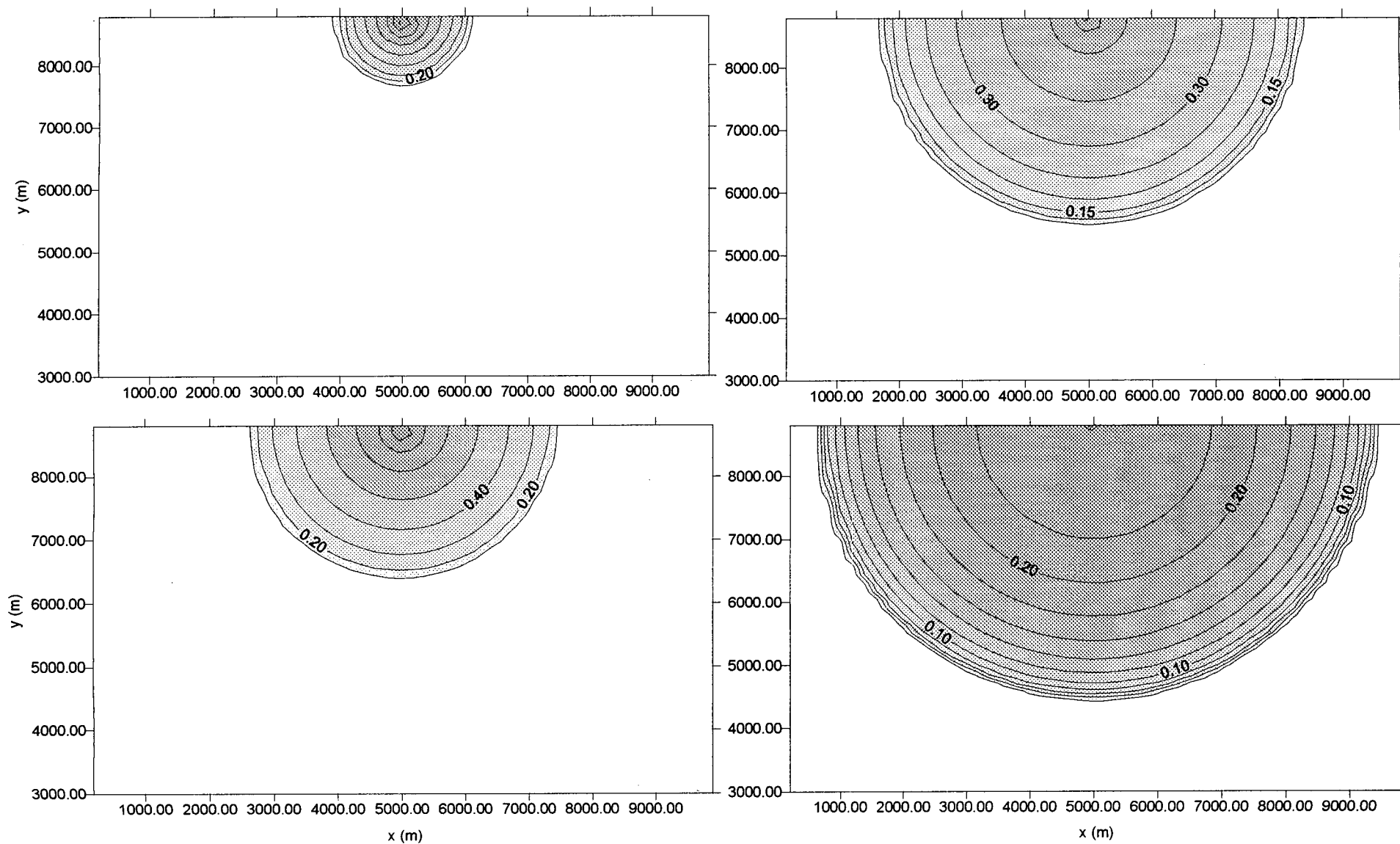


Fig.3.6.6 Contour plot for run R2. On the left: top t=4h, bottom t=6h; on the right: top t=8h, bottom t= 12 hours (scale in meter).

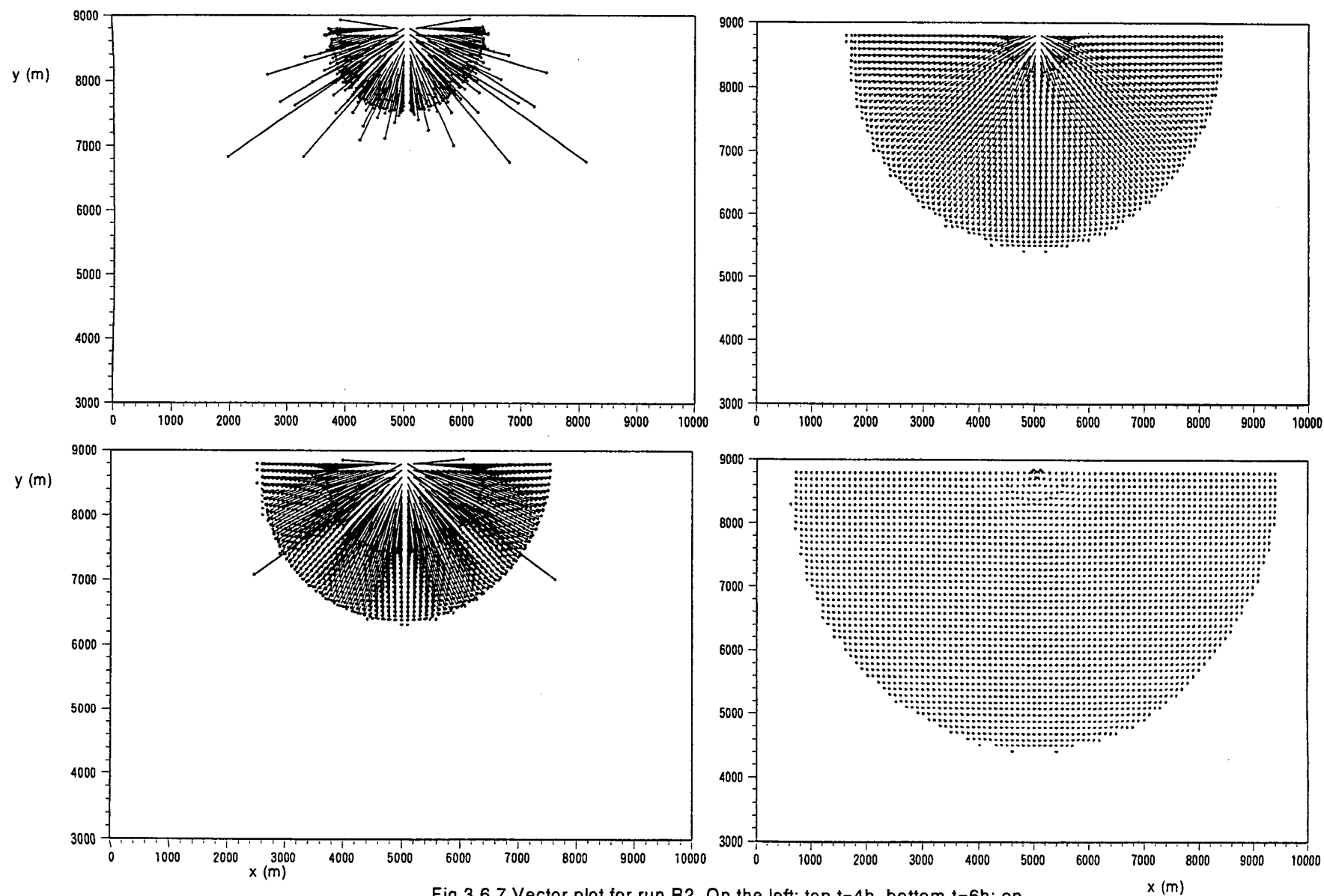


Fig.3.6.7 Vector plot for run R2. On the left: top $t=4h$, bottom $t=6h$; on the right: top $t=8h$, bottom $t=12h$. The scale for the vector flux (m^2/s) is 5000 times the plot unit.

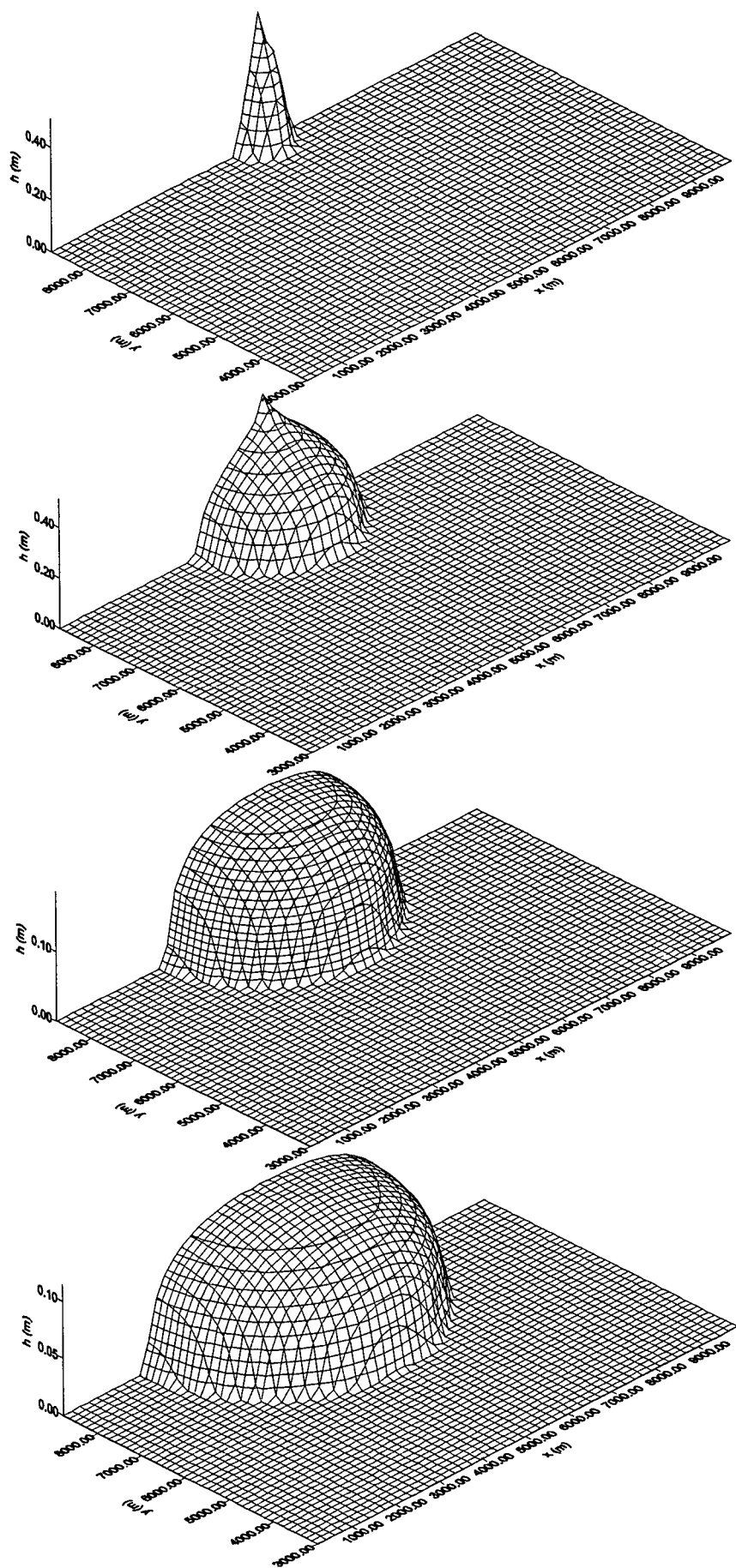


Fig.3.6.8 Surface plot for run R3. From top to bottom: $t=4h$, $t=6h$, $t=8h$ and $t=12$ hours (x , y and z scale in meters).

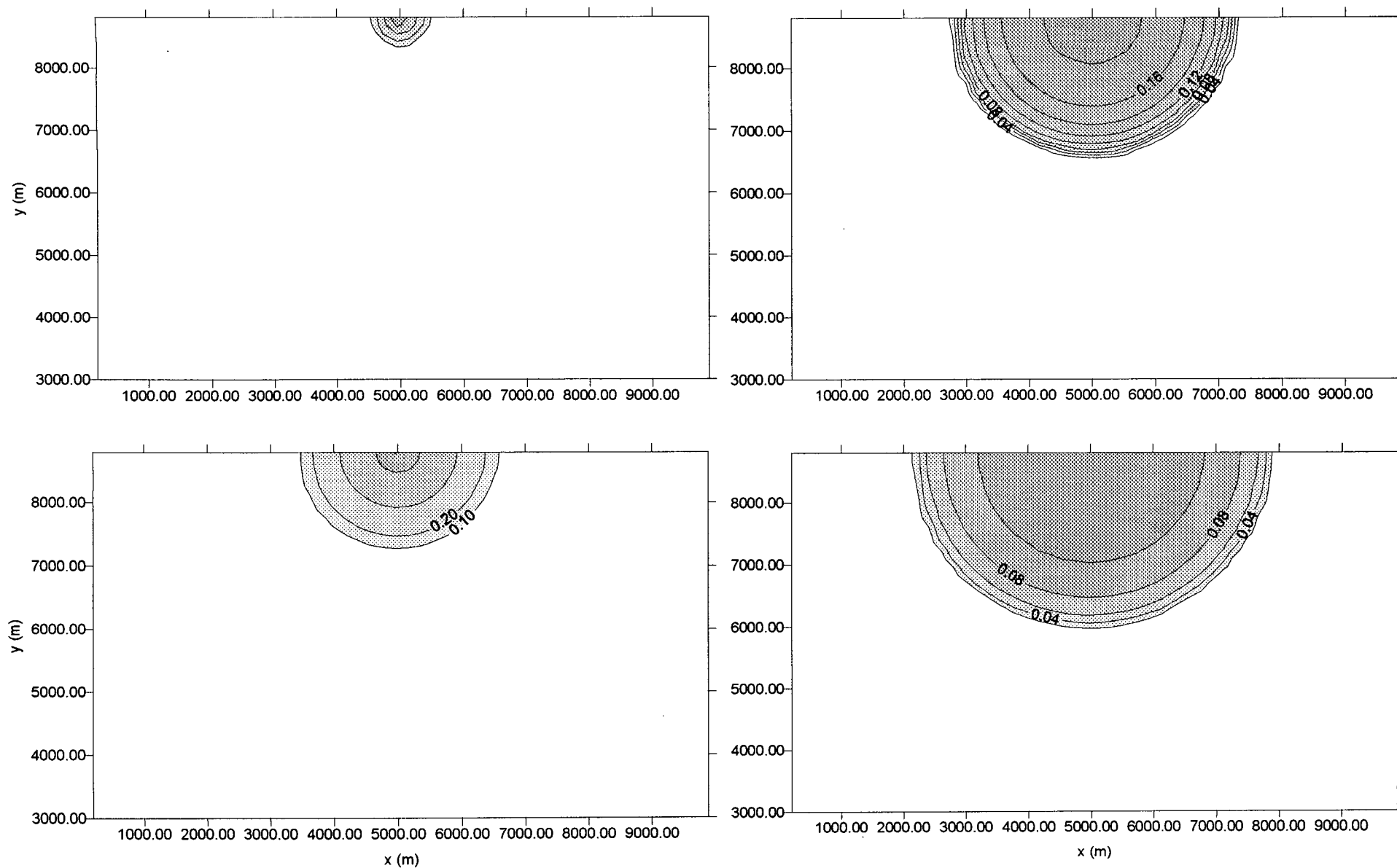


Fig.3.6.9 Contour plot for run R3. On the left: top t=4h, bottom t=6h; on the right: top t=8h, bottom t= 12 hours (scale in meter).

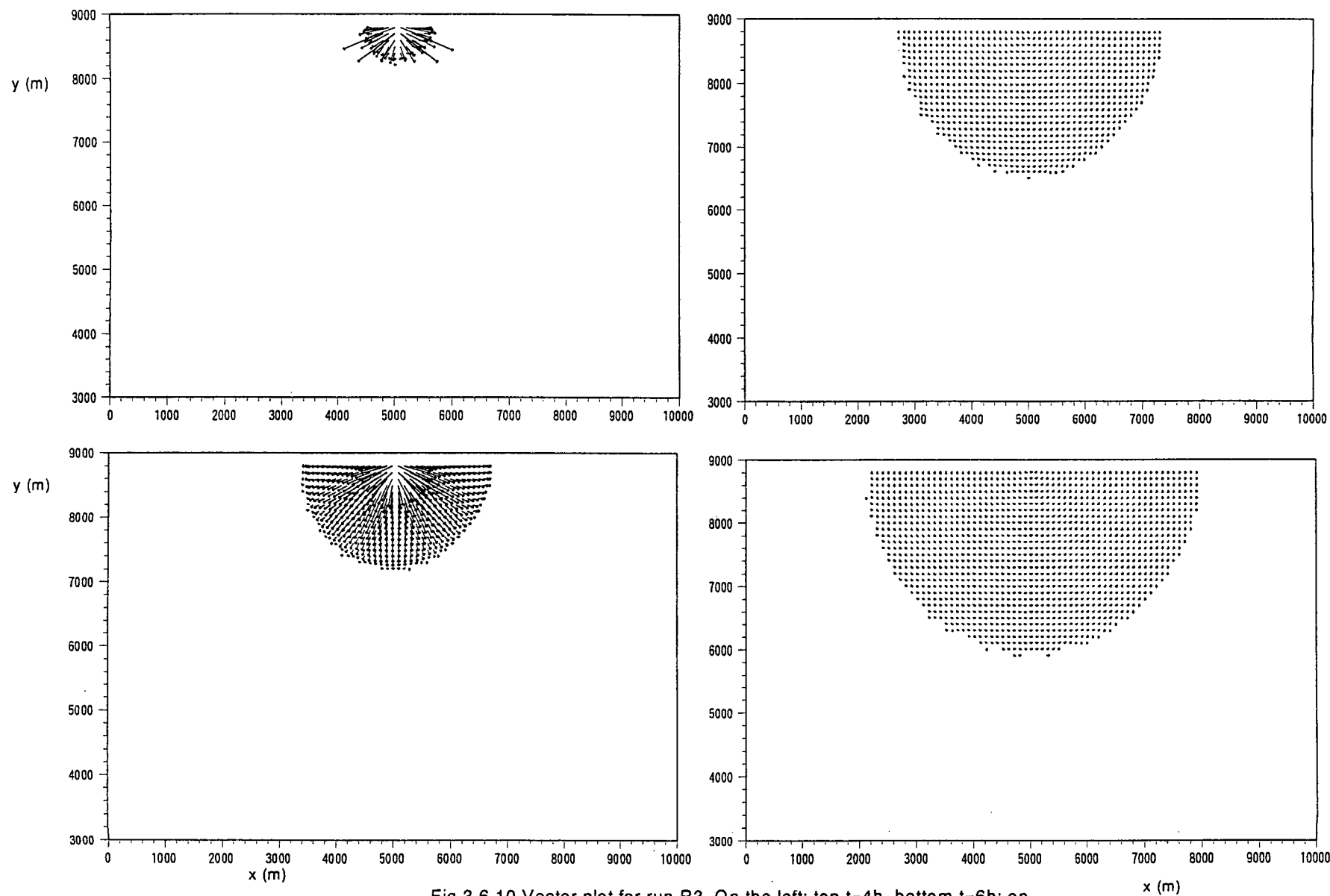


Fig.3.6.10 Vector plot for run R3. On the left: top $t=4h$, bottom $t=6h$; on the right: top $t=8h$, bottom $t=12h$. The scale for the vector flux (m^2/s) is 5000 times the plot unit.

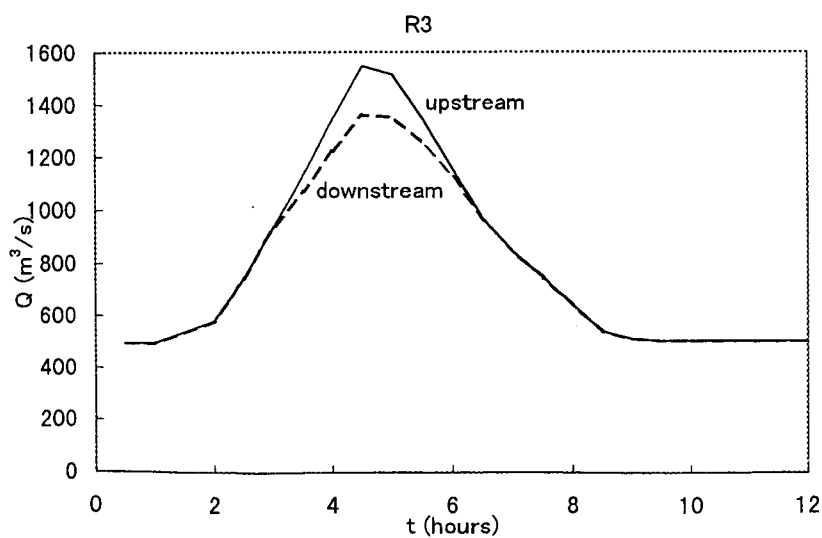
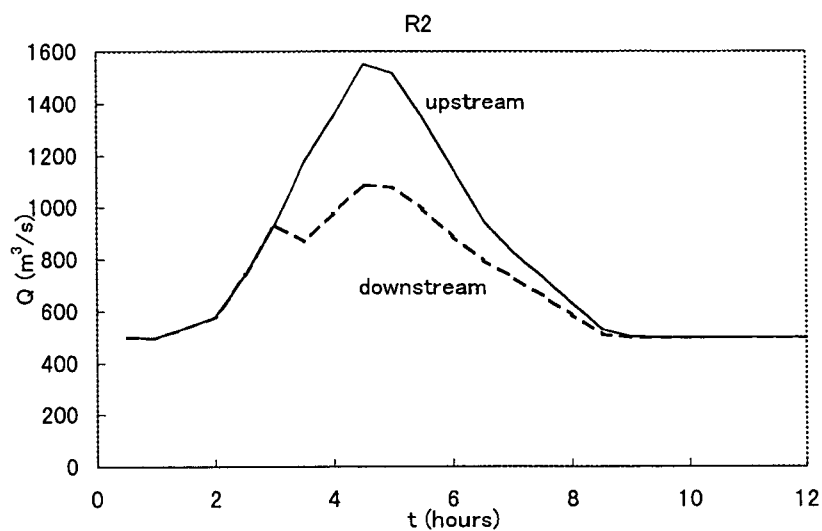
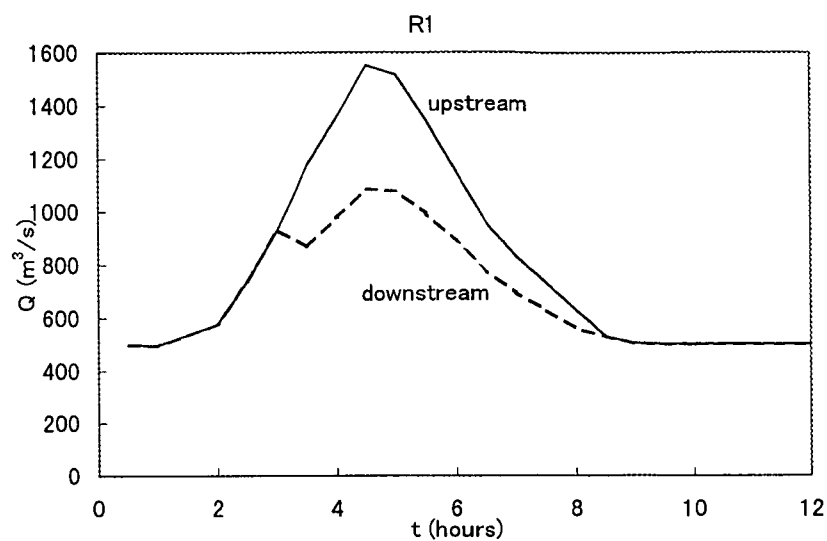


Fig.3.6.11 Hydrographs upstream and downstream of the levee break for run R1, R2, R3

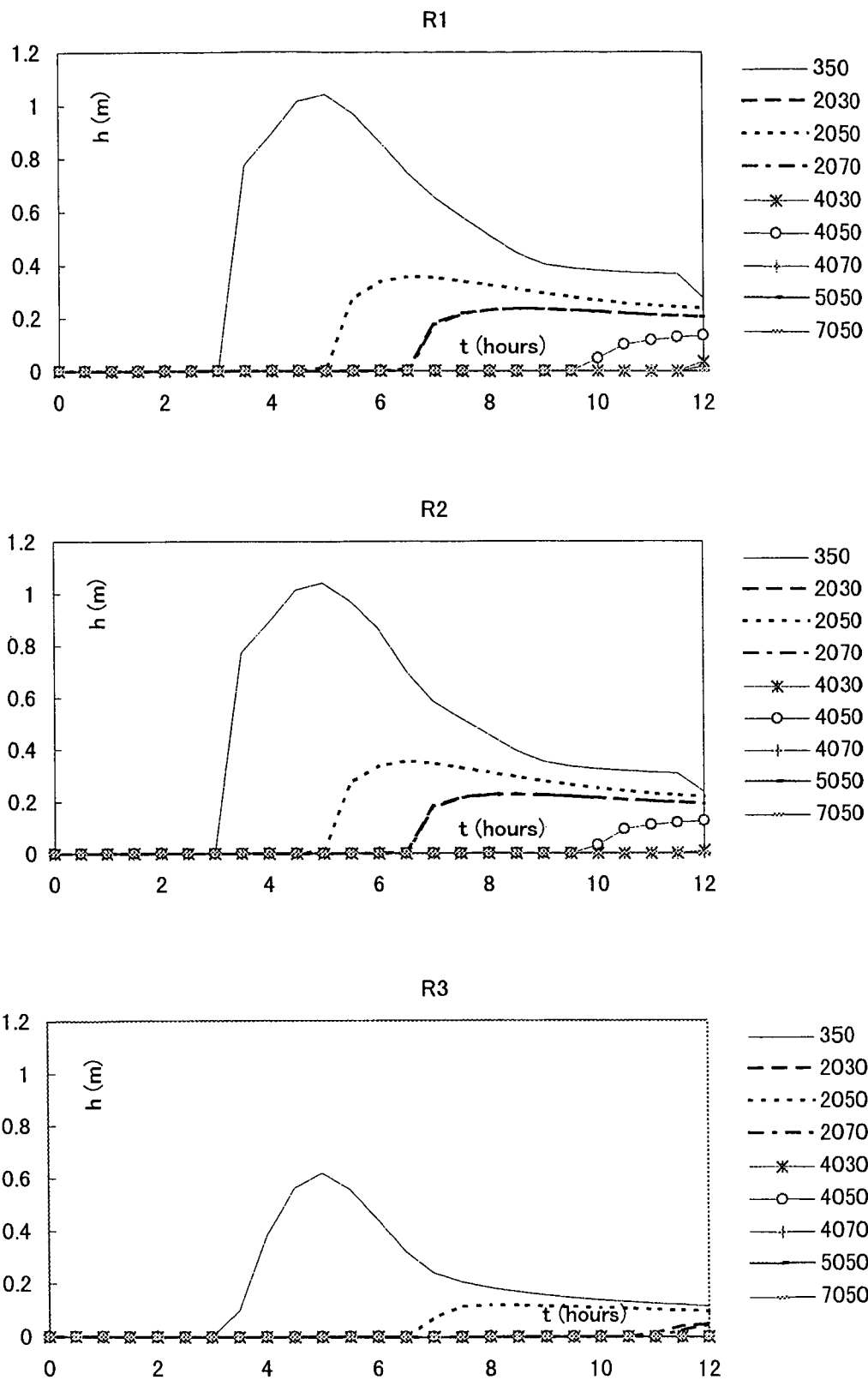


Fig.3.6.12 Water depth as a function of time for selected point for run R1, R2, R3

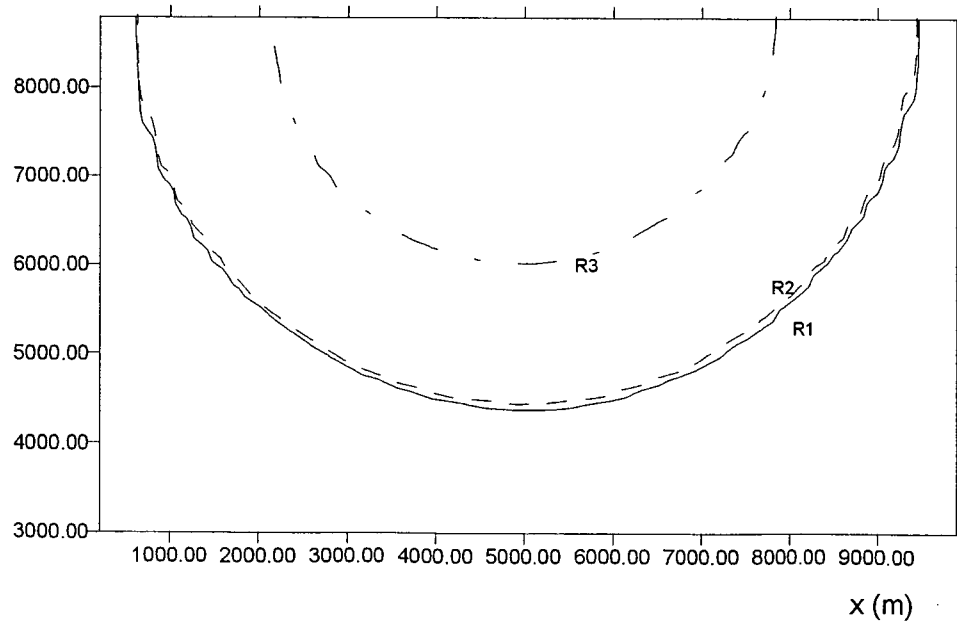
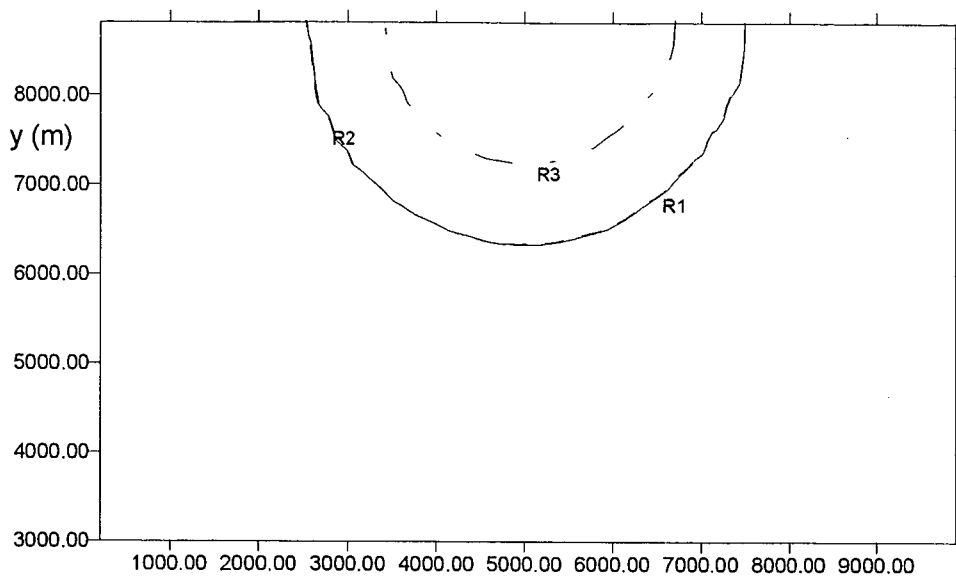


Fig.3.6.13 Comparison between run R1, R2 and R3 for $t=6h$ and $t=12h$

4. SIMULATION OF REAL FLOODPLAIN - SERCHIO RIVER NEAR PISA

In this chapter, a real floodplain will be described; some numerical simulations will be carried out in order to understand the effect on the flow pattern due to the presence of structures in the inundated plain.

4.1 DESCRIPTION OF THE ZONE

The floodplain is located in Tuscany (Italy), between the Arno and Serchio river near the city of Pisa (Fig.4.1.1); in the plain are located some small villages and the north part of the city of Pisa. The inundated plan is indicated in the map with a star symbol.

Serchio river has a basin of about 1400 km² and represents the second major river of the Tuscany region. It has some interesting characteristics and for this reason has been classified as "Pilot basin" by a recent Italian law. A description of the basin is reported in Pagliara et al. (1996).

The Serchio basin is characterized by strong rainfalls that, also in recent years, have caused relevant peak discharges and levees overtopping. The river has levees on both sides for the last 30 km and in some part the levees are about six meter high. The presence of many villages along the last part of the stream and the plain that we are going to considerate, make such a study interesting.

The hydrograph chosen for the simulation has a peak flow of 2200m³/s that corresponds roughly to the maximum discharge historically measured in the last part of the river.

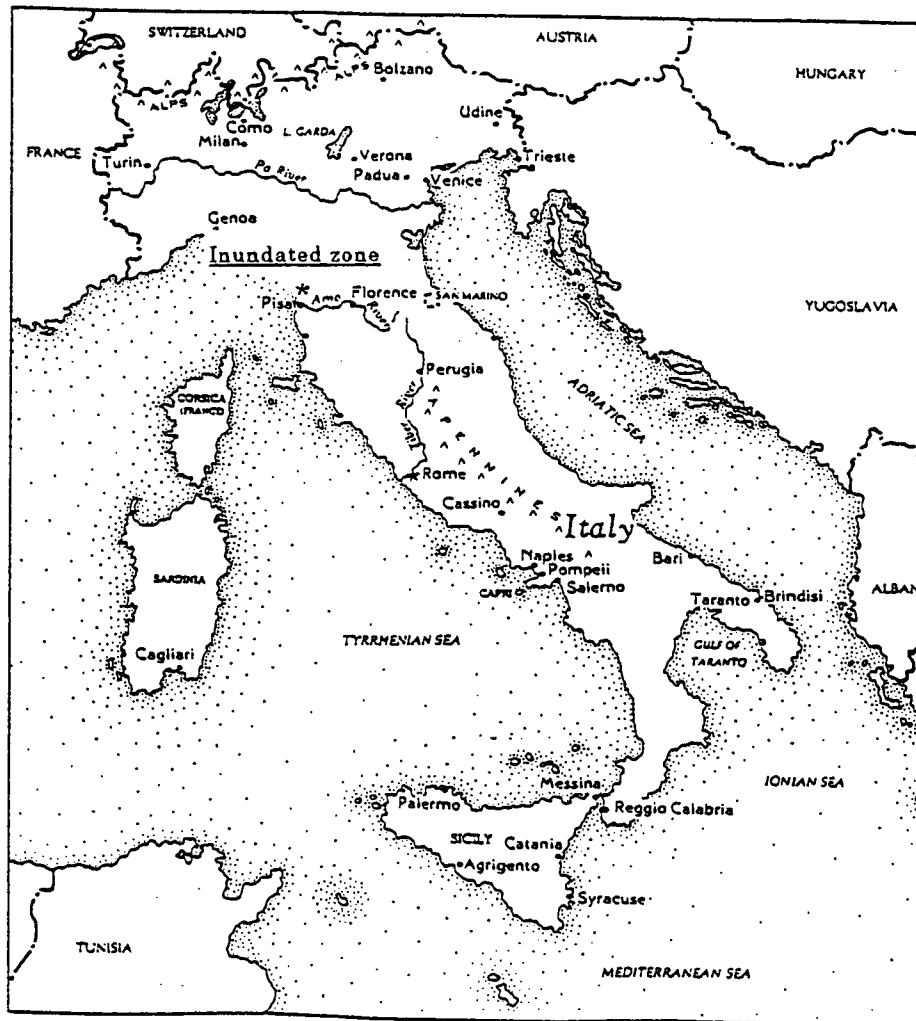
The simulated plain covers an area of 9x9 Km and is delimited at north by the Serchio river itself, south by the Arno river, in the west direction is the park of 'San Rossore' that confines with the Tyrrhenian sea while the east part is characterized by some hills and some zone with low ground level.

For the study, the levee break has been locate, between the villages of Pontasserchio and Pappiana (Fig.4.1.2). The break is assumed to occur in the north east part of the floodplain in the cell No.76 in the left bank of the river. This is a really dangerous point, in which the river makes a 90 degrees bend and in which the flow exerted a large pressure on the levee itself.

Downstream of the break are located the villages of Pappiana, Pontasserchio and Orsignano. The water, following the natural slope will go south and spread out on the floodplain in east-west direction.

In both directions are located small villages and south of that zone is located the city of

In the plain are located some roads, railways, one highway and some small drainage channels; the only channel that is important for the purpose of this study is the "Fiume Morto" that flows in direction east-west north of the city of Pisa with a longitudinal slope that is practically horizontal.



The dimension of the cells has been set equal to 200x200m that represents a good compromise between the computational effort and a detailed description of the structures

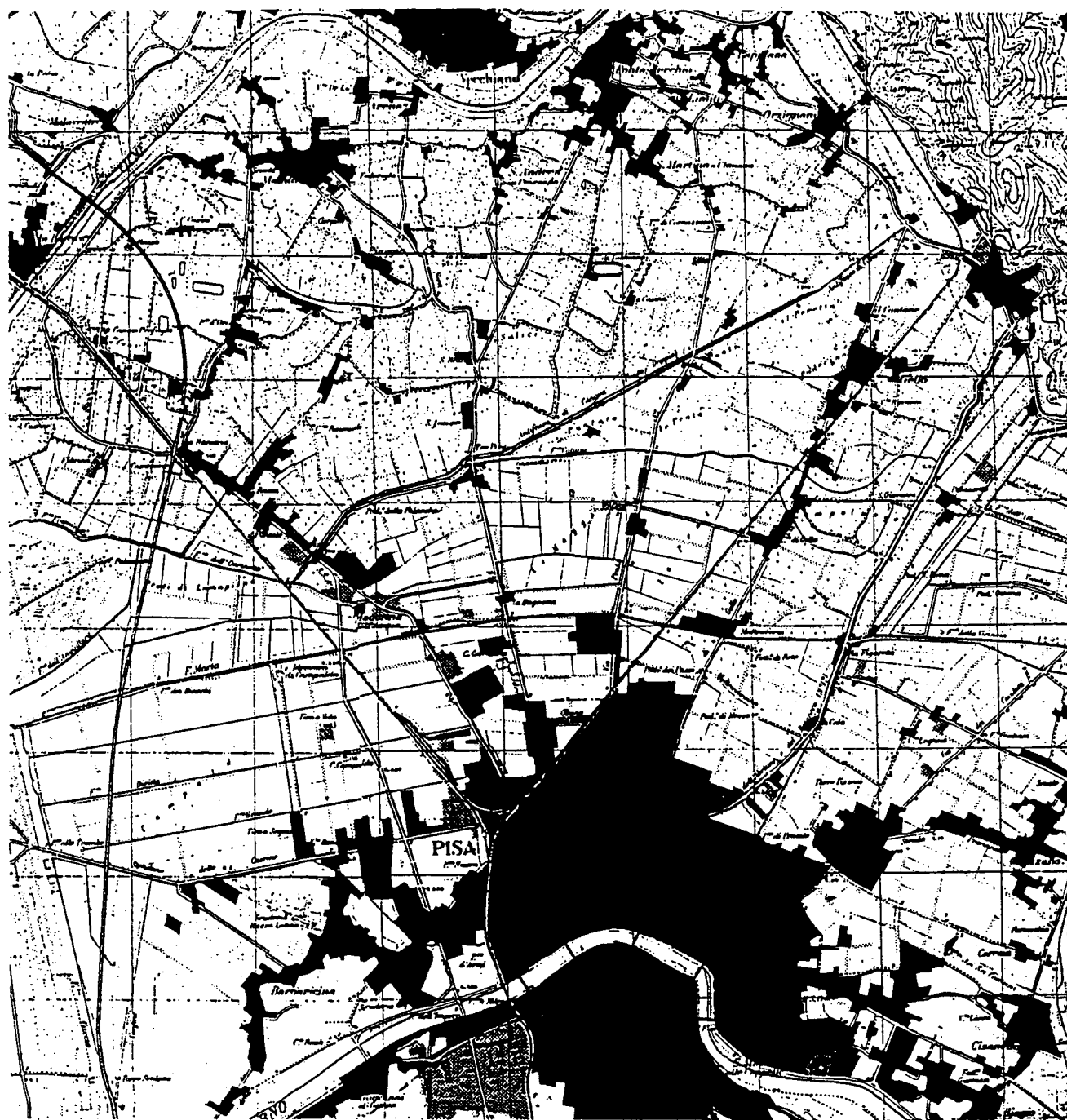


Fig.4.1.2 Plan view of the studied zone (Scale 1:50000)

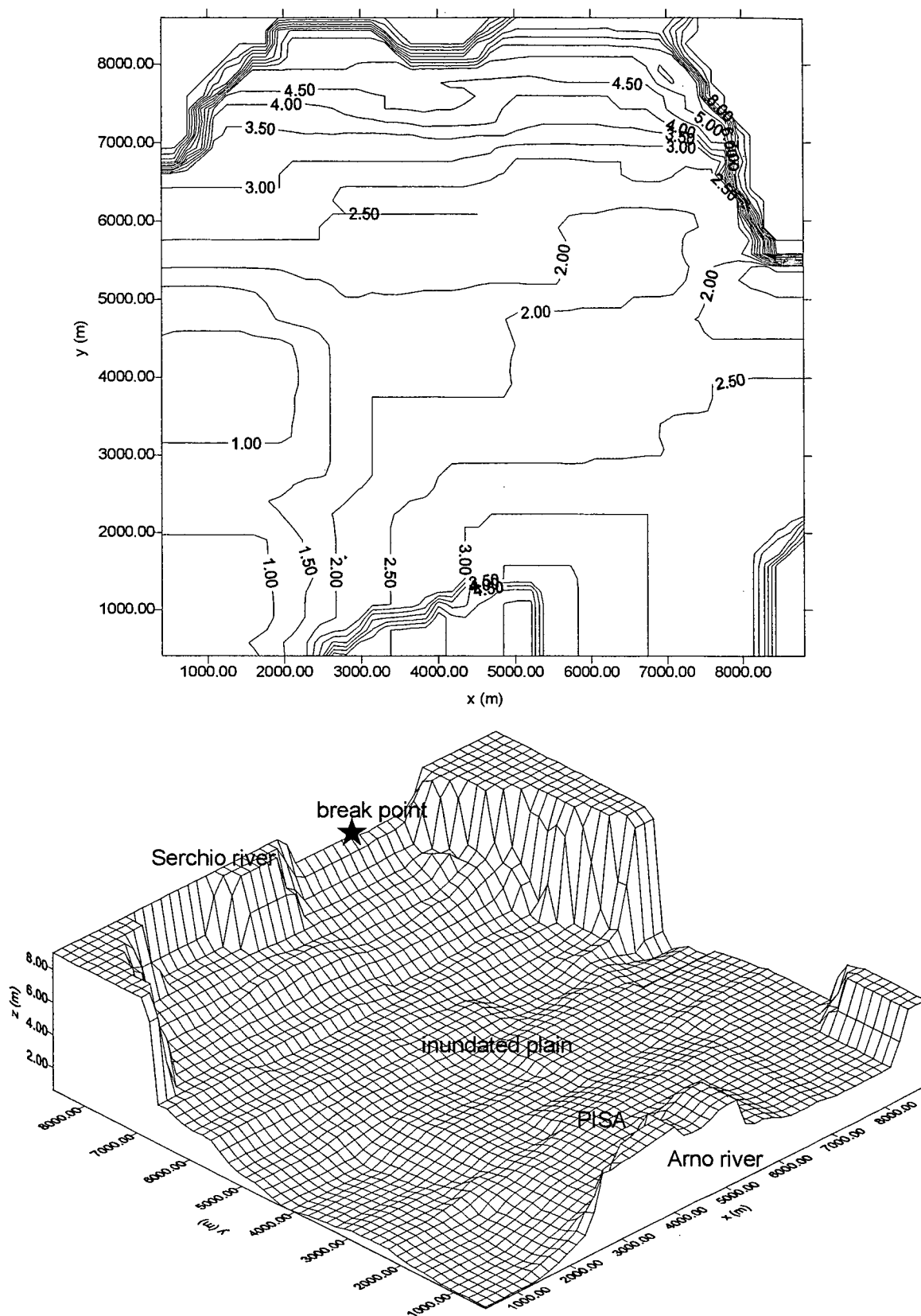


Fig.4.1.3 Floodplain simulated in the series SR. On the top: contour plot; on the bottom: surface plot (north in the direction of y-axes).

present in the zone.

4.2 NUMERICAL SIMULATIONS AND RESULTS

Eight numerical simulations has been carried out in order to understand the dynamic of the flow during its propagation in the plain and the influence of the various structures present in the zone; Fig.4.2.1 shows a scheme of the main structures that are a railway, one highway and some roads. The presence of little drainage channels has not been considered and only the so called "Fiume morto" channel has been considered. Tab 4.2.1 illustrates the various numerical runs. The roughness Manning coefficient has been assumed equal to 0.05. The urbanization effect on the roughness is accounted by means of eq 3.1.1.

Table 4.2.1 Numerical simulations for the case of the Serchio river

Run No.	Description
SR1	boundary conditions with zero flux
SR2	real boundary conditions (base condition)
SR3	base condition + railway (without culverts)
SR4	base condition + railway (with culverts)
SR5	base condition + "Fiume Morto" channel
SR6	base condition + roads
SR7	base condition + highway
SR8	real situation

The first run (No. SR1) considers the hypothetical situation in which the boundary of the floodplain doesn't allow exchange of water so that, all the water that will enter from the break cannot go out.

The second run considers a most real case in which the boundaries are such that the water can go out of the floodplain. In particular is considered the situation in which no submergence from outside of the plain is present. This can be an optimistic hypothesis in case in which, due to heavy rainfall in the zone other floods, due to the minor drainage network will occur. This condition represents what is called the "base condition", in the

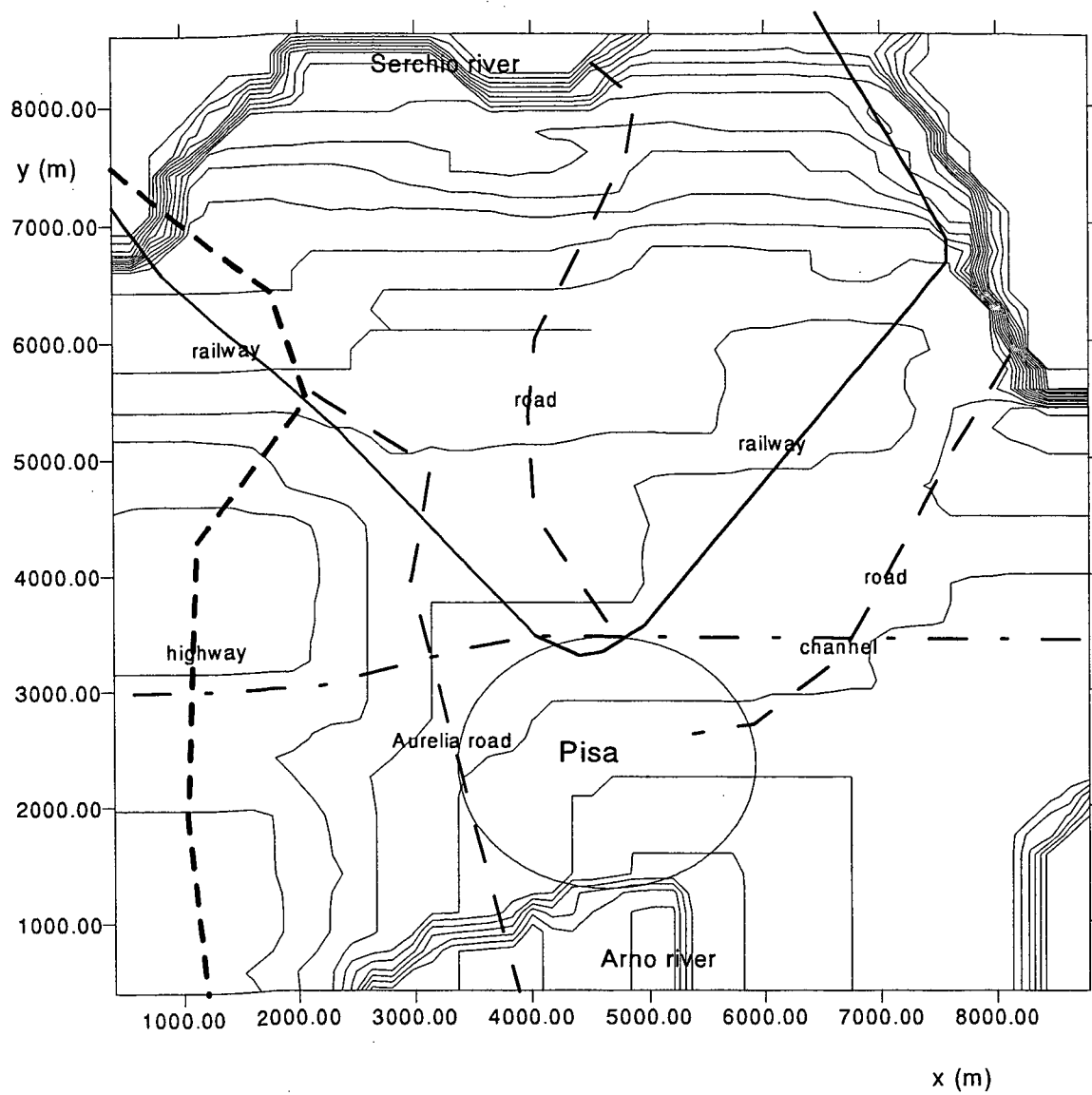
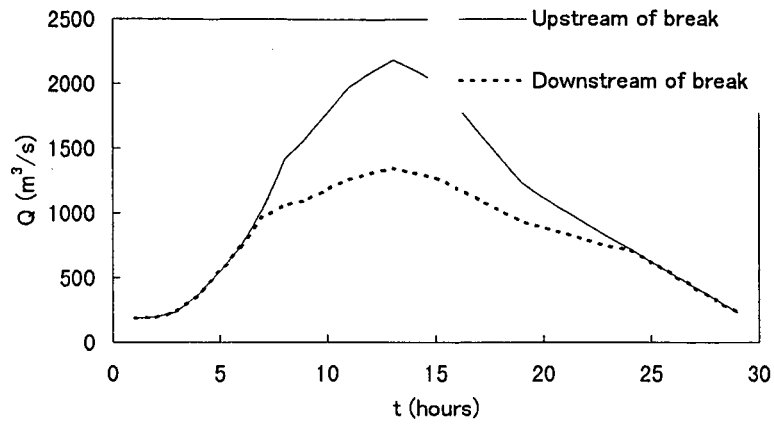
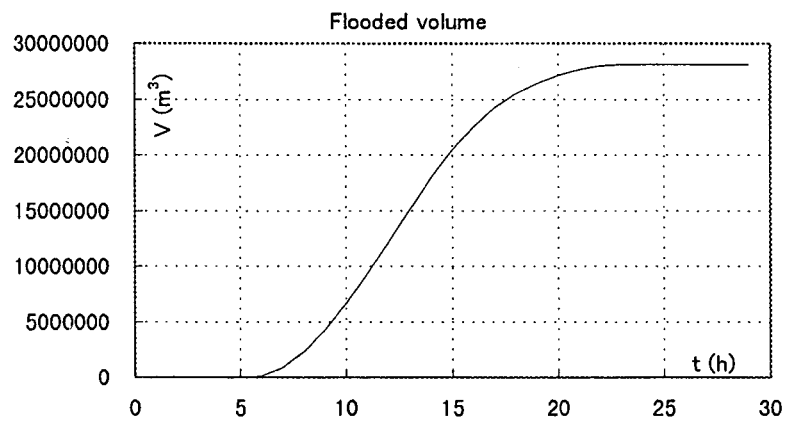


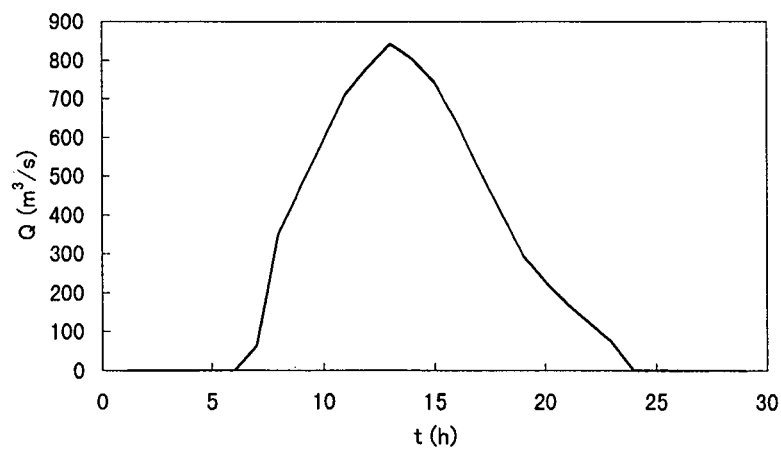
Fig.4.2.1 Sketch of the main structures present in the floodplain.
Contour lines are the same of Fig.4.1.3



a)



b)



c)

Fig.4.2.2 a)Hydrographs on the Serchio river upstream and downstream of the levee break. b) cumulated volume of water that enters in the floodplain. c) flooding hydrograph

sense that it will represents the base on which all the structures and channels present in the plain will be superimposed.

The third run considers the base condition plus the presence of the railway that constitutes a bank with a v shape north of the city of Pisa. The railway has some reaches in which the level is at the ground level and others in which it constitute a real bank. In this run the presence of culverts under the railway are not considered .

The fourth run represents the same situation as the third one except for the presence of the culverts. Culverts represent, bridges, tunnel and drainage pipes locate along the railway's bank.

The fifth run considers the base condition plus the presence of a drainage channel ("Fiume morto" channel) that is present, north of the city of Pisa and that flows in east-west direction.

The sixth run considers the presence of the main system of roads. They mainly goes in north-south direction and for long reaches constitute a bank for the flooding flow.

The seventh run considers the base condition plus the presence of the highway that is located along the east border of the plane.

Finally the eighth simulation account for the presence of all the infrastructures together and represents the actual real situation of the floodplain (condition SR2+SR4+SR5+SR6+SR7).

The break is located in the cell 76. A final break of width equal to 100 m has been supposed. The hydrographs in the river before and after the break point are presented in Fig.4.2.2 . In the figure is also reported the flooding volume and the resulting flooding hydrograph.

A total volume of 28 millions of cubic meter enters the plain during the simulated time. It is a value certainly realistic in case of levee break, for a river that has a peak discharge of more than 2000 m³/s.

The volume of the flood is the same for all the simulations, because it is not influenced by the water level in the floodplain due to the lower elevation of this one. The total simulation time has been set in 30 hours, while the time step of the calculation has been chosen equal to 4 seconds.

Fig.4.2.3 to 4.2.26 represent the results of the eighth simulations described above. For each run is reported, for time equal to $t=8^h, 10^h, 12^h, 15^h, 17^h, 20^h, 25^h$ and 29^h , a surface plot, a contour plot and a vector plot of the flow inside the inundated plain. The surface and contour plots represents water depth above the ground level, while the vector plot shows the flux from each cell of the mesh.

For the run SR1 (Fig.4.2.3-4.2.5), the water tends to accumulates in the east and west

border that represents depressed zones. This is due to the fact that, for this prove, the flux at the boundary is zero.

In the second case (Figg.4.2.6-4.2.8), can be seen the benefic effect of the discharge from the border to outside. In this case the boundary is open and the water can go outside the plan; for this purpose, at the border of the plan has been inserted a total of 14 pumps located in the lower points. As a consequence, the water level decrease and at the end of the simulation time only 11 millions of cubic meter of water are present in the floodplain against the 28 that has been entered.

Case SR3 (Figg.4.2.9-4.2.11) shows the effect of the railway in the particular case of absence of culverts. It is evident the effect of confining due to the presence of the railway bank.

Case SR4 (Figg.4.2.12-4.2.14) shows the situation in which the real culverts are added inside the railway bank. The effect of the culverts is, in this case, not very important, and comports only local change in the water depth.

Figg.4.2.15-4.2.17 (run SR5) show the effect of the drainage channel constitute by the "Fiume morto" channel. It is evident, in this case, looking at the contour plot, the effect of the stream.

Figg.4.2.18-4.2.20 reports the elaborations in the case of the presence of the road system (run SR6). Like in the case of the railway, the effect on the flow pattern is important.

Run SR7 is illustrated in Figg.4.2.21-4.2.23. They show the effect of the highway, that, however is limited to the western part of the plain.

Finally, Figg.4.2.24-4.2.26 shows the real situation (run SR8) with all the infrastructures and the channel. The figures reports the sum of all the effects described for the preceding runs.

Fig.4.2.27 shows the total volume of water presents in the plain at different time. The effect of the drainage channel (run SR5) is evident in term of volume presents at the end of the simulation; in this case only ten million of cubic meter are in the plan at the end of the simulation. In all the simulation in which are present roads or railway, the total volume at the end is slightly greater. The worst situation, except the run SR1 is represented by the real situation (Run SR8).

Figg.4.2.28a-h) show the 'envelope surface of water', representing the maximum water depth for each cell in the mesh, for all the simulations. For each run is reported a contour and a surface plot.

In Figg.4.2.29-4.2.30a-g) are shown the differences, in term of water depth, for each run in respect to the base condition. This graphs has been obtained subtracting, from the maximum water level for each cell and for each simulation, the corresponding level

relative to the base condition (run SR2). These figures show how much, a single structure influences the distribution of water level in the floodplain. This kind of graph can be important in the analysis or in the design of structures that are related with change in the surface hydraulic behaviour. Fig.4.2.31 shows the depth of water as a function of time for ten selected points as described in Tab.4.2.2

Tab.4.2.2 Selected points in the plan

Cell No.	Description
120	'Pappiana' village
213	'Orzignano' village
296	'S.Martino Ulmiano' village
843	'Gello' village
1006	'Madonna dell'acqua' village
1286	Pisa "Porta a Lucca' zone
1370	Pisa 'Porta Nuova' zone
1465	Pisa 'Stadio' zone
1545	Pisa 'Barbaricina' zone
1555	Pisa center

Fig. 4.2.32 shows the comparison relative to all the simulations for the points located in the cells 843, 1006, 1286 and 1370 . For the cell No.843 located in the village of Gello, the level of the water is maximum for the real situation (run SR8) and reaches a value of about 1.7 m due to the effect of banking of the nearby railway. For the cell No.1006, located in another little village, the level of water reaches a value of about 1 m and the increase respect to the base condition is due to the presence of road banks. In the cell No.1286, located in Pisa, the water level is maximum for the run SR6 and slightly minor for the real situation. In the cell 1370, also located in Pisa, the water depth is maxima for the real situation and reach a value of about 50 cm. This graph shows clearly the effect of each structures and can be very useful in decision processes for planning purposes.

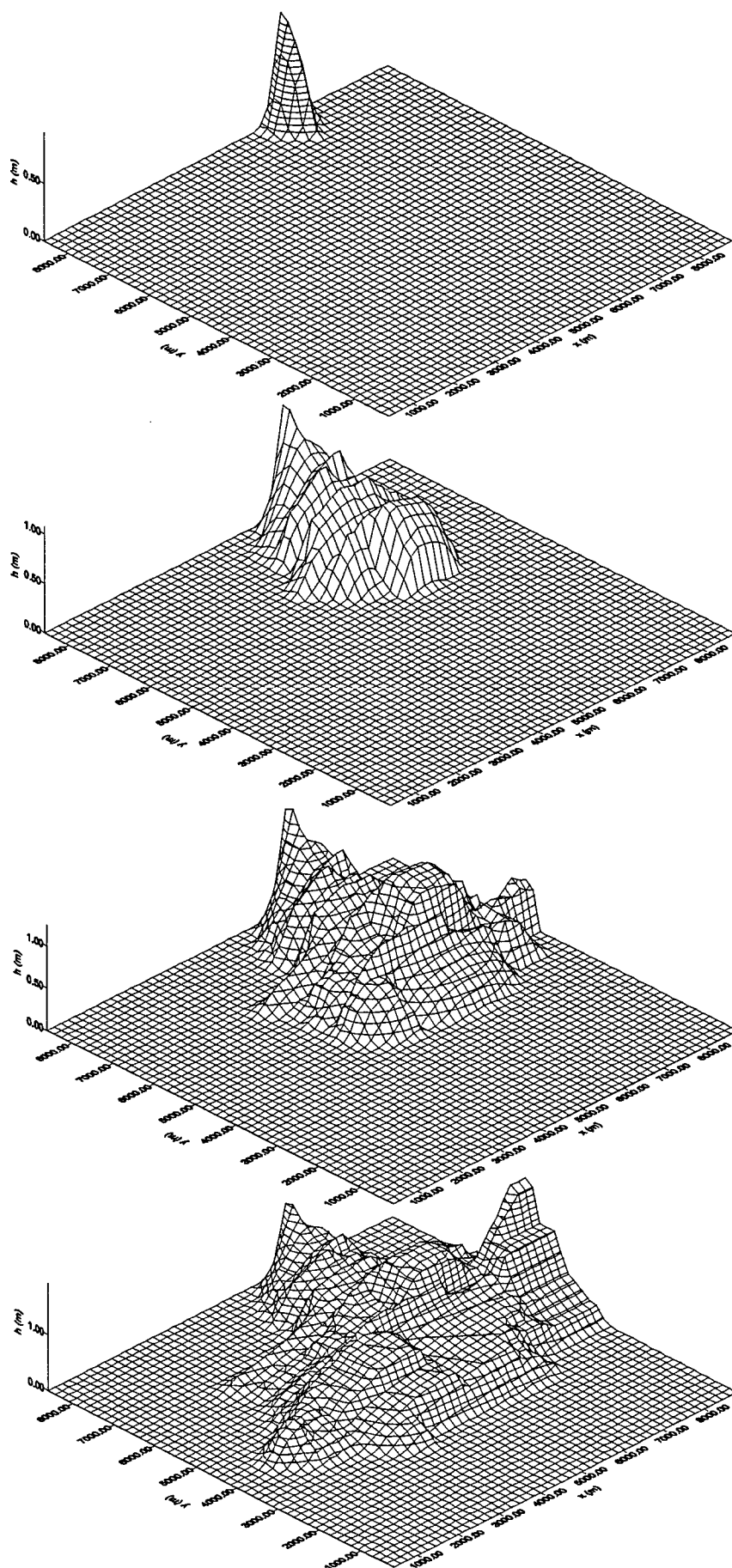


Fig.4.2.3a) Surface plot for run SR1. From top to bottom: $t=8h$, $t=10h$, $t=12h$ and $t=15h$ (x , y and z scale in meters).

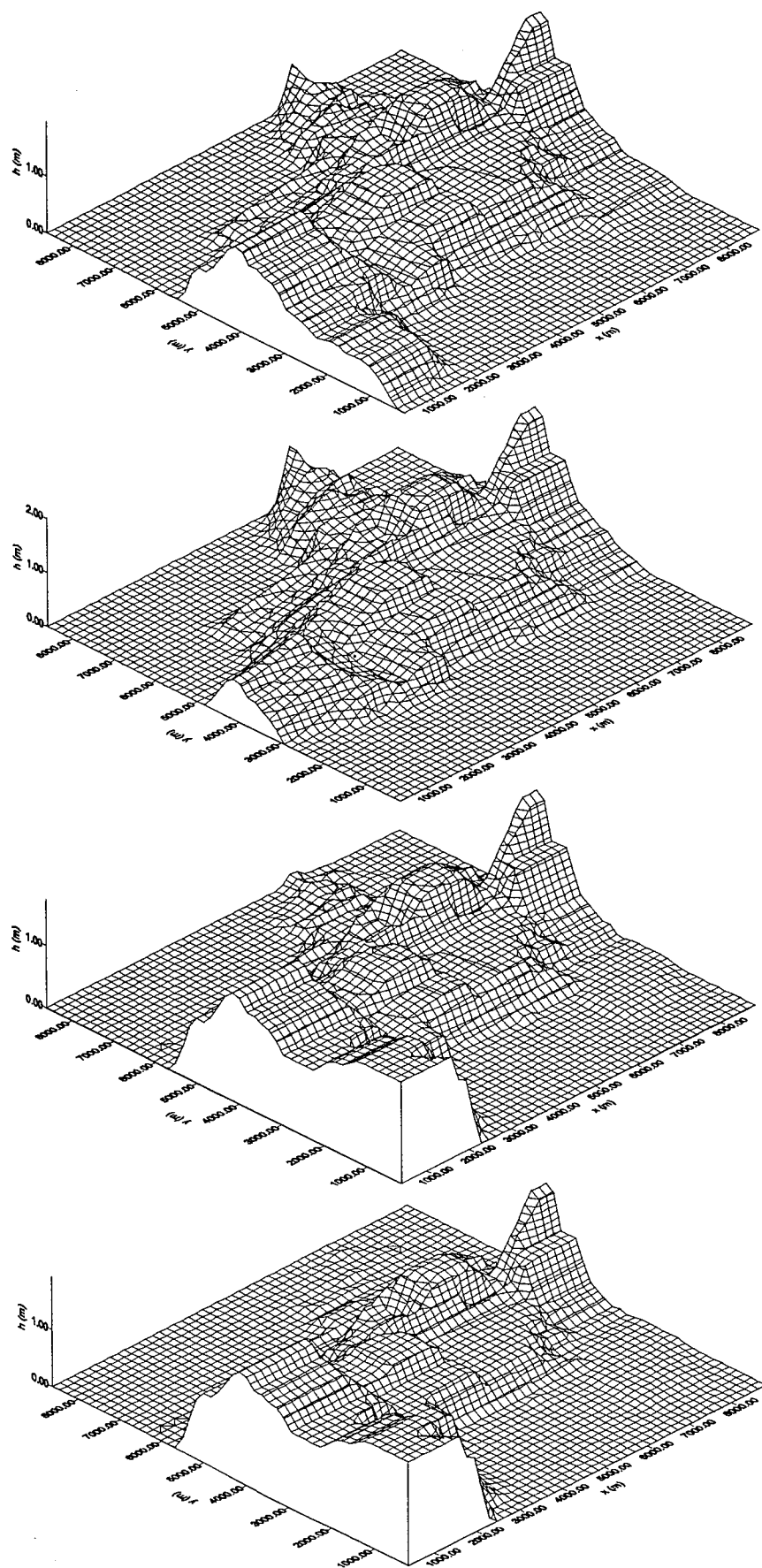


Fig.4.2.3b) Surface plot for run SR1. From top to bottom: $t=17\text{h}$, $t=20\text{h}$, $t=25\text{h}$ and $t=29\text{h}$ (x , y and z scale in meters).

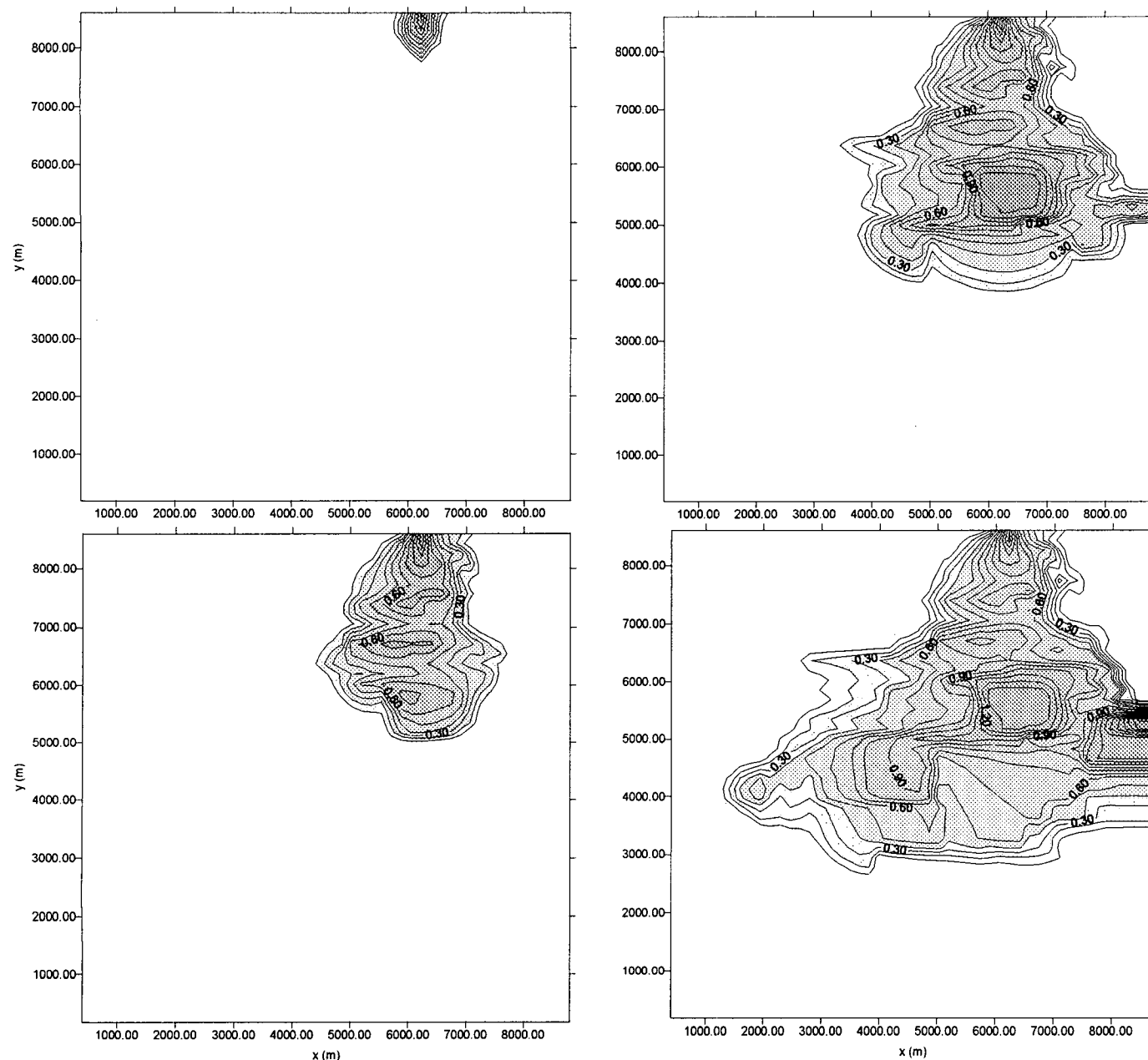


Fig.4.2.4a) Contour plot for run SR1. On the left: top $t=8h$, bottom $t=10h$;
on the right: top $t=12h$, bottom $t=15$ hours (scale in meter).

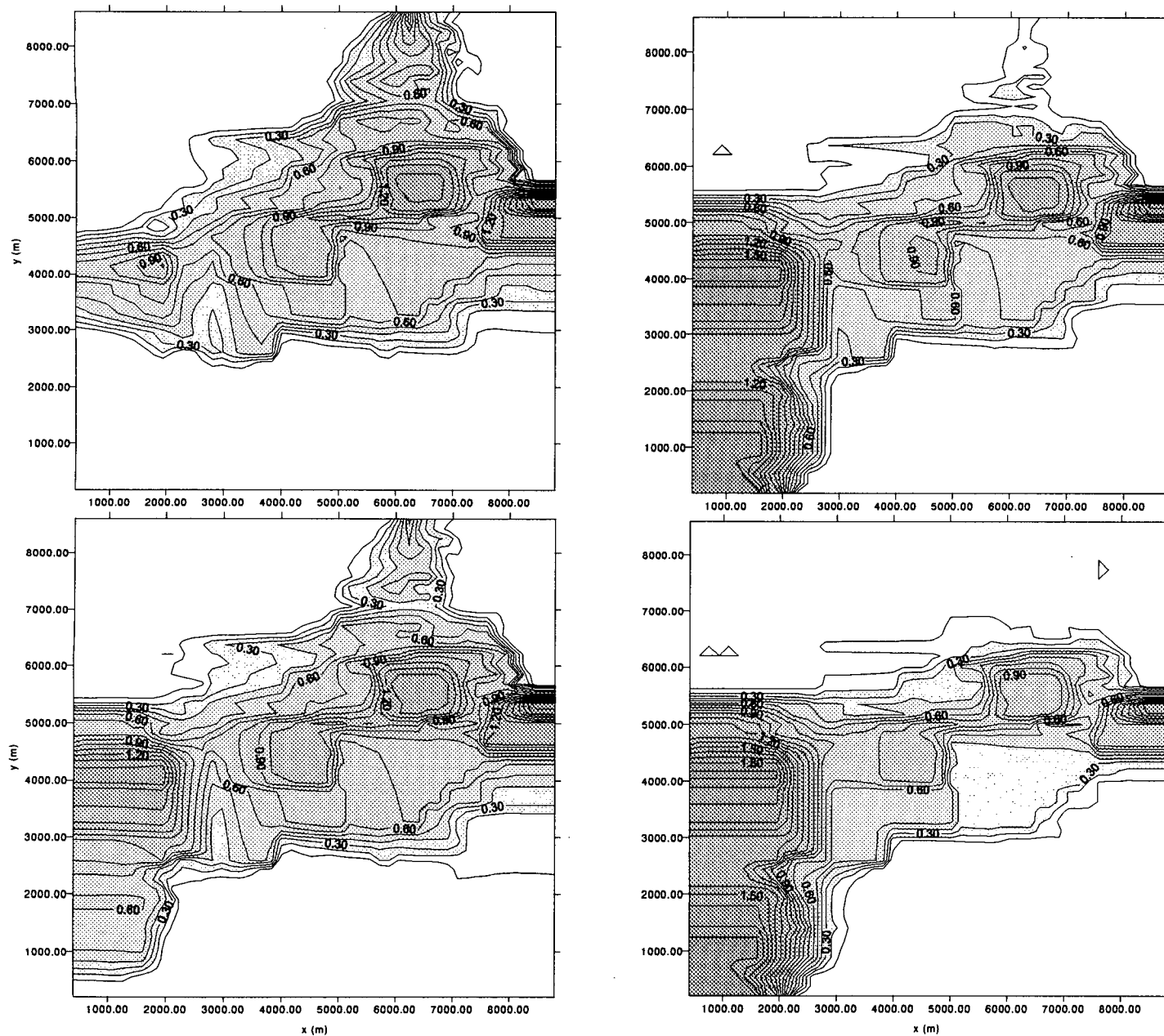


Fig.4.2.4b) Contour plot for run SR1. On the left: top t=17h, bottom t=20h; on the right: top t=25h, bottom t= 29 hours (scale in meter).

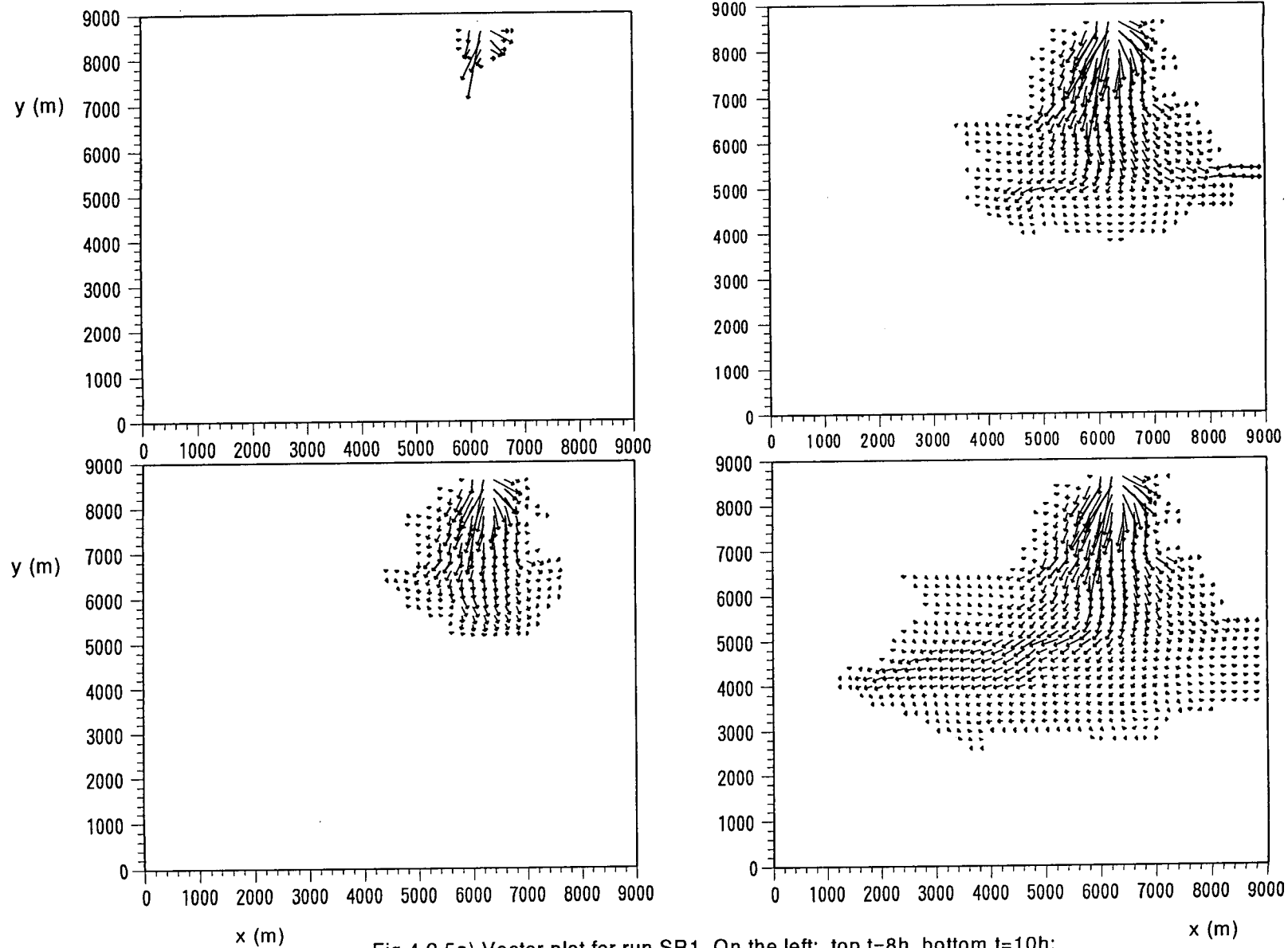


Fig.4.2.5a) Vector plot for run SR1. On the left: top $t=8\text{h}$, bottom $t=10\text{h}$; on the right: top $t=12\text{h}$, bottom $t=15\text{h}$. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

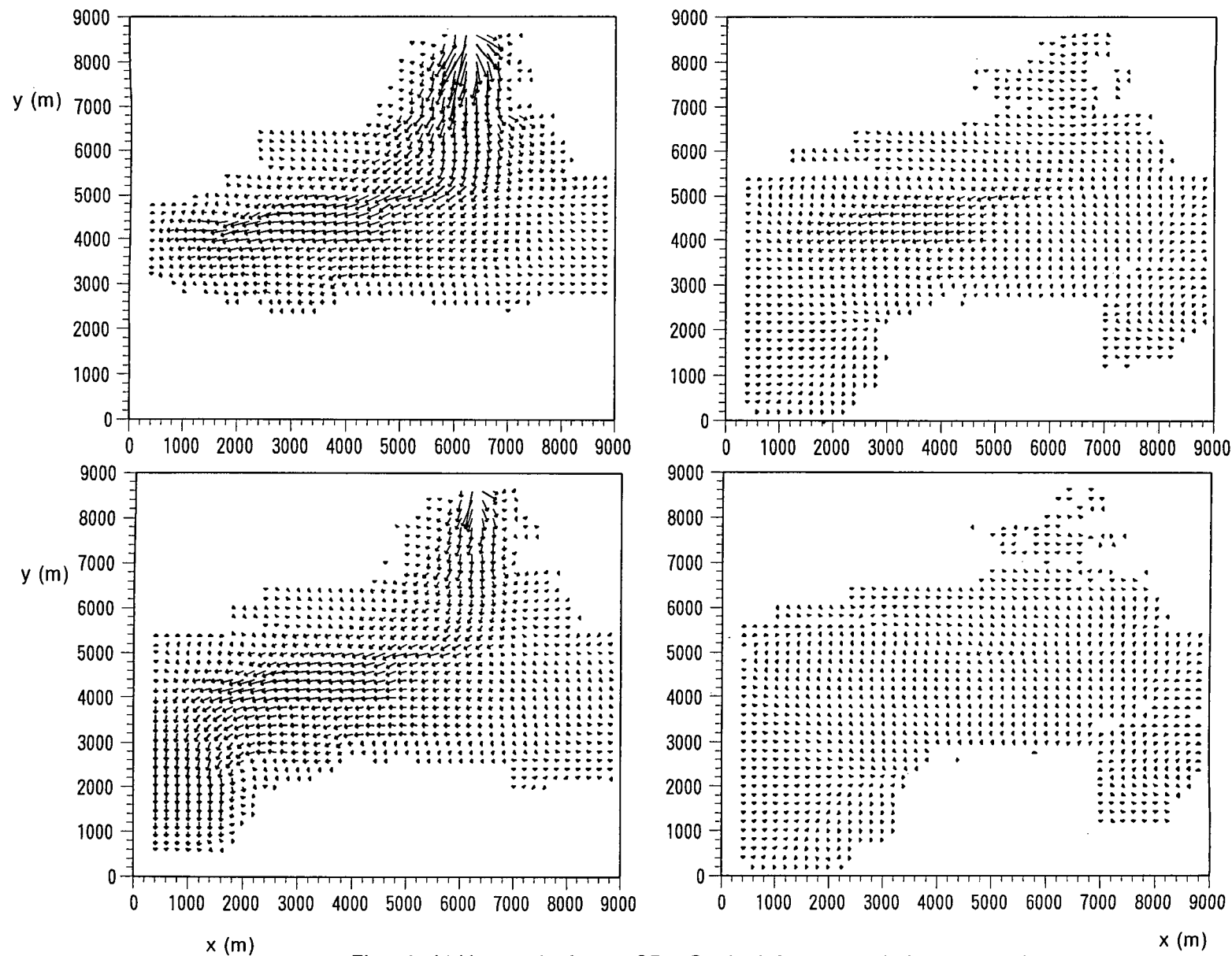


Fig.4.2.5b) Vector plot for run SR1. On the left: top $t=17h$, bottom $t=20h$; on the right: top $t=25h$, bottom $t=29h$. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

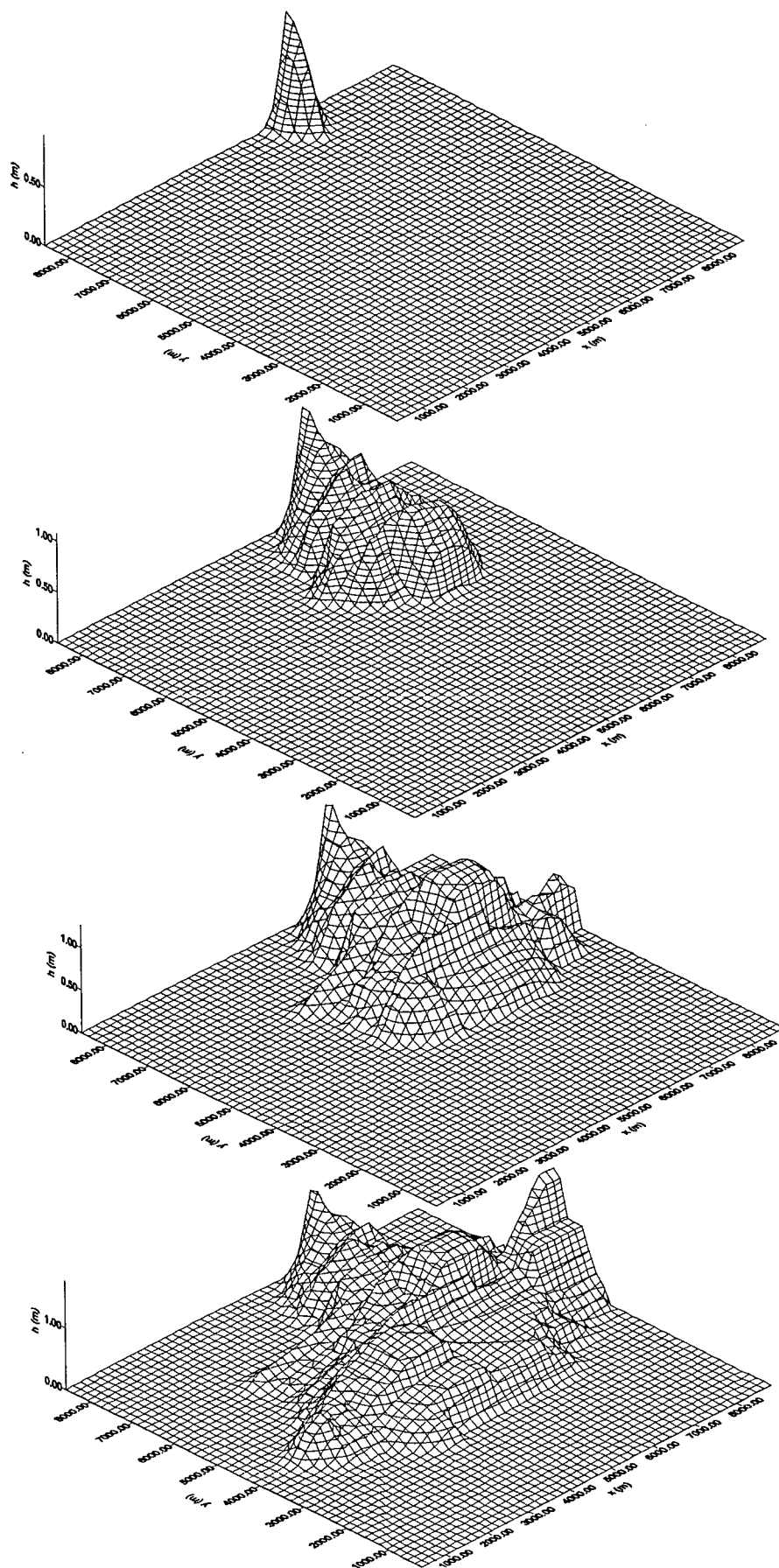


Fig.4.2.6a) Surface plot for run SR2. From top to bottom: $t=8h$, $t=10h$, $t=12h$ and $t=15$ hours (x , y and z scale in meters).

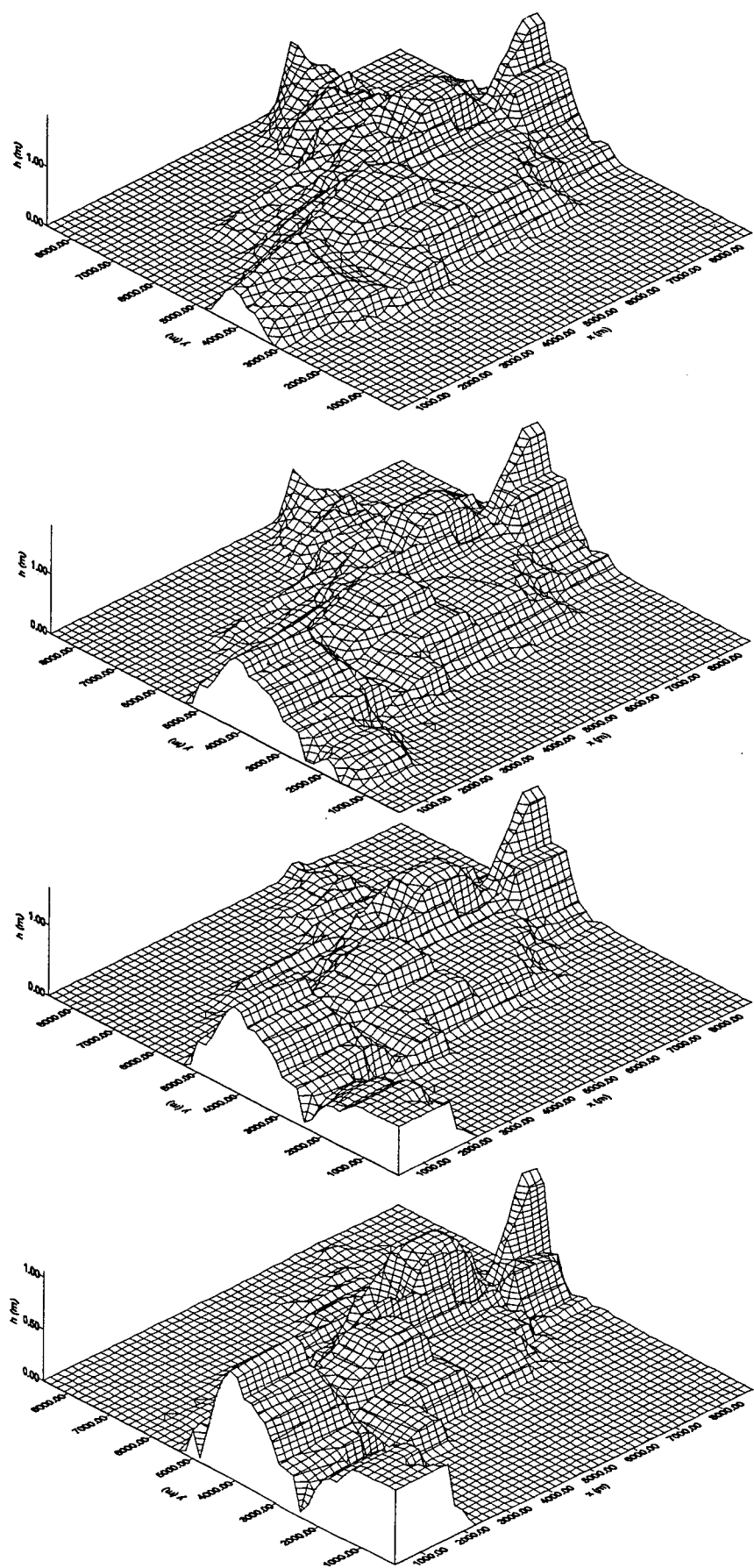


Fig.4.2.6b) Surface plot for run SR2. From top to bottom: $t=17h$, $t=20h$, $t=25h$ and $t=29$ hours (x , y and z scale in meters).

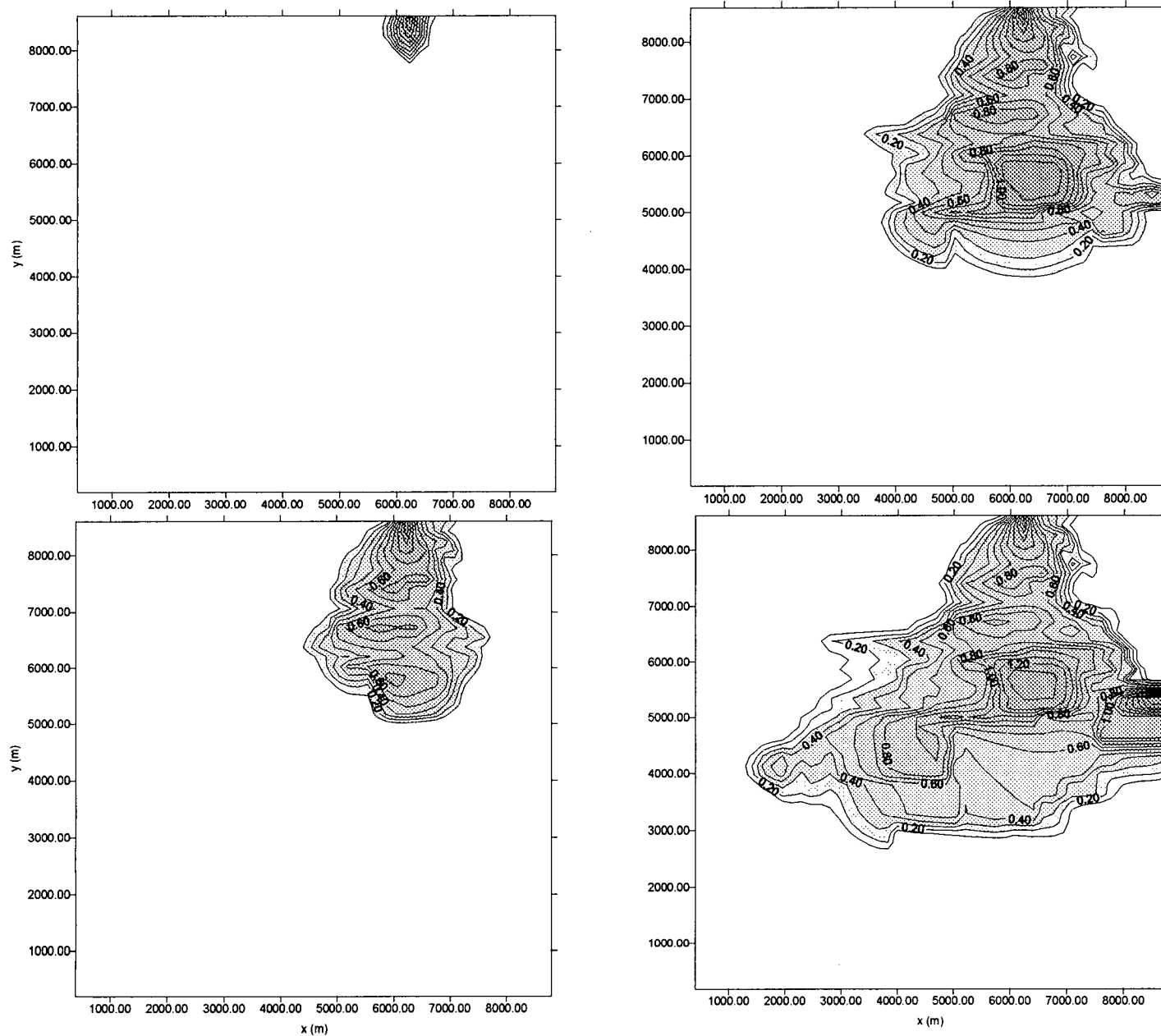


Fig.4.2.7a) Contour plot for run SR2. On the left: top $t=8h$, bottom $t=10h$; on the right: top $t=12h$, bottom $t=15h$ (scale in meter).

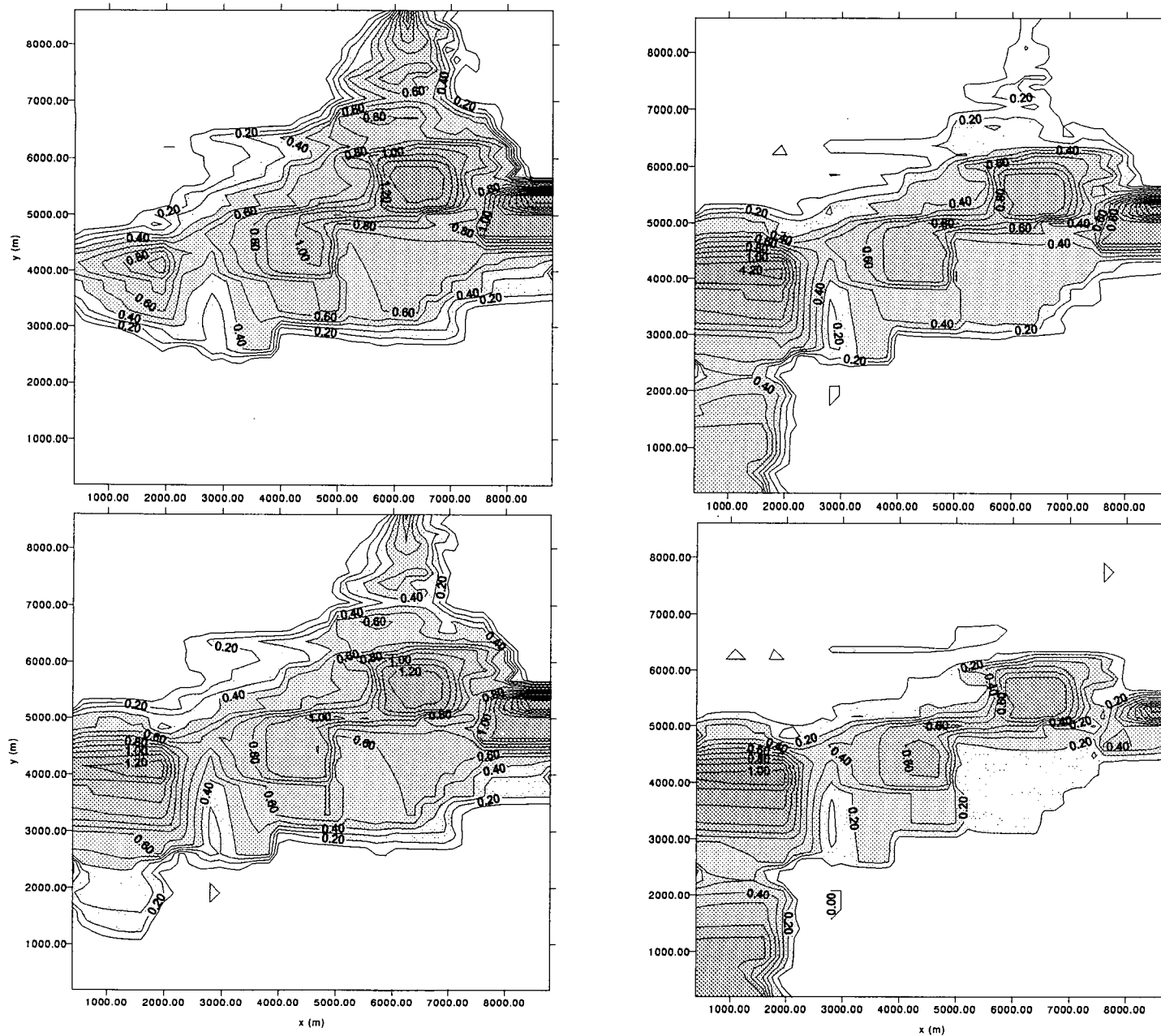


Fig.4.2.7b) Contour plot for run SR2. On the left: top t=17h, bottom t=20h; on the right: top t=25h, bottom t= 29 hours (scale in meter).

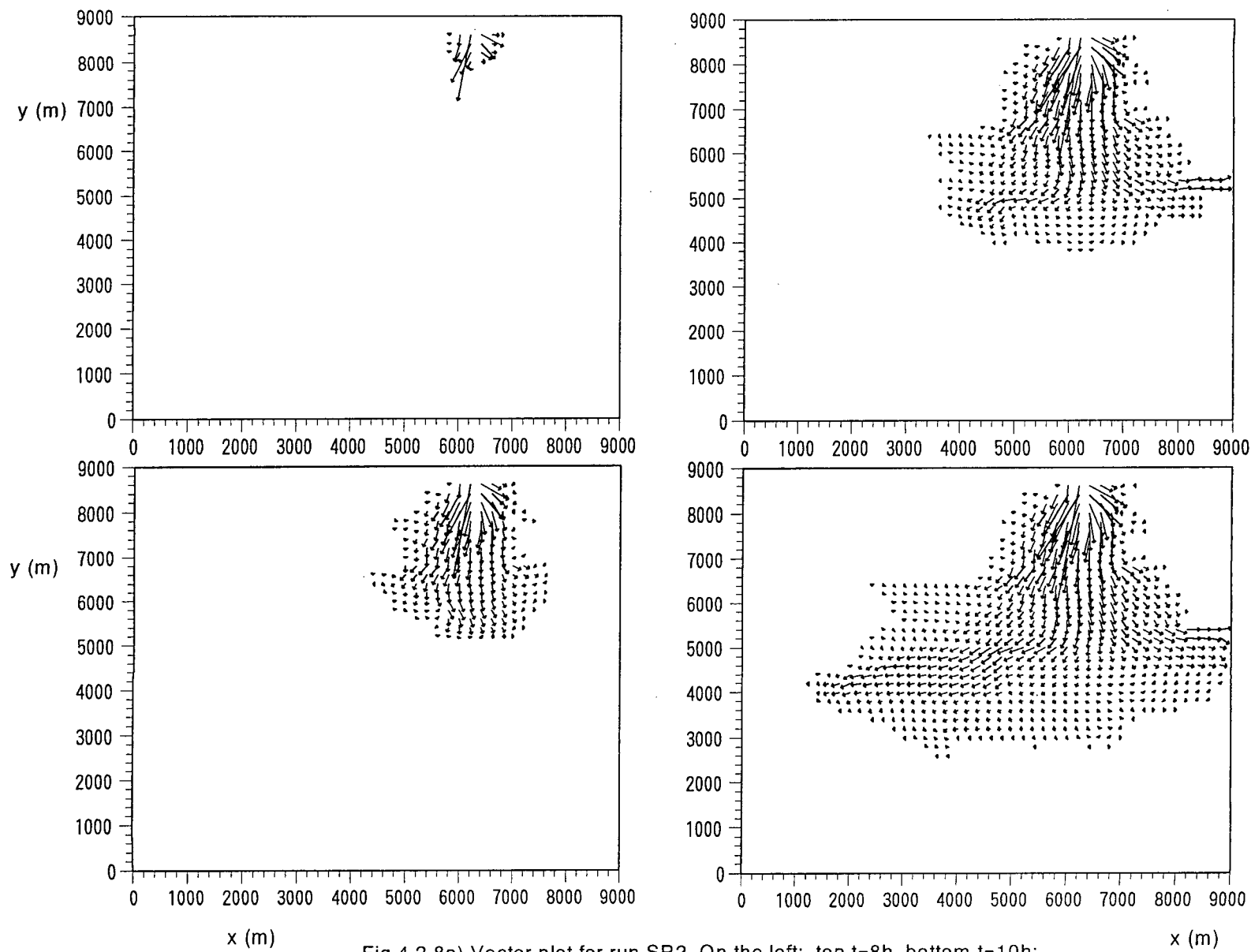


Fig.4.2.8a) Vector plot for run SR2. On the left: top $t=8h$, bottom $t=10h$; on the right: top $t=12h$, bottom $t=15$ hours. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

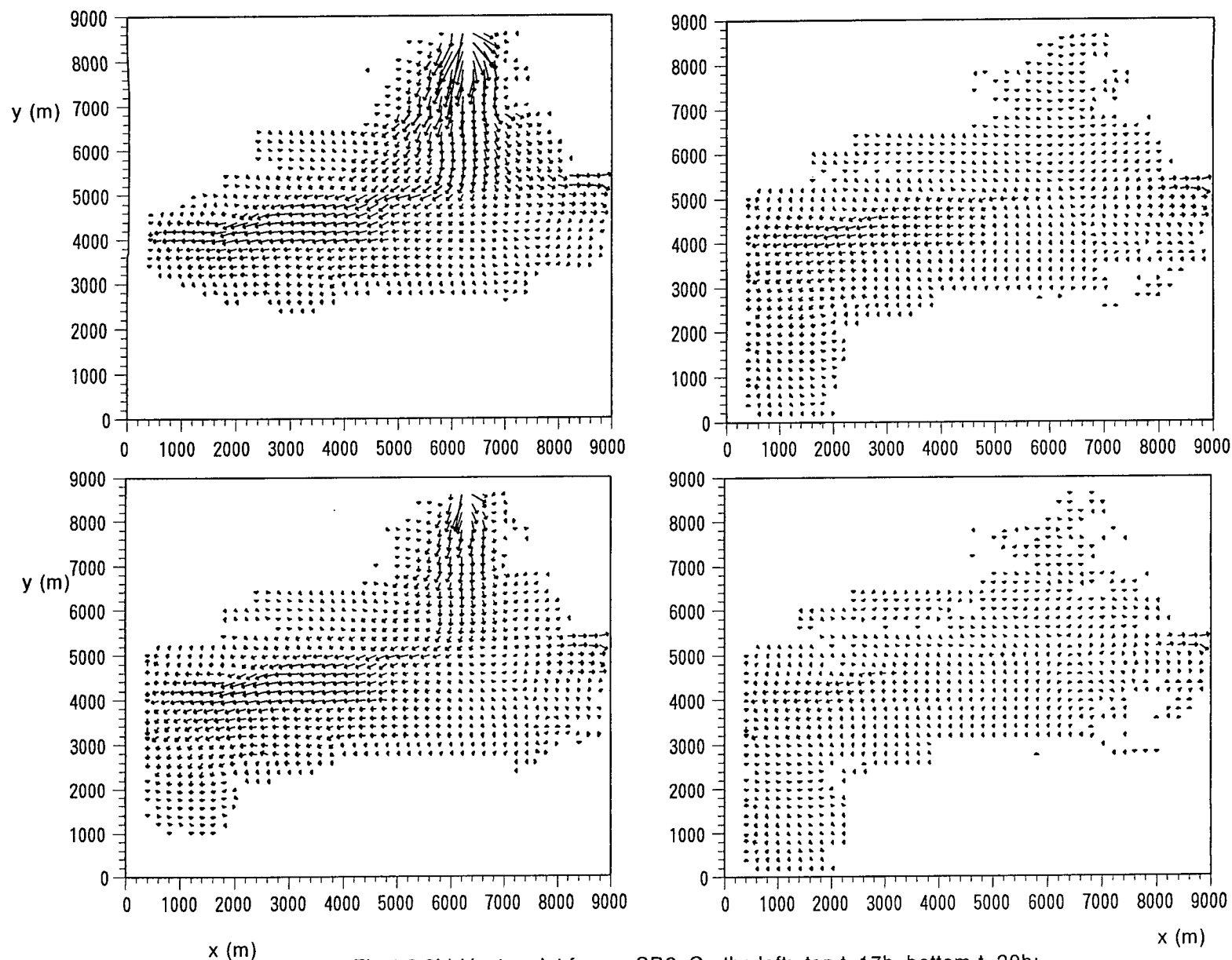


Fig.4.2.8b) Vector plot for run SR2. On the left: top $t=17h$, bottom $t=20h$; on the right: top $t=25h$, bottom $t=29$ hours. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

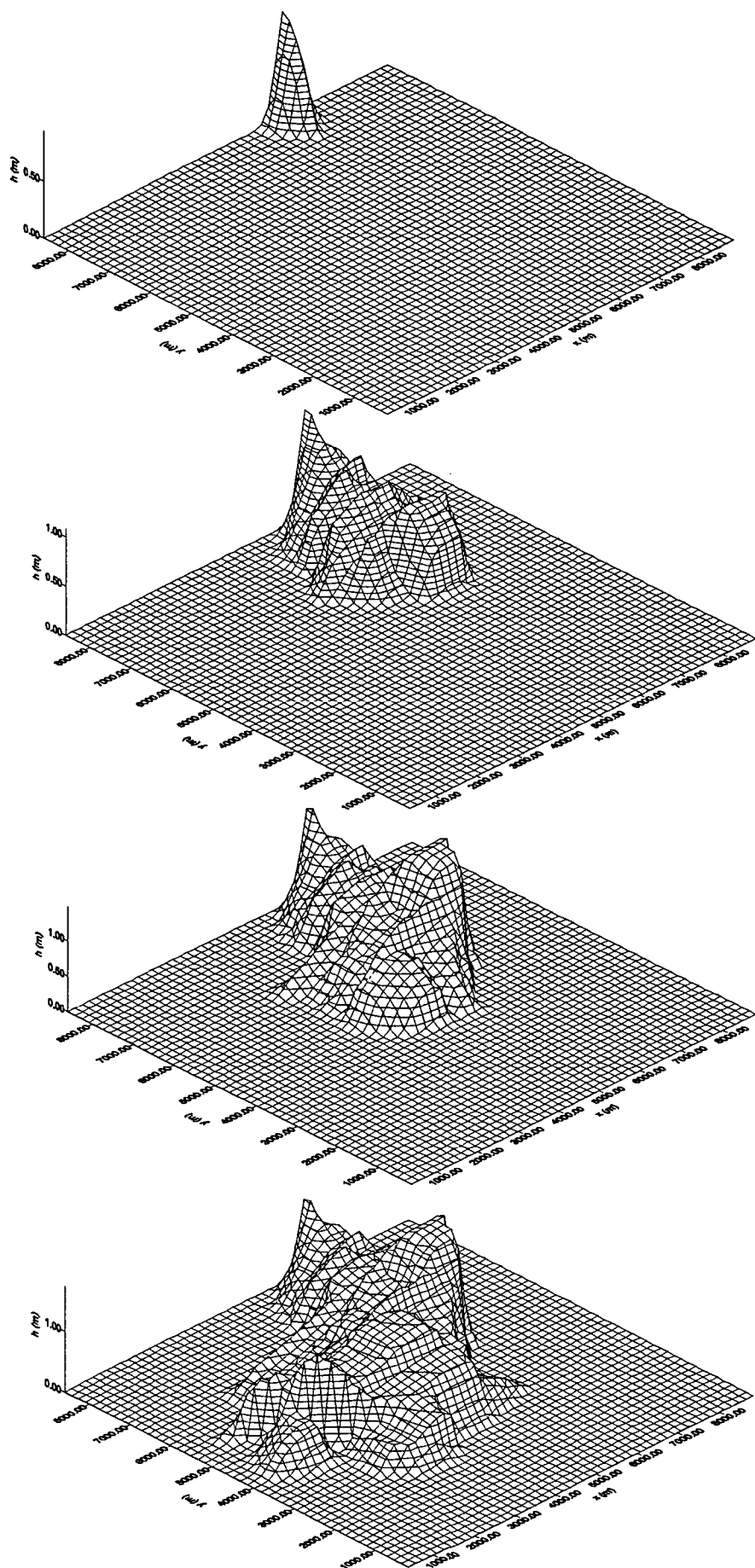


Fig.4.2.9a) Surface plot for run SR3. From top to bottom: $t=8h$, $t=10h$, $t=12h$ and $t=15h$ hours (x , y and z scale in meters).

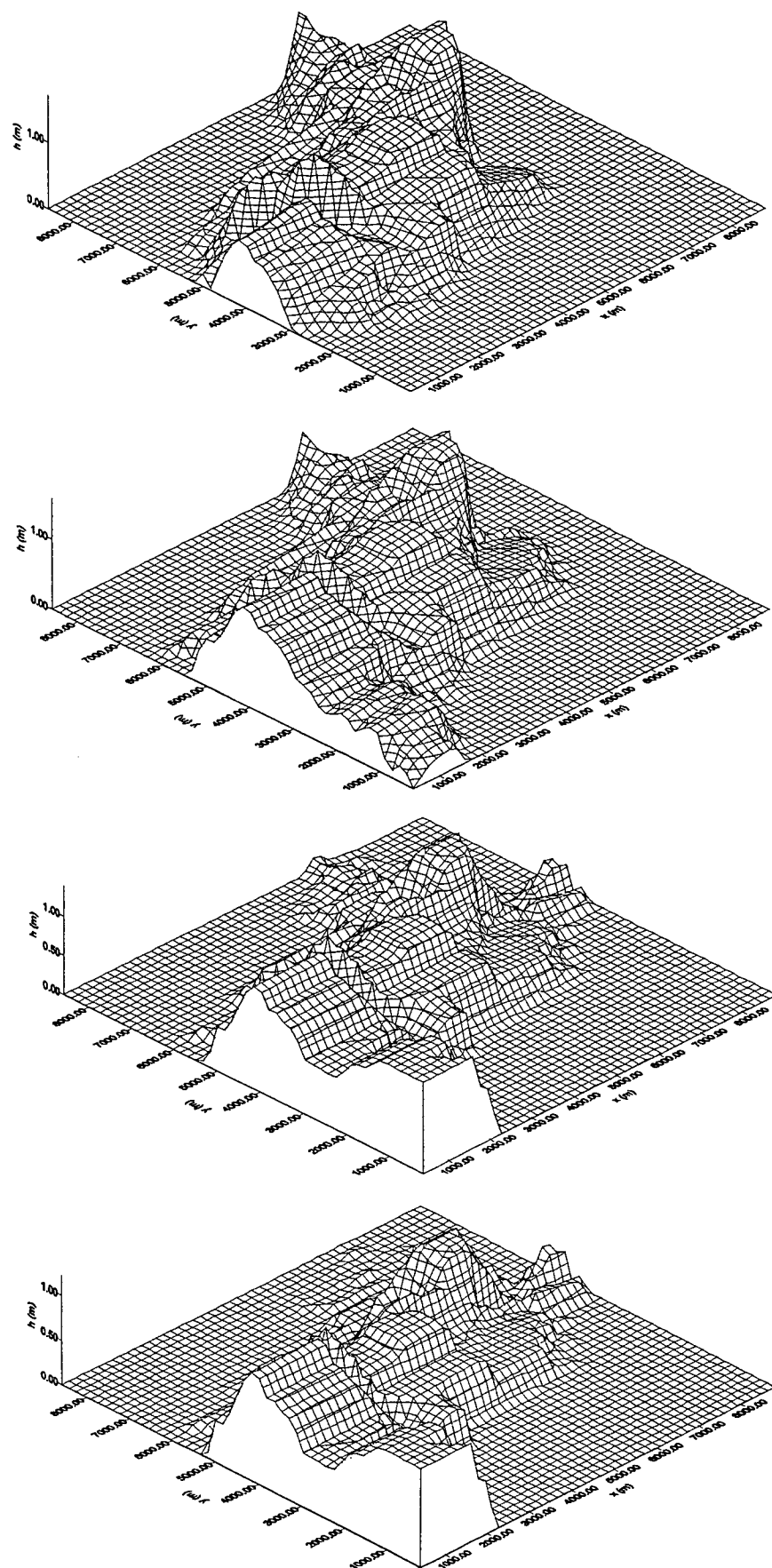


Fig.4.2.9b) Surface plot for run SR3. From top to bottom: $t=17h$, $t=20h$, $t=25h$ and $t=29h$ (x, y and z scale in meters).

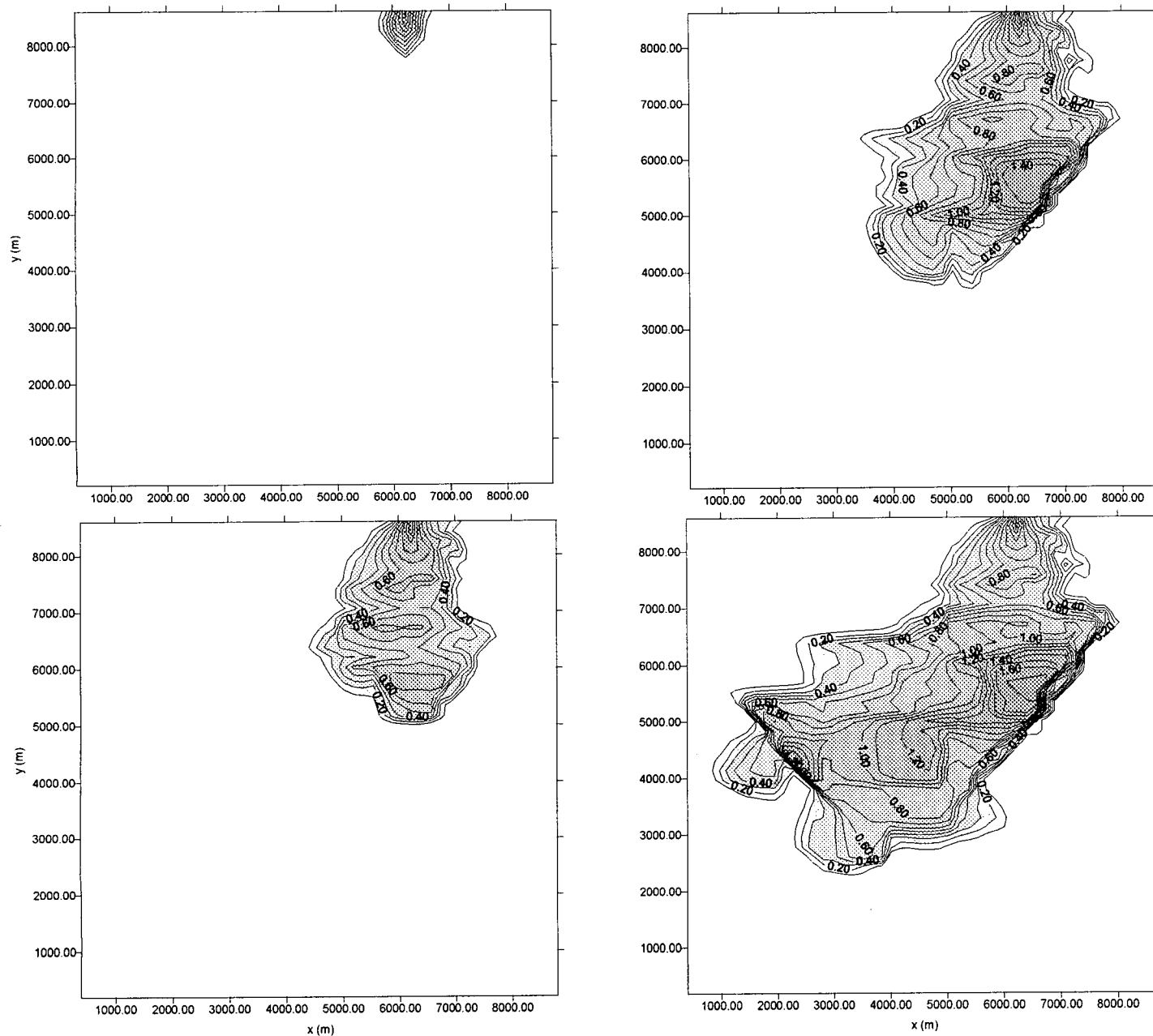


Fig.4.2.10a) Contour plot for run SR3. On the left: top $t=8h$, bottom $t=10h$; on the right: top $t=12h$, bottom $t=15h$ (scale in meter).

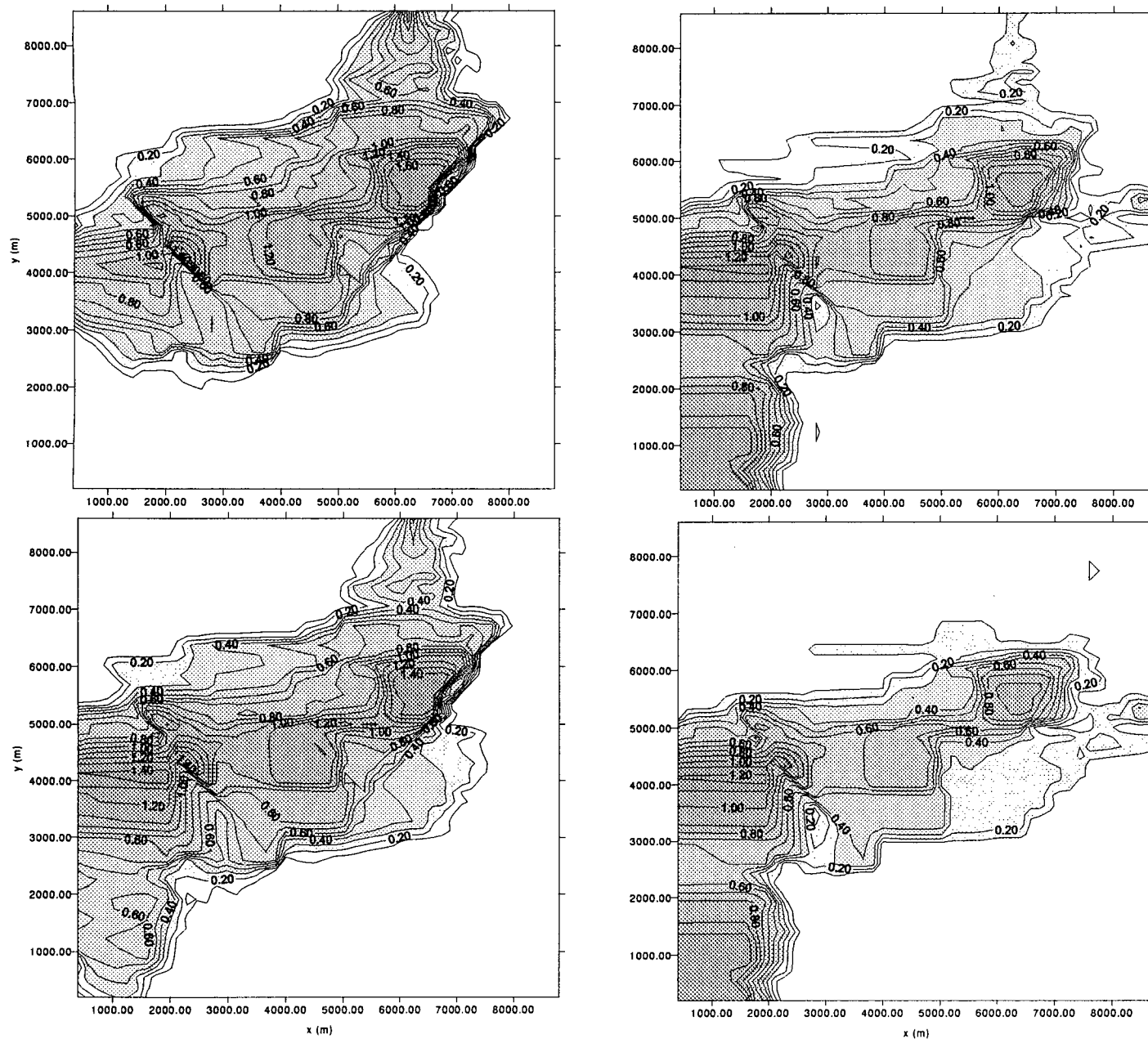


Fig.4.2.10b) Contour plot for run SR3. On the left: top t=17h, bottom t=20h; on the right: top t=25h, bottom t= 29 hours (scale in meter).

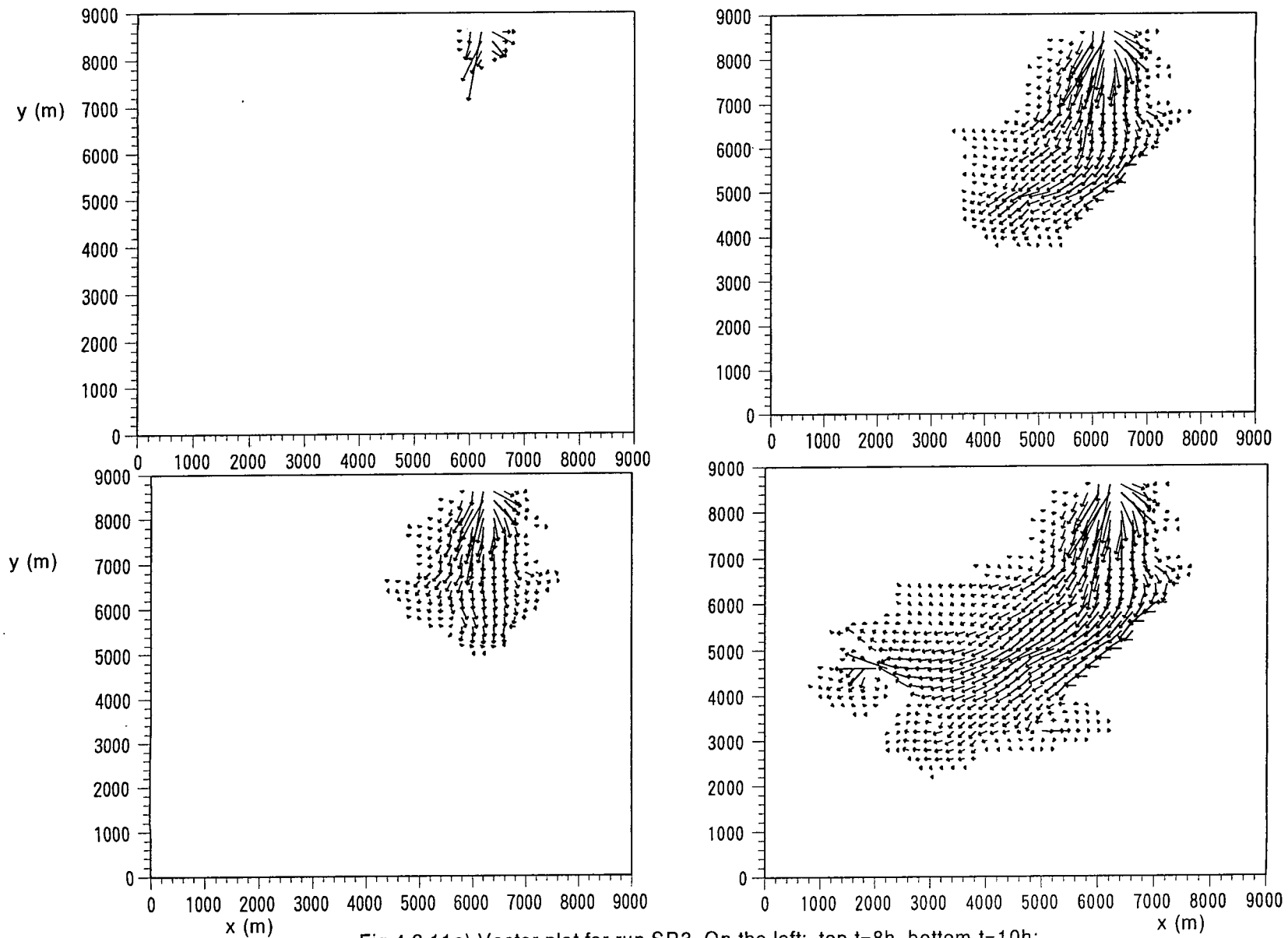


Fig.4.2.11 a) Vector plot for run SR3. On the left: top $t=8h$, bottom $t=10h$; on the right: top $t=12h$, bottom $t=15$ hours. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

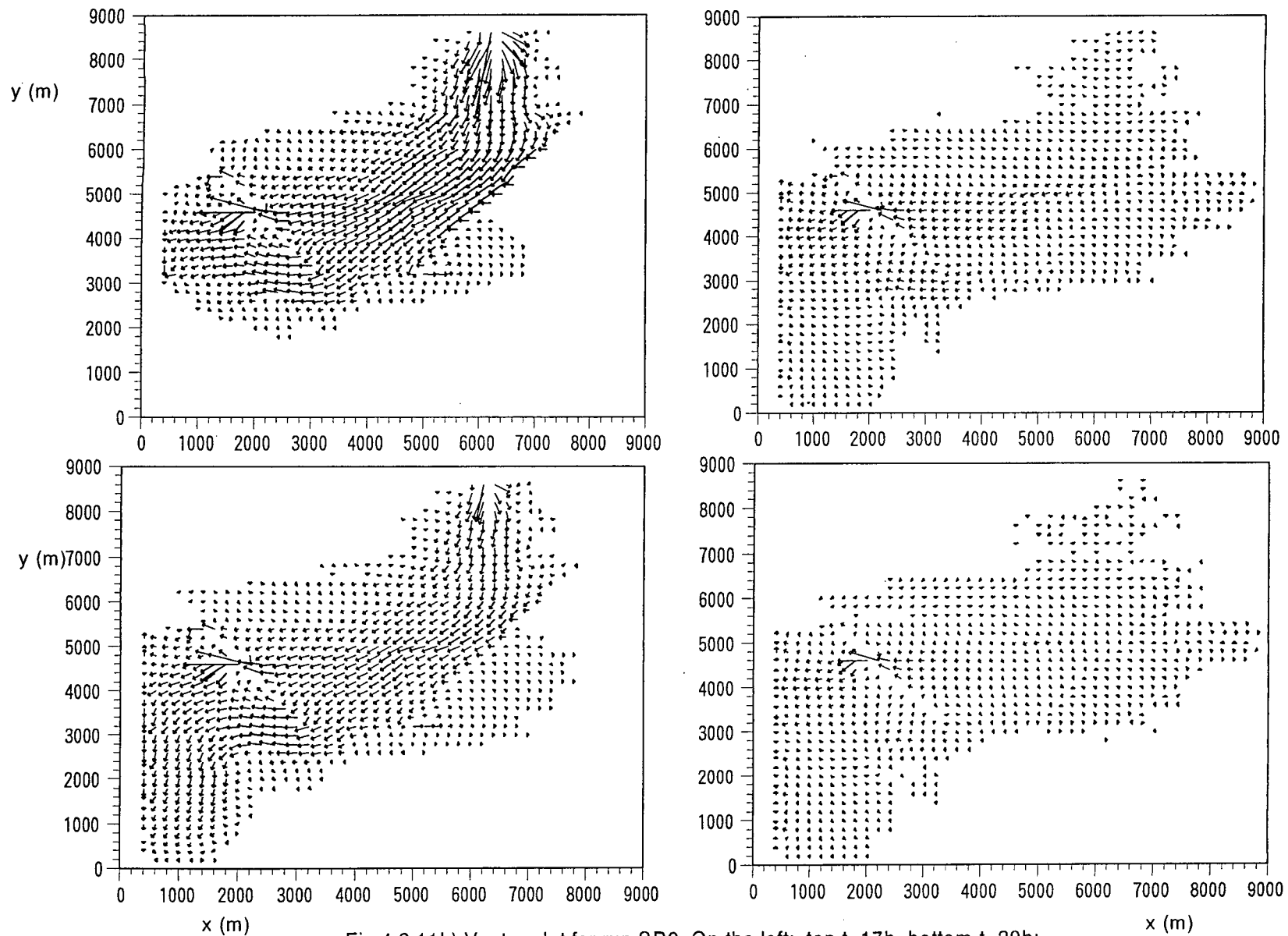


Fig.4.2.11b) Vector plot for run SR3. On the left: top $t=17\text{h}$, bottom $t=20\text{h}$; on the right: top $t=25\text{h}$, bottom $t=29\text{h}$. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

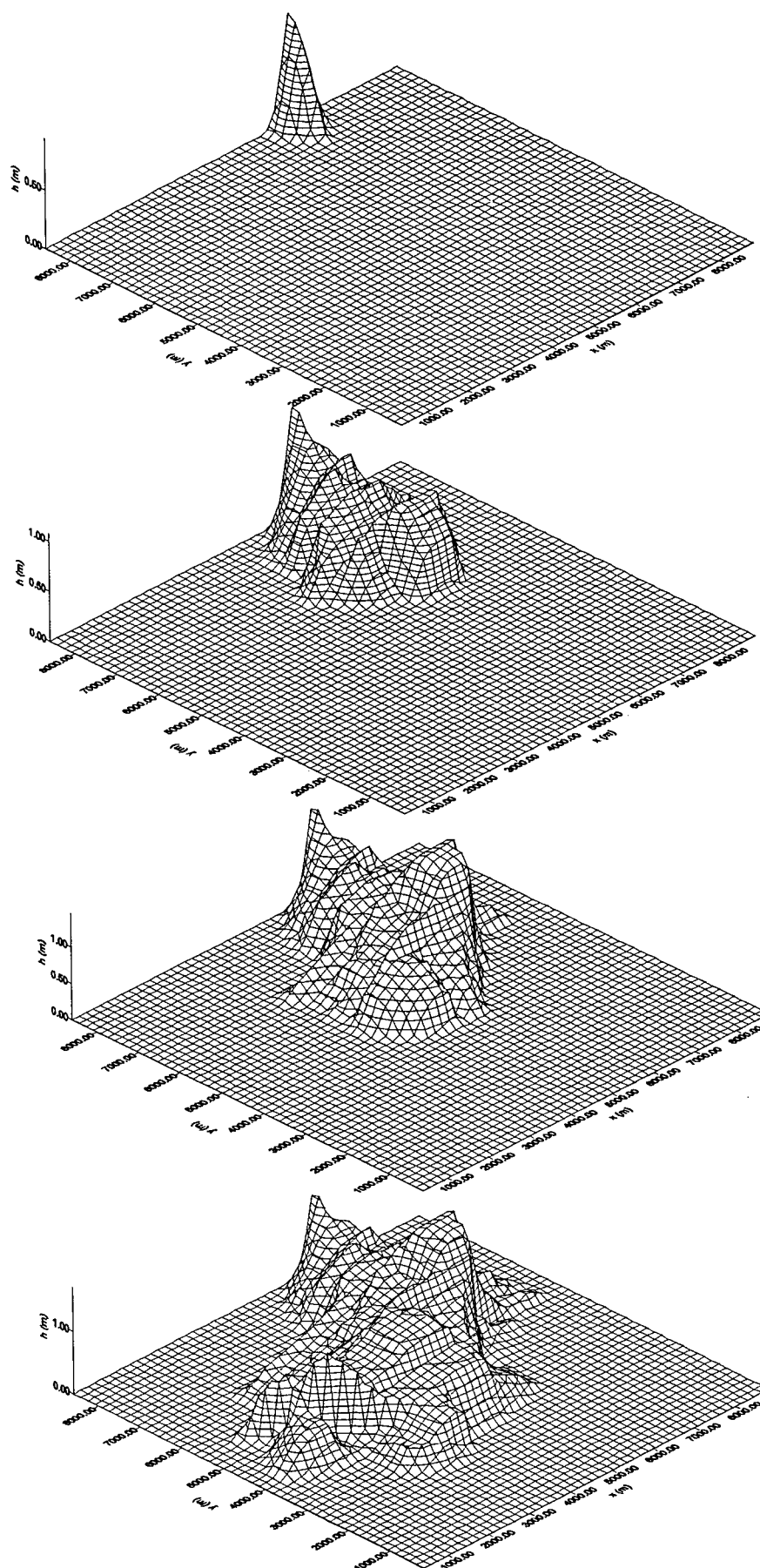


Fig.4.2.12a) Surface plot for run SR4. From top to bottom: $t=8h$, $t=10h$, $t=12h$ and $t=15$ hours (x , y and z scale in meters).

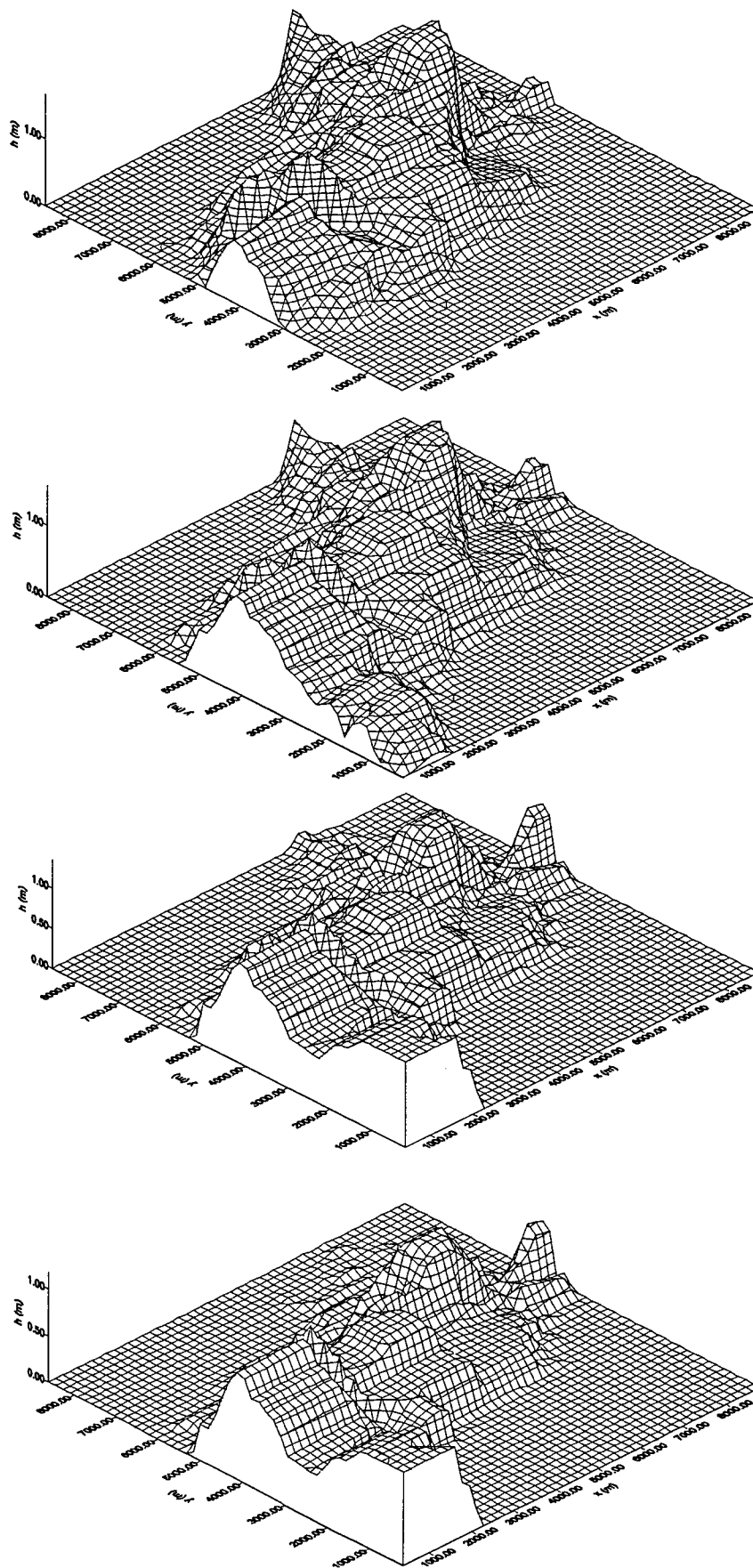


Fig.4.2.12b) Surface plot for run SR4. From top to bottom: $t=17h$, $t=20h$, $t=25h$ and $t=29$ hours (x , y and z scale in meters).

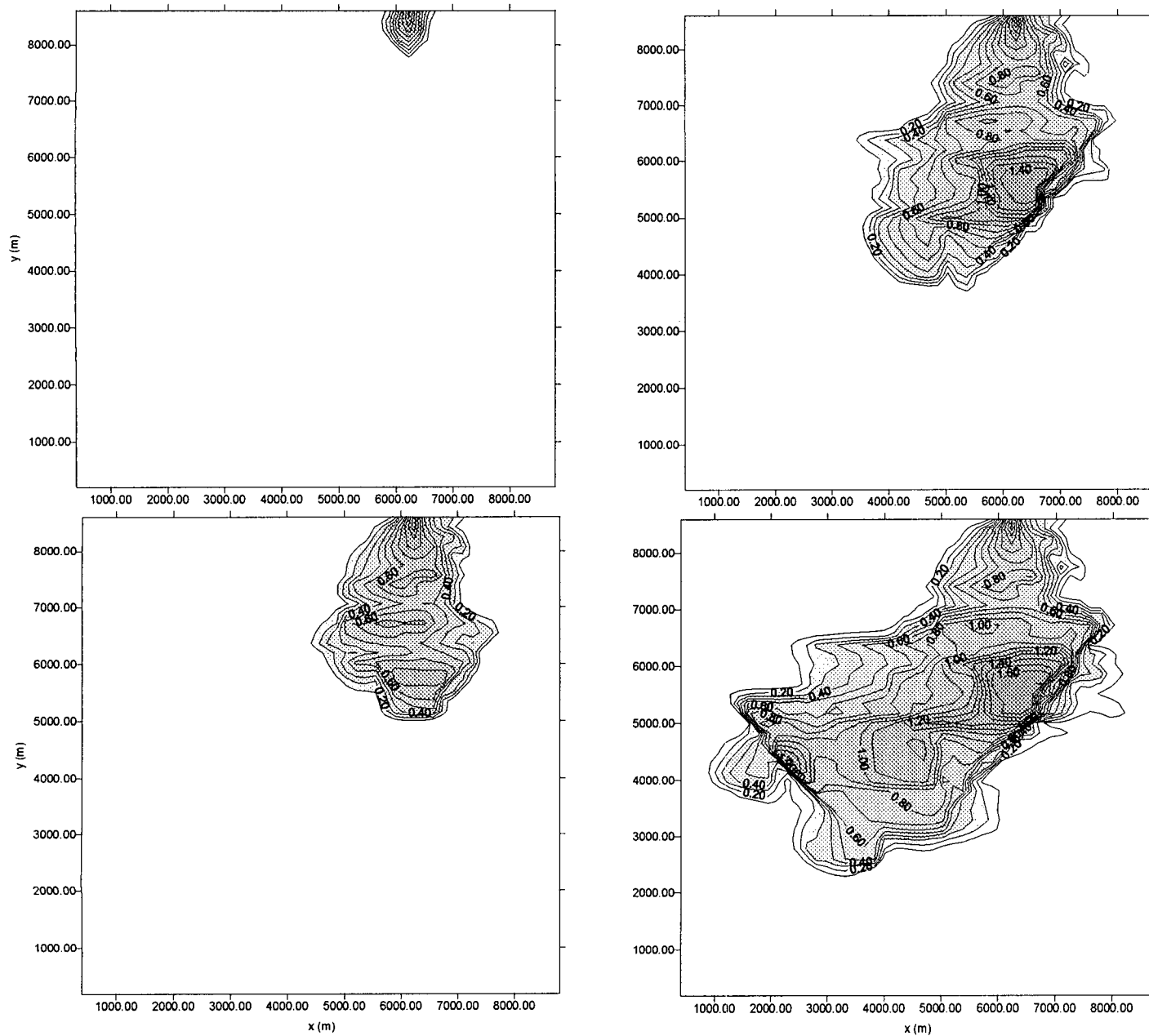


Fig.4.2.13a) Contour plot for run SR4. On the left: top $t=8h$, bottom $t=10h$;
on the right: top $t=12h$, bottom $t=15$ hours (scale in meter).

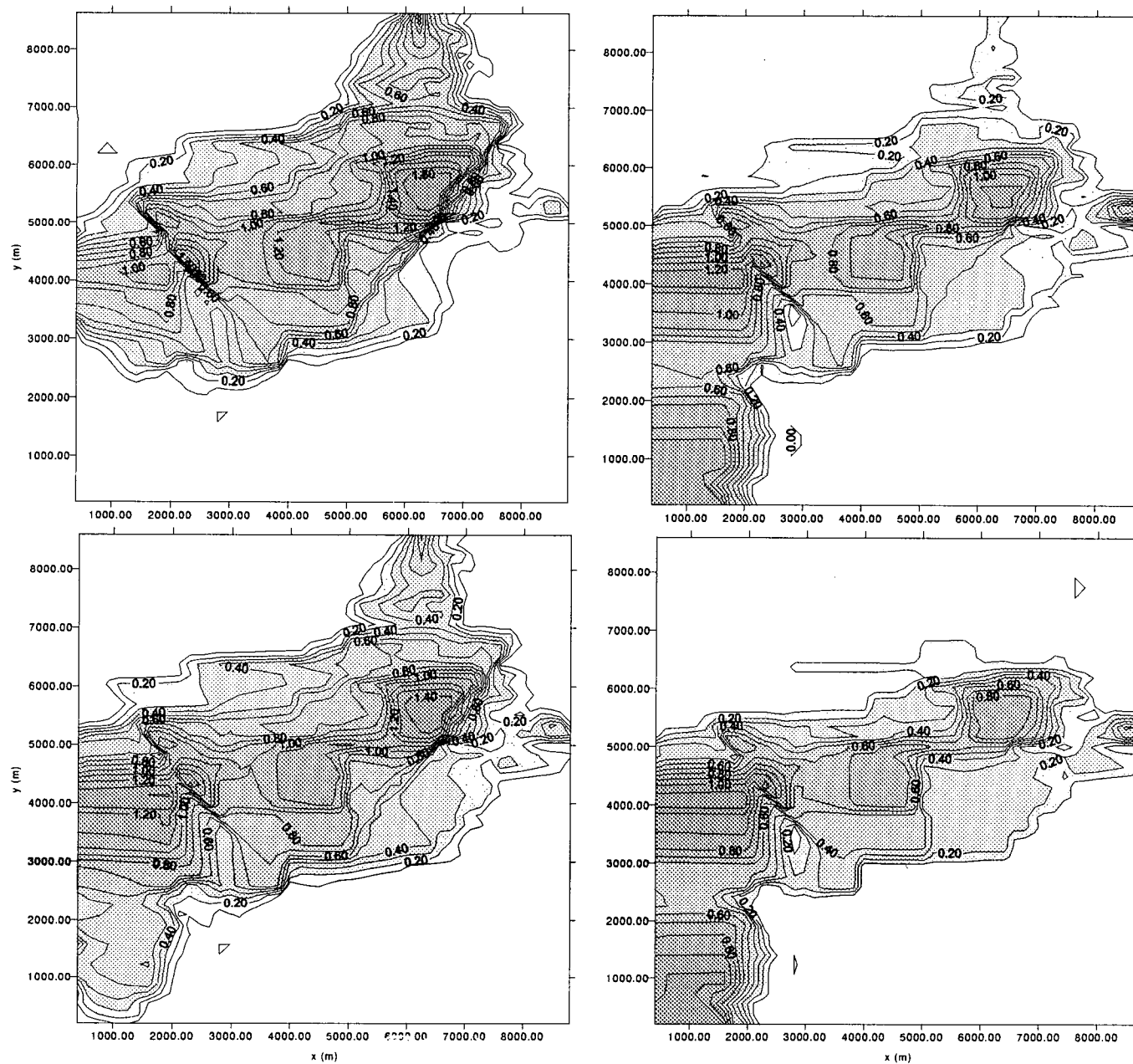


Fig.4.2.13b) Contour plot for run SR4. On the left: top t=17h, bottom t=20h; on the right: top t=25h, bottom t= 29 hours (scale in meter).

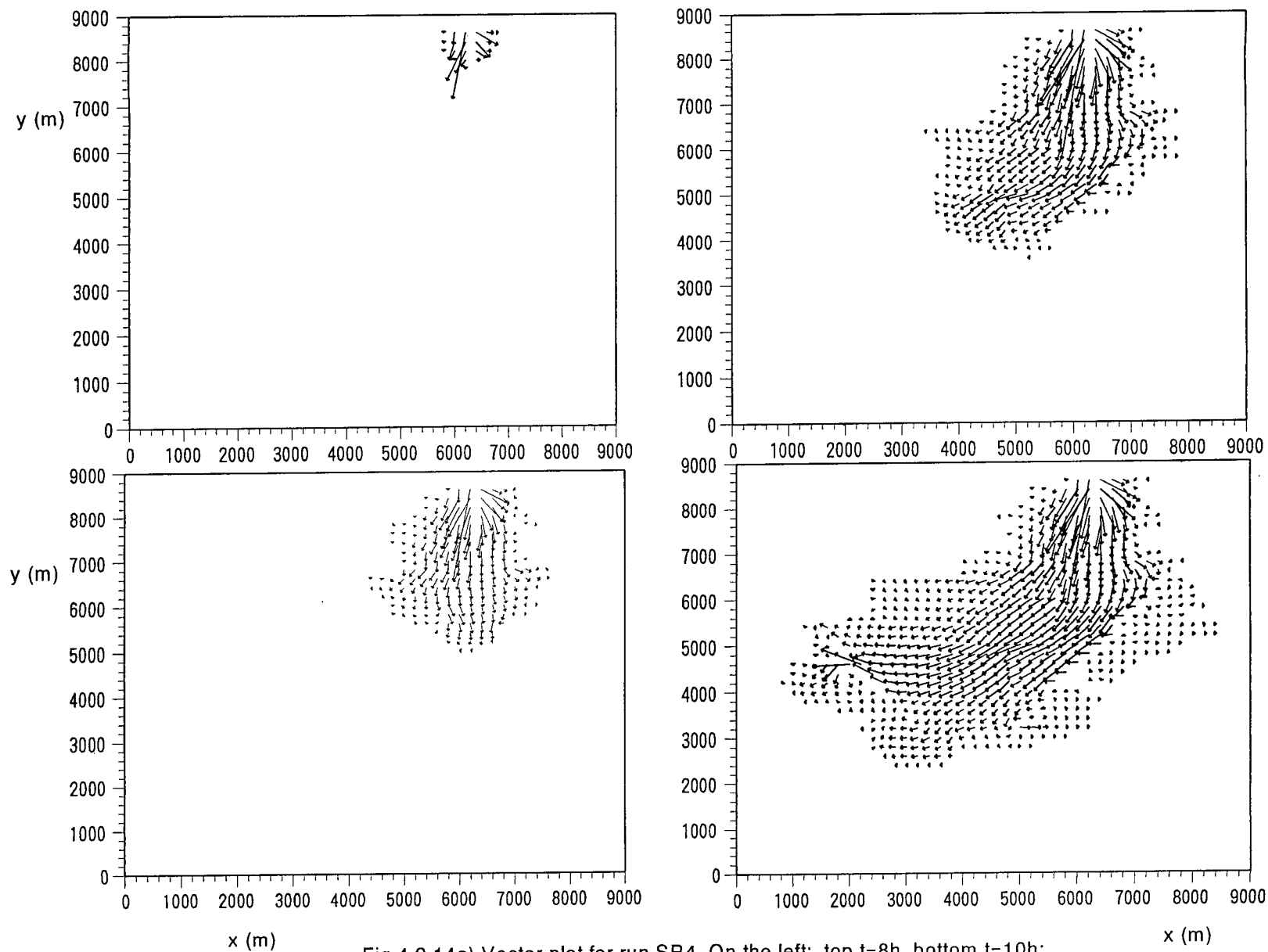


Fig.4.2.14a) Vector plot for run SR4. On the left: top $t=8h$, bottom $t=10h$; on the right: top $t=12h$, bottom $t=15$ hours. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

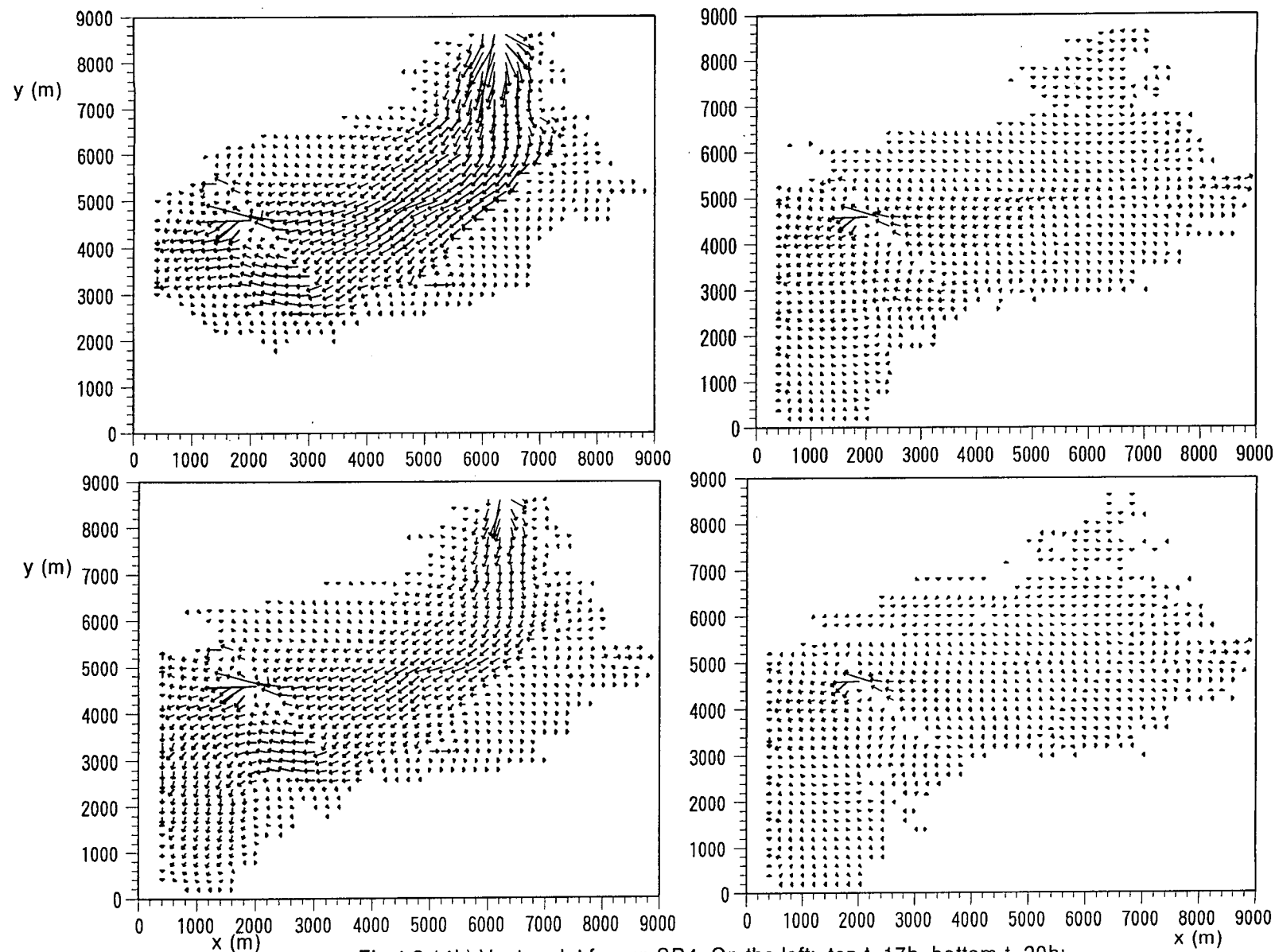


Fig.4.2.14b) Vector plot for run SR4. On the left: top $t=17h$, bottom $t=20h$; on the right: top $t=25h$, bottom $t=29h$. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

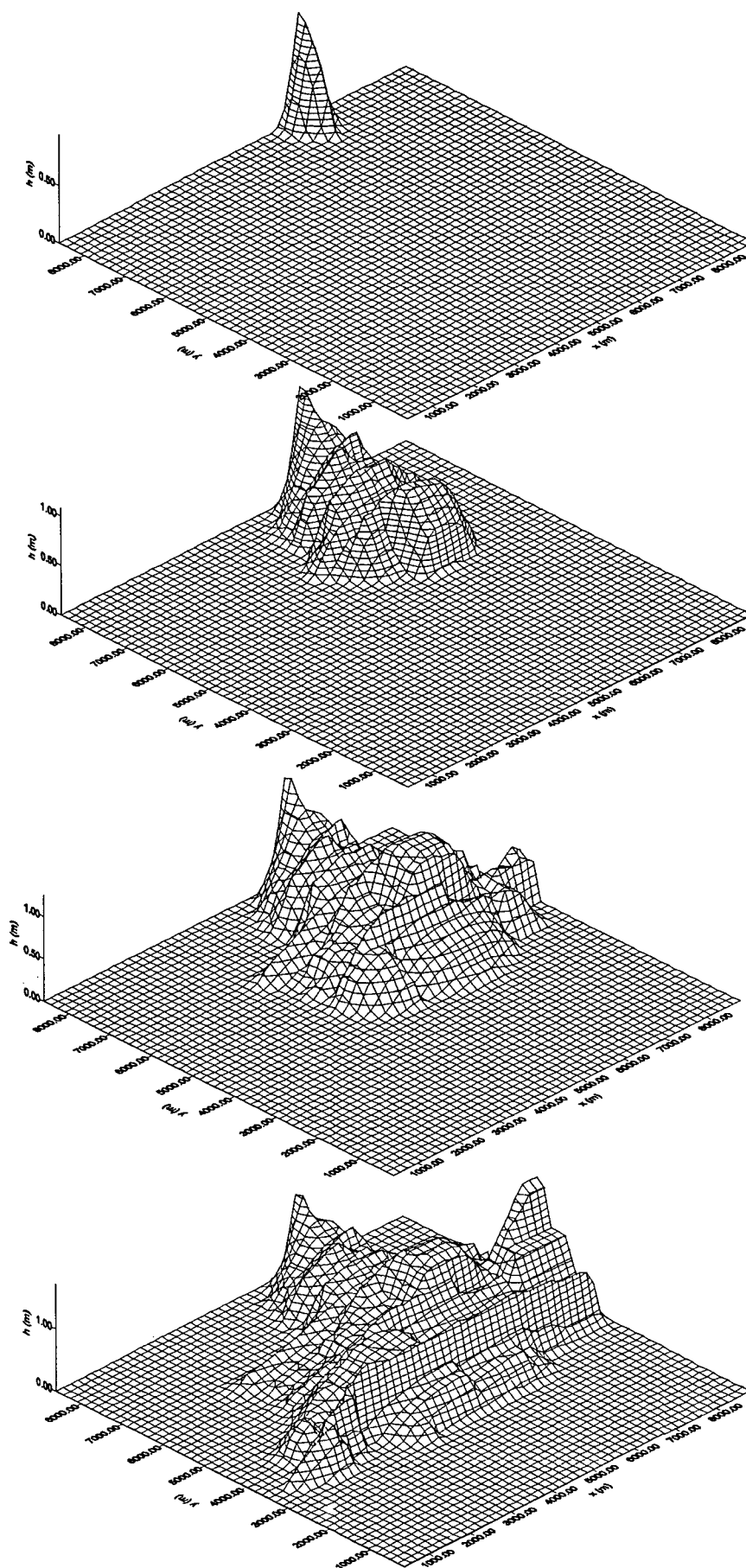


Fig.4.2.15a) Surface plot for run SR5. From top to bottom: $t=8\text{h}$, $t=10\text{h}$, $t=12\text{h}$ and $t=15\text{h}$ (x , y and z scale in meters).

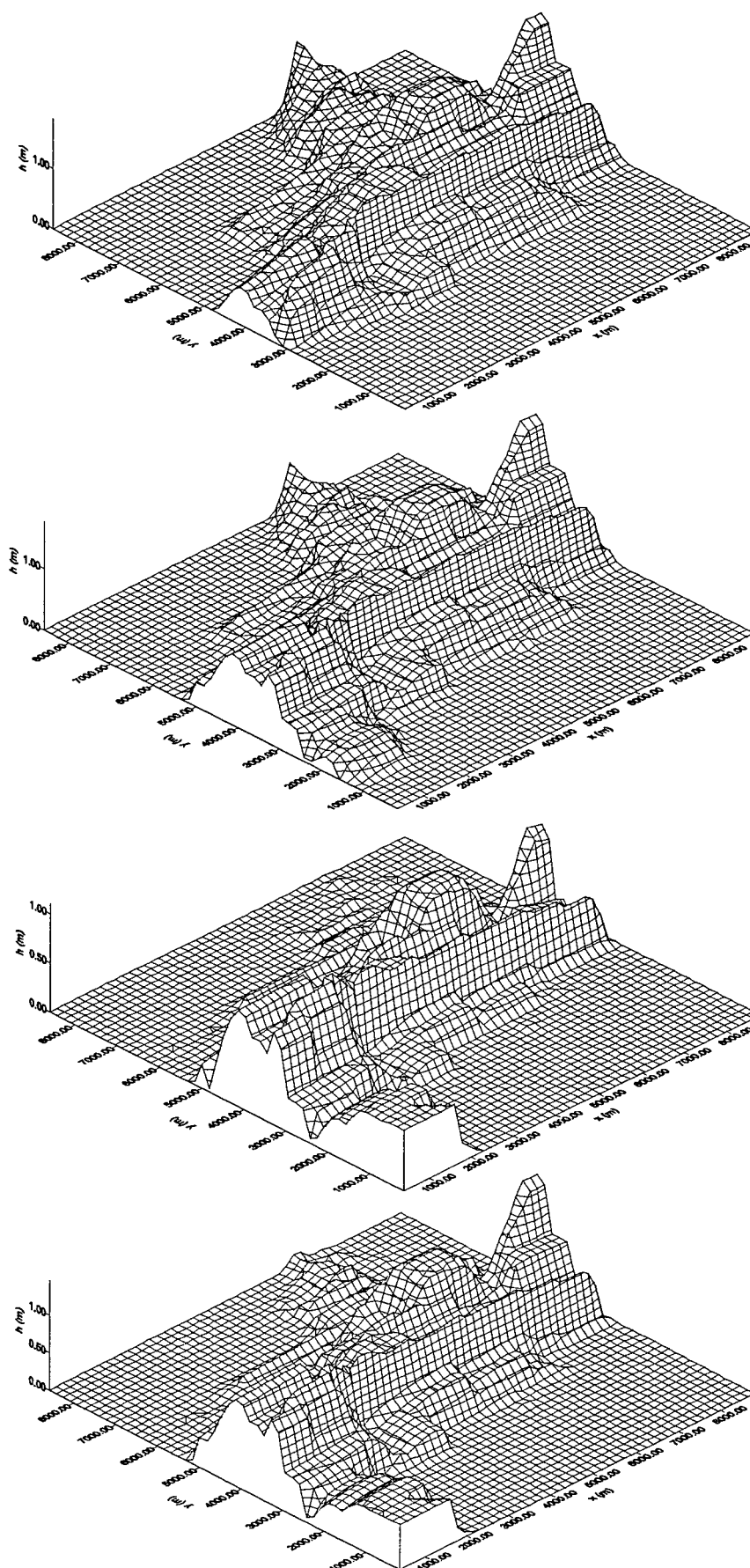


Fig.4.2.15b) Surface plot for run SR5. From top to bottom: $t=17h$, $t=20h$, $t=25h$ and $t=29h$ (x , y and z scale in meters).

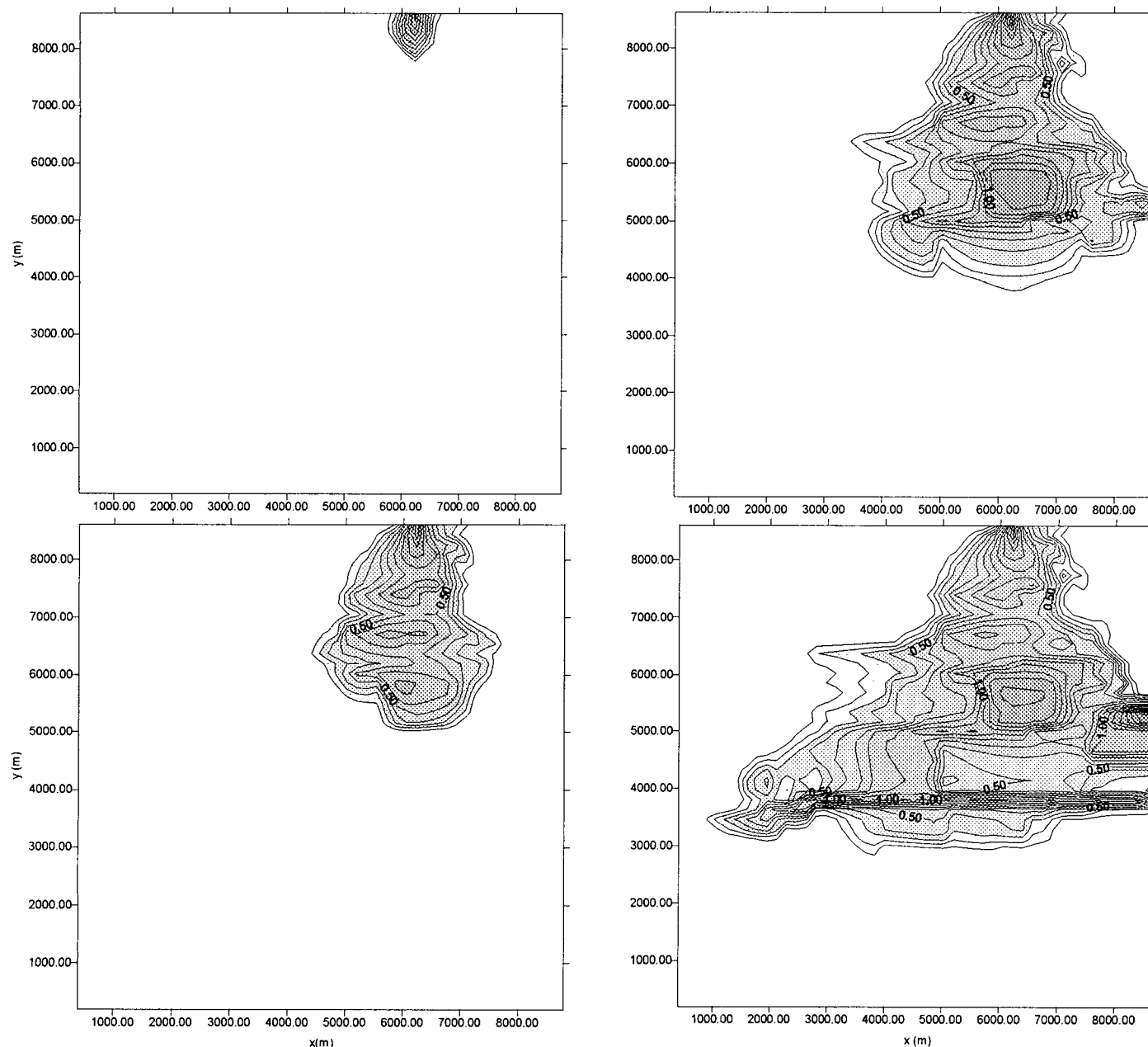


Fig.4.2.16a) Contour plot for run SR5. On the left: top t=8h, bottom t=10h; on the right: top t=12h, bottom t= 15 hours (scale in meter).

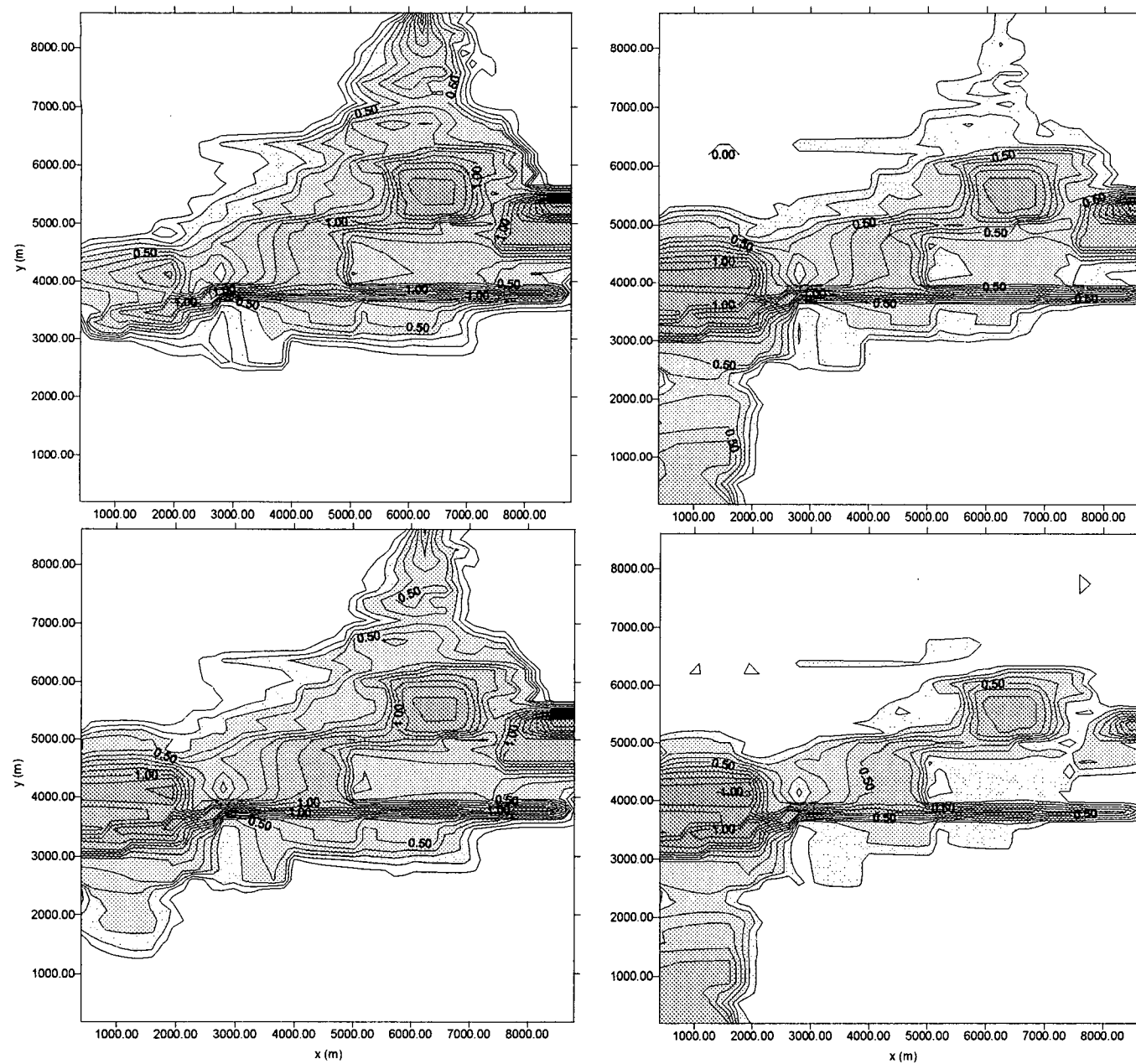


Fig.4.2.16b) Contour plot for run SR5. On the left: top t=17h, bottom t=20h; on the right: top t=25h, bottom t= 29 hours (scale in meter).

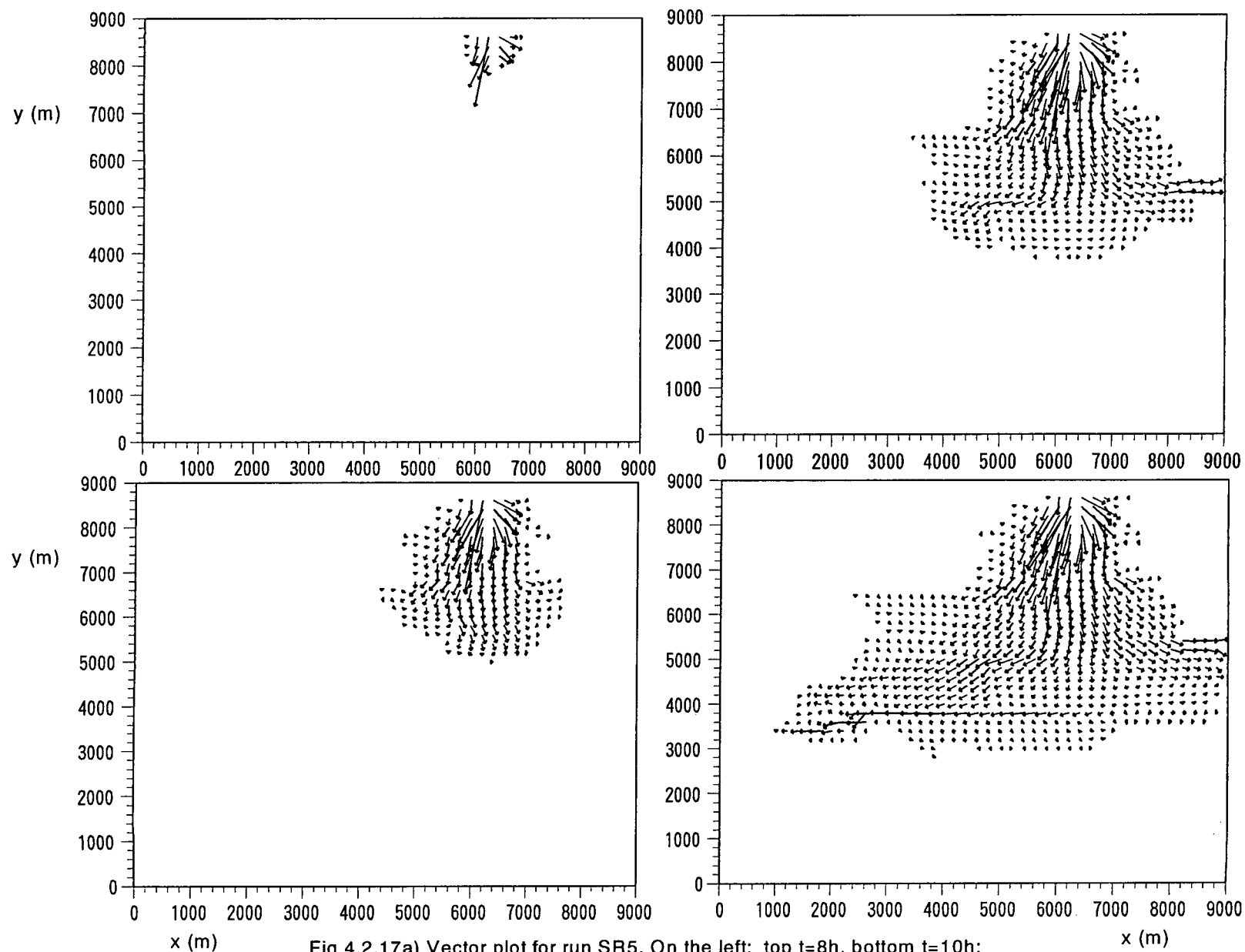


Fig.4.2.17a) Vector plot for run SR5. On the left: top $t=8h$, bottom $t=10h$; on the right: top $t=12h$, bottom $t=15h$. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

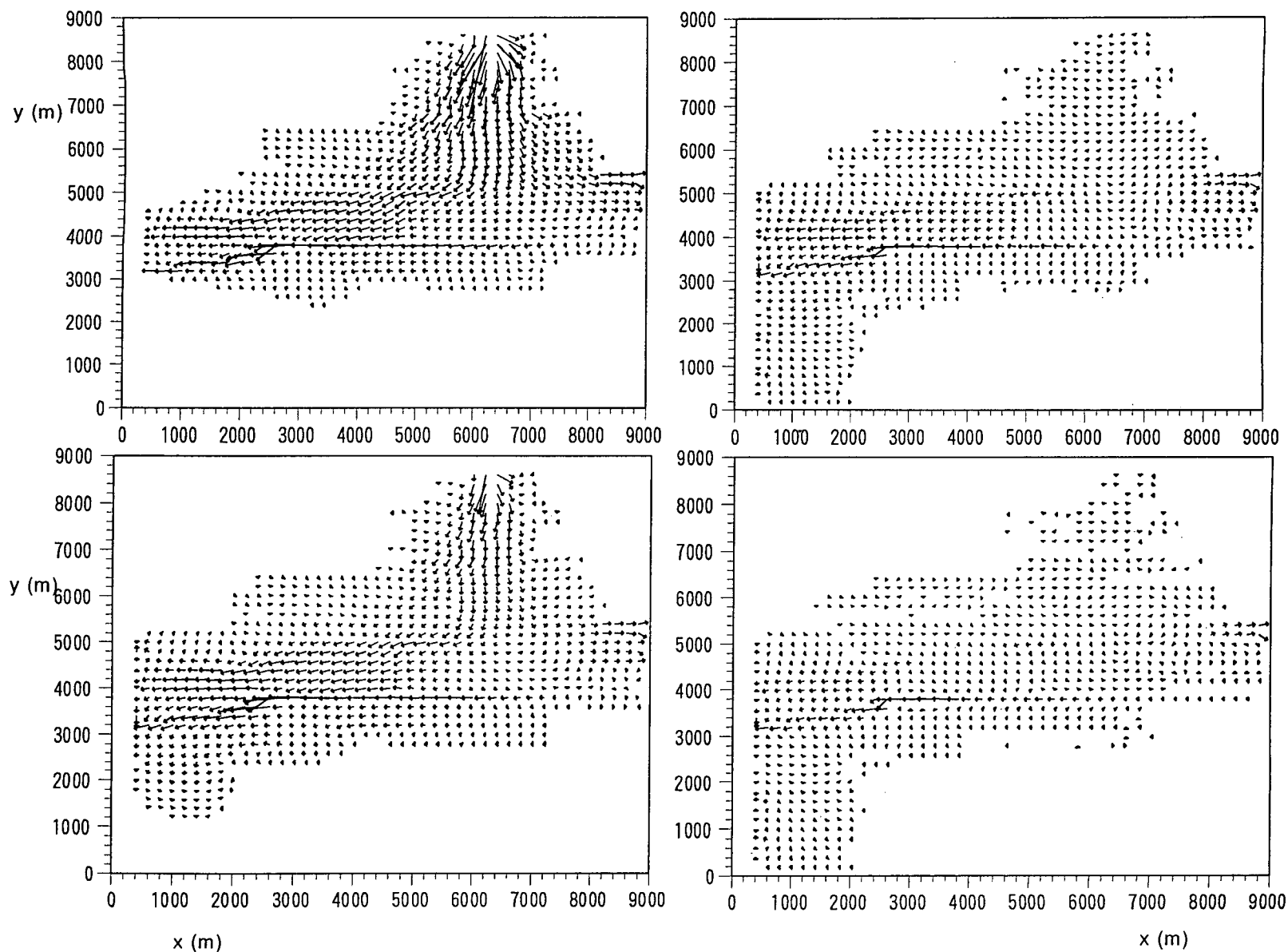


Fig.4.2.17b) Vector plot for run SR5. On the left: top $t=17\text{h}$, bottom $t=20\text{h}$; on the right: top $t=25\text{h}$, bottom $t=29\text{h}$. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

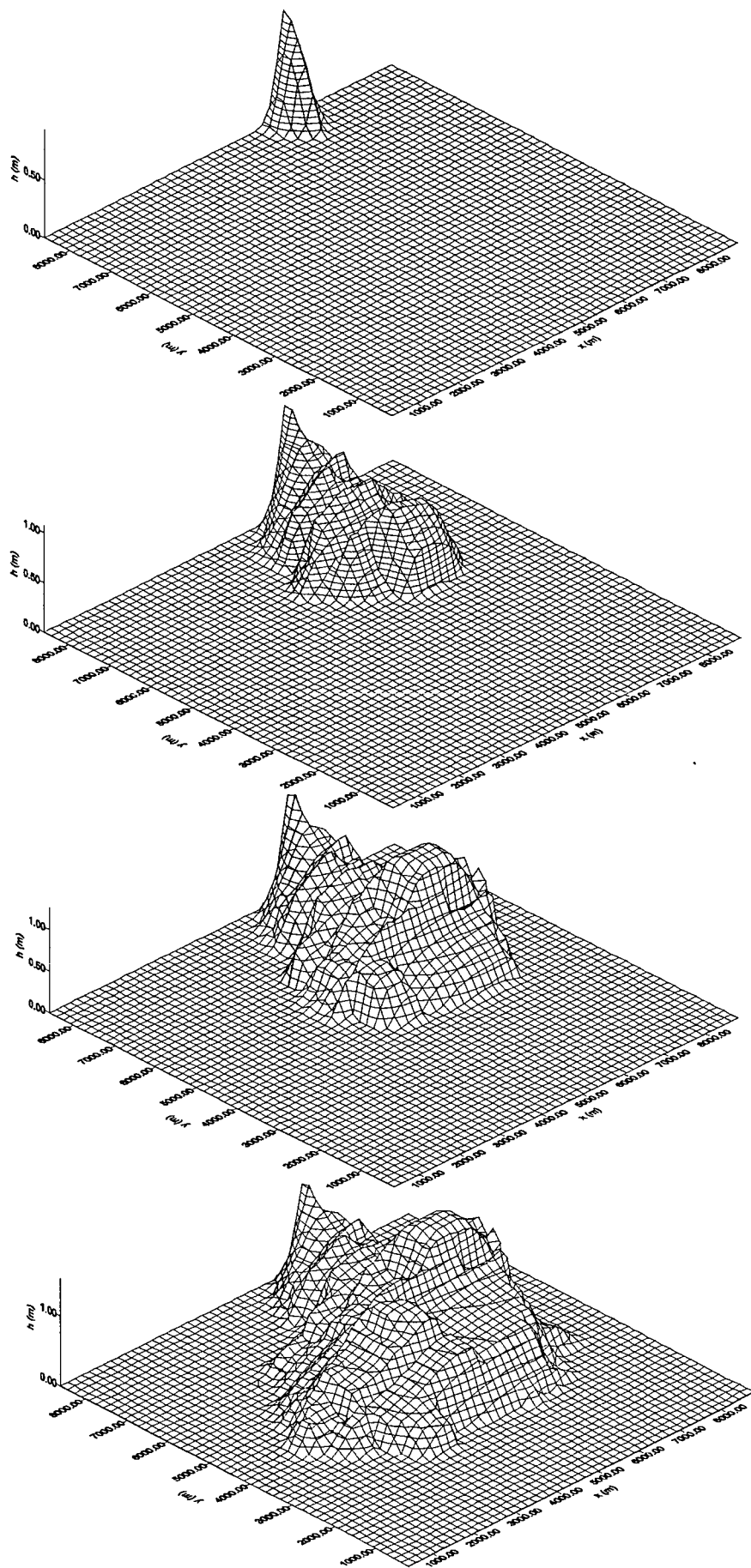


Fig.4.2.18a) Surface plot for run SR6. From top to bottom: $t=8h$, $t=10h$, $t=12h$ and $t=15h$ (x , y and z scale in meters).

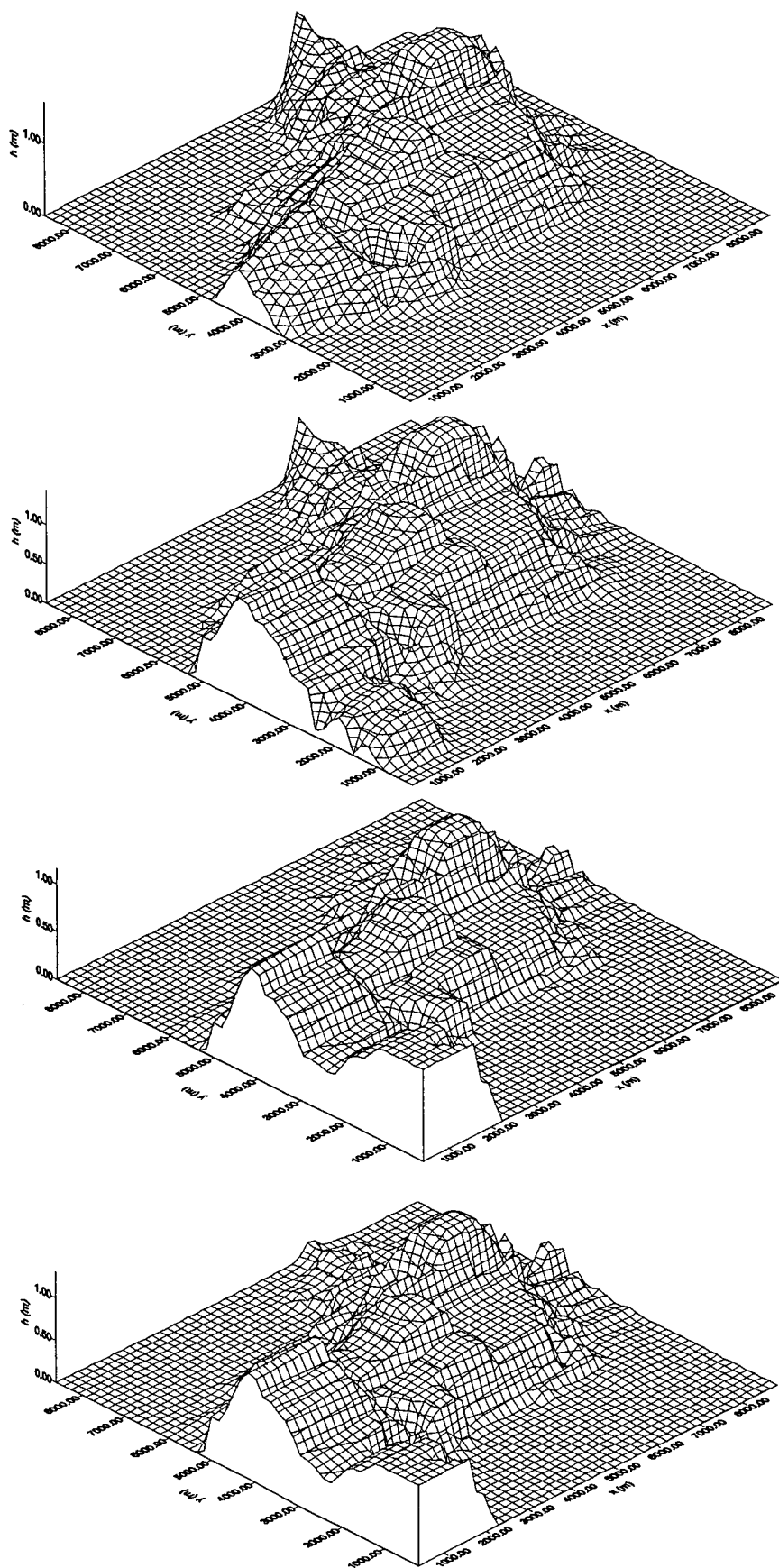


Fig.4.2.18b) Surface plot for run SR6. From top to bottom: $t=17h$, $t=20h$, $t=25h$ and $t=29h$ (x, y and z scale in meters).

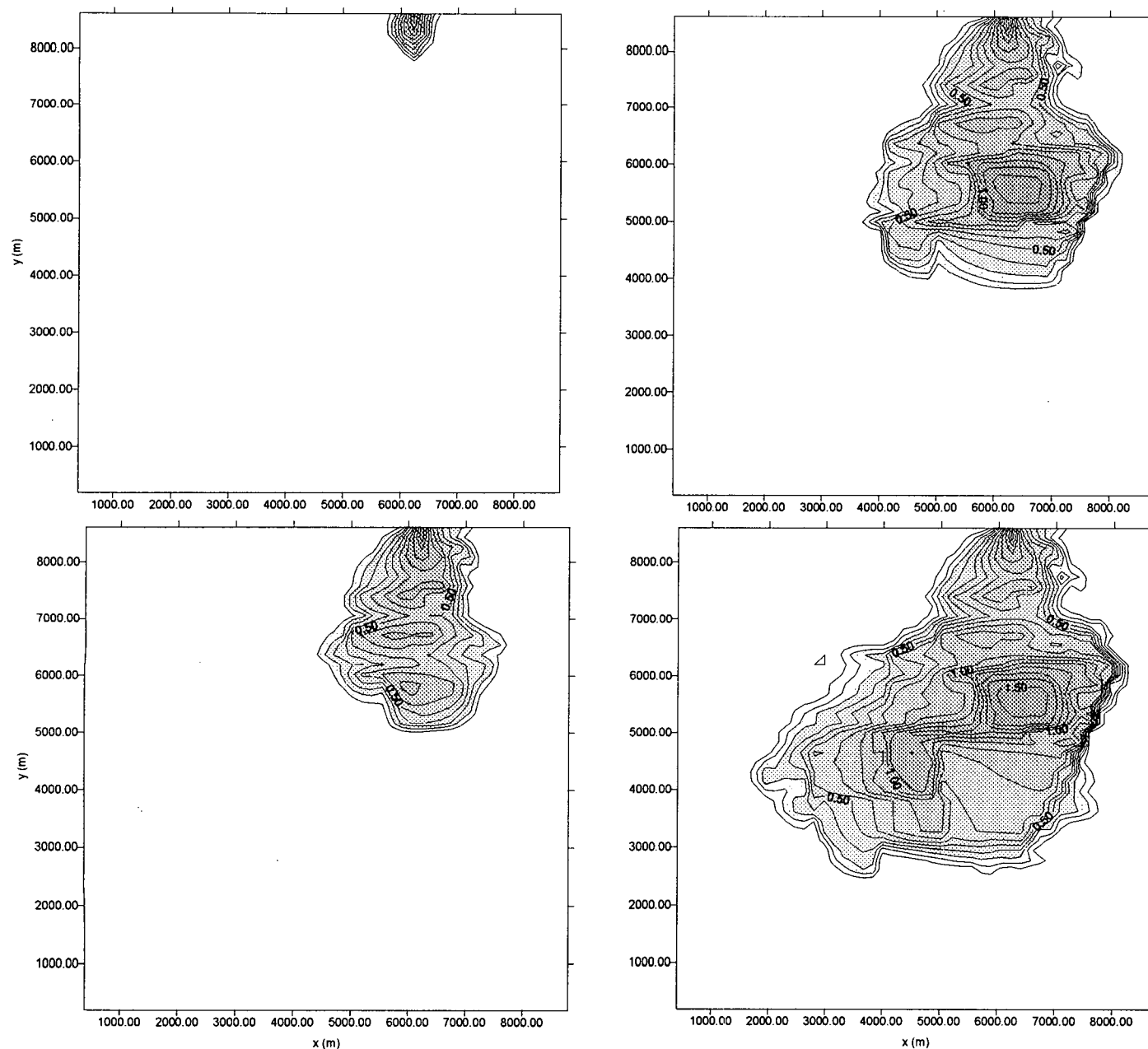


Fig.4.2.19a) Contour plot for run SR6. On the left: top t=8h, bottom t=10h; on the right: top t=12h, bottom t= 15 hours (scale in meter).

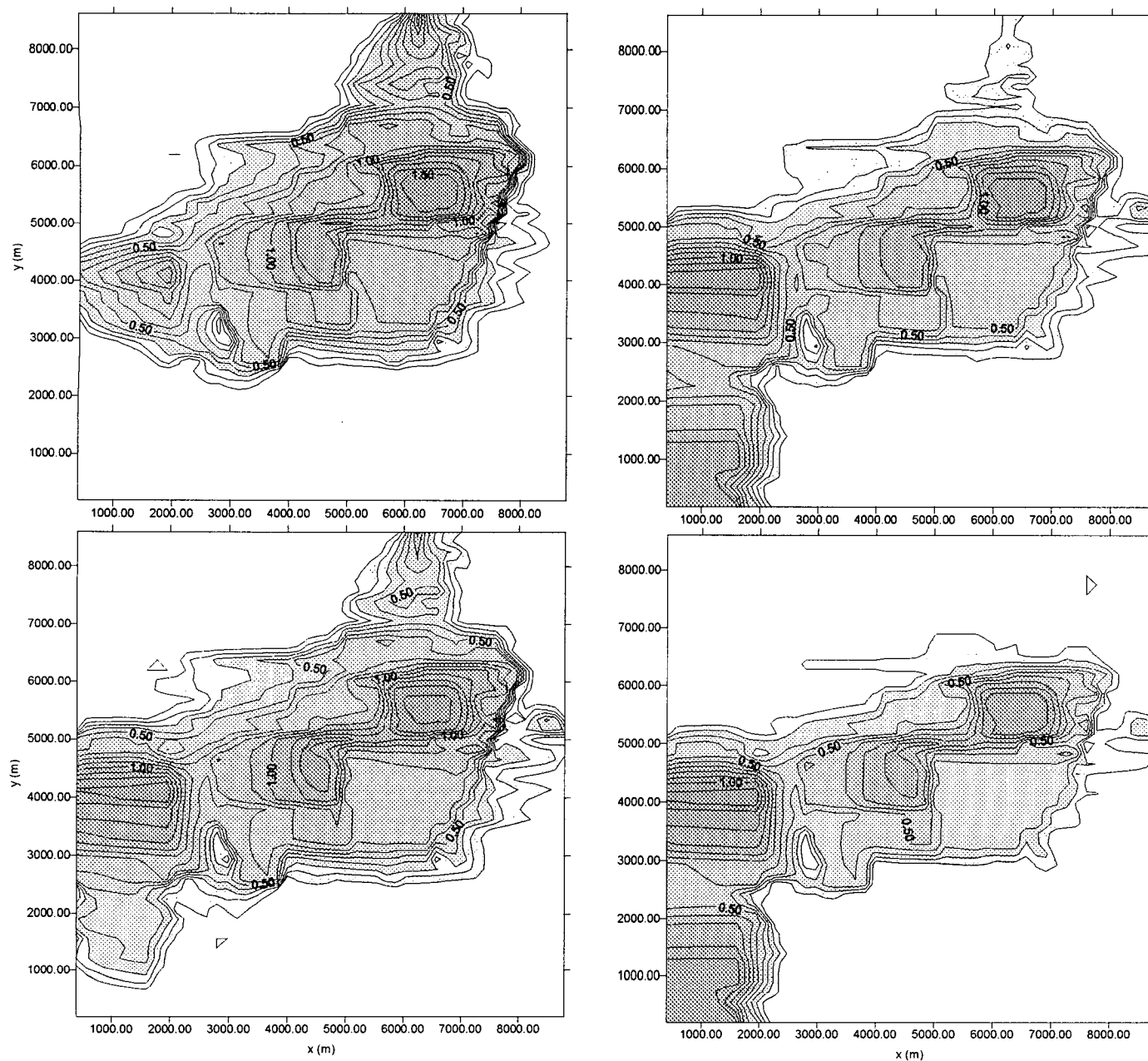


Fig.4.2.19b) Contour plot for run SR6. On the left: top t=17h, bottom t=20h; on the right: top t=25h, bottom t= 29 hours (scale in meter).

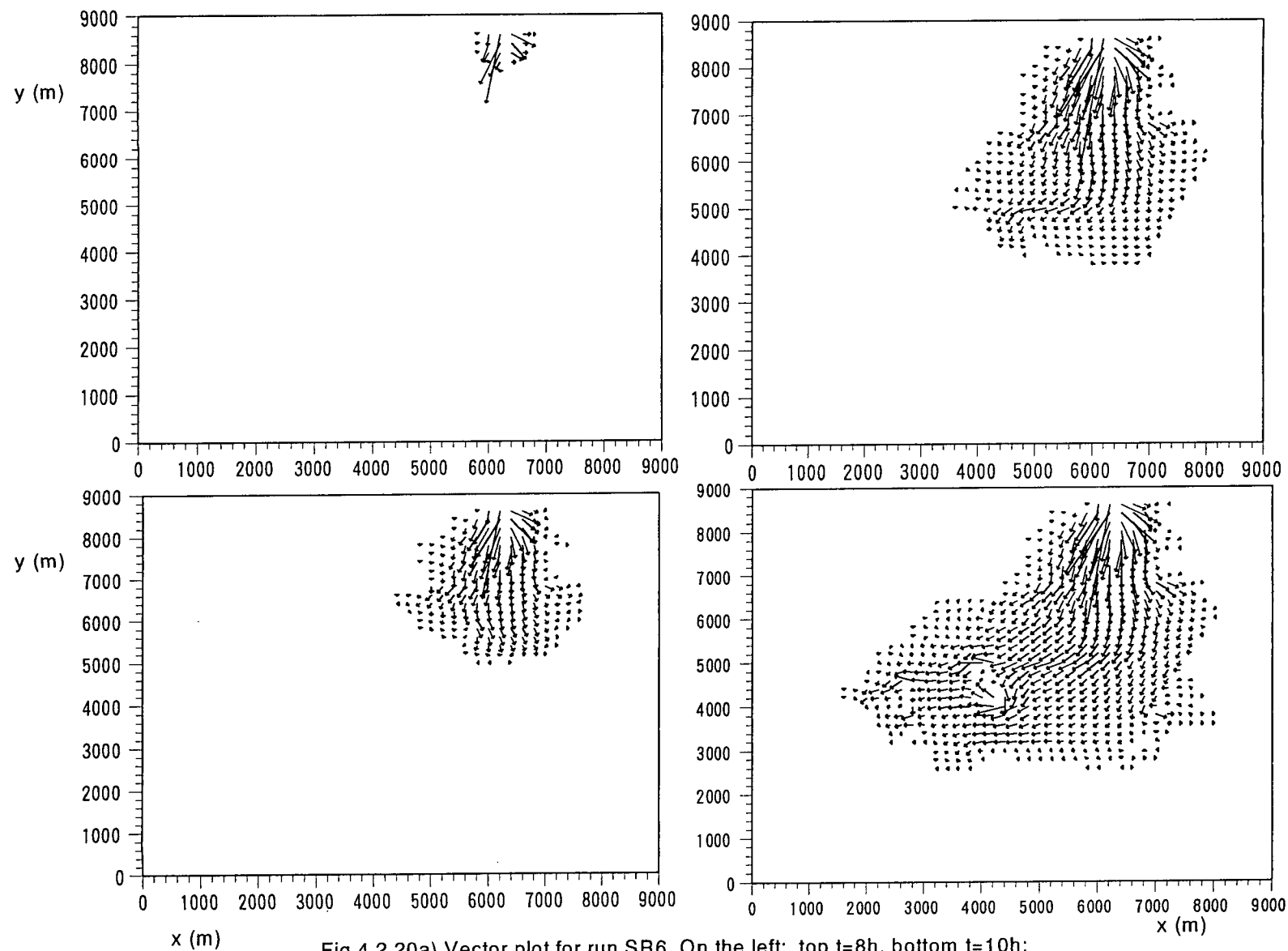


Fig.4.2.20a) Vector plot for run SR6. On the left: top $t=8h$, bottom $t=10h$; on the right: top $t=12h$, bottom $t=15$ hours. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

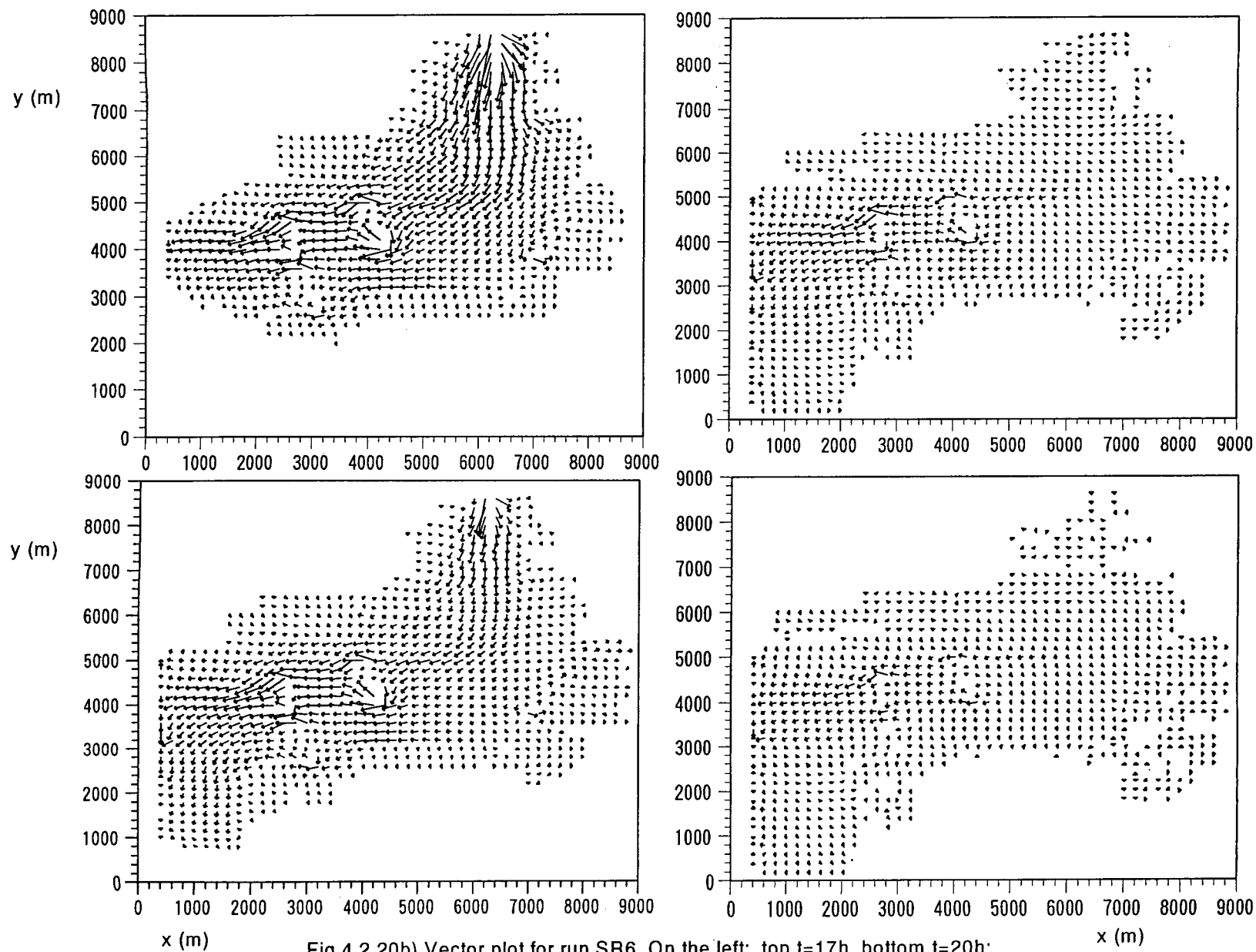


Fig.4.2.20b) Vector plot for run SR6. On the left: top $t=17\text{h}$, bottom $t=20\text{h}$; on the right: top $t=25\text{h}$, bottom $t=29\text{h}$. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

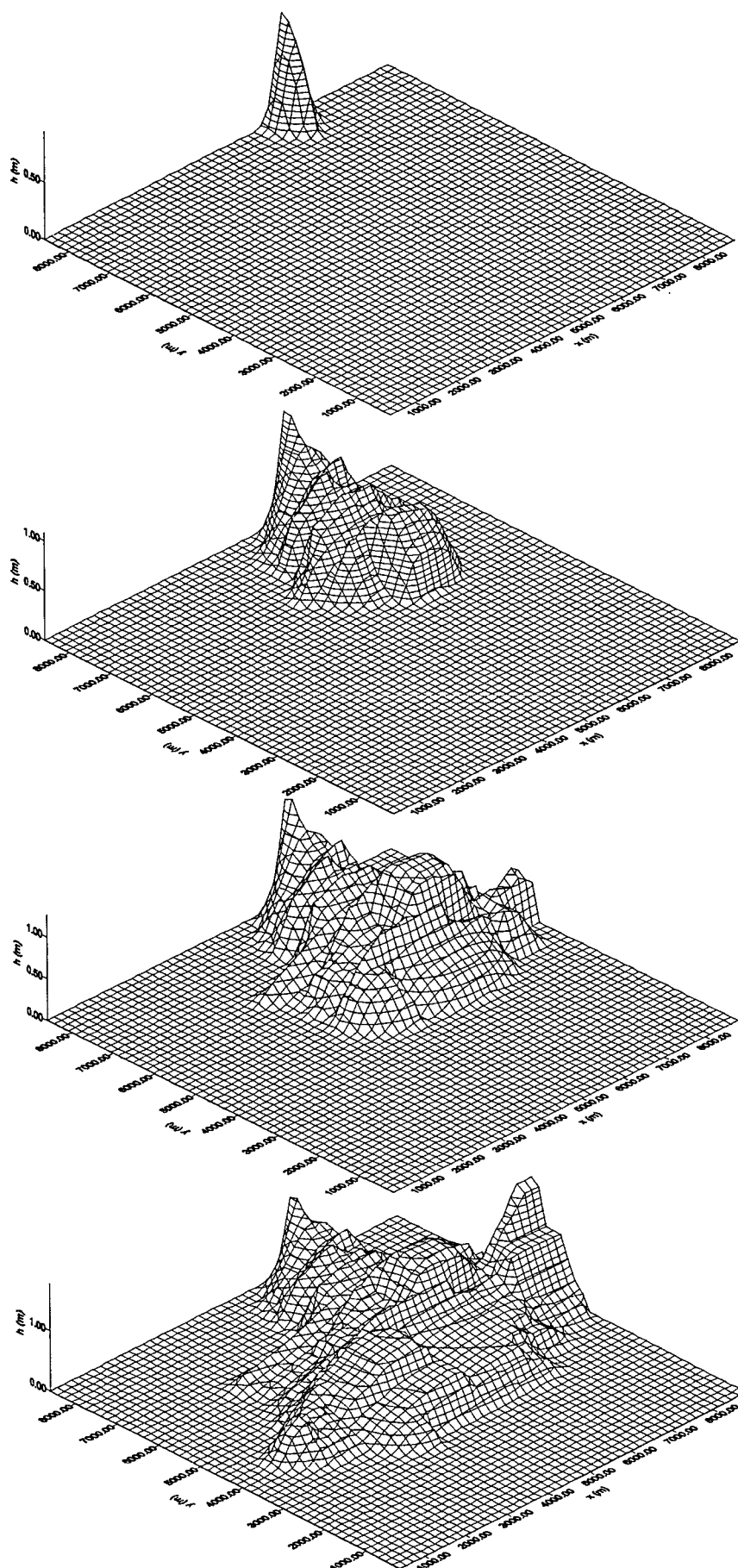


Fig.4.2.21a) Surface plot for run SR7. From top to bottom: $t=8h$, $t=10h$, $t=12h$ and $t=15$ hours (x , y and z scale in meters).

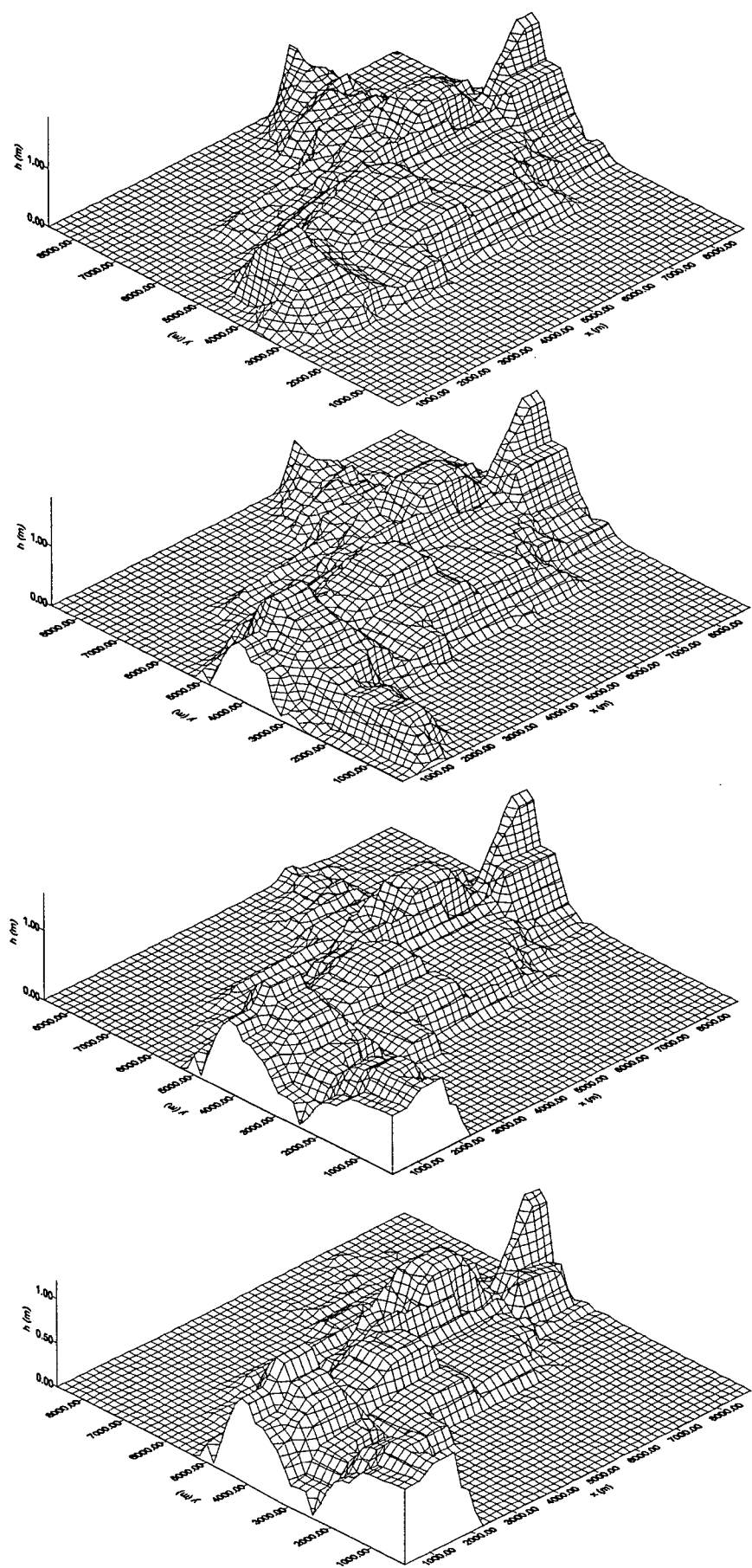


Fig.4.2.21b) Surface plot for run SR7. From top to bottom: $t=17\text{h}$, $t=20\text{h}$, $t=25\text{h}$ and $t=29\text{h}$ (x , y and z scale in meters).

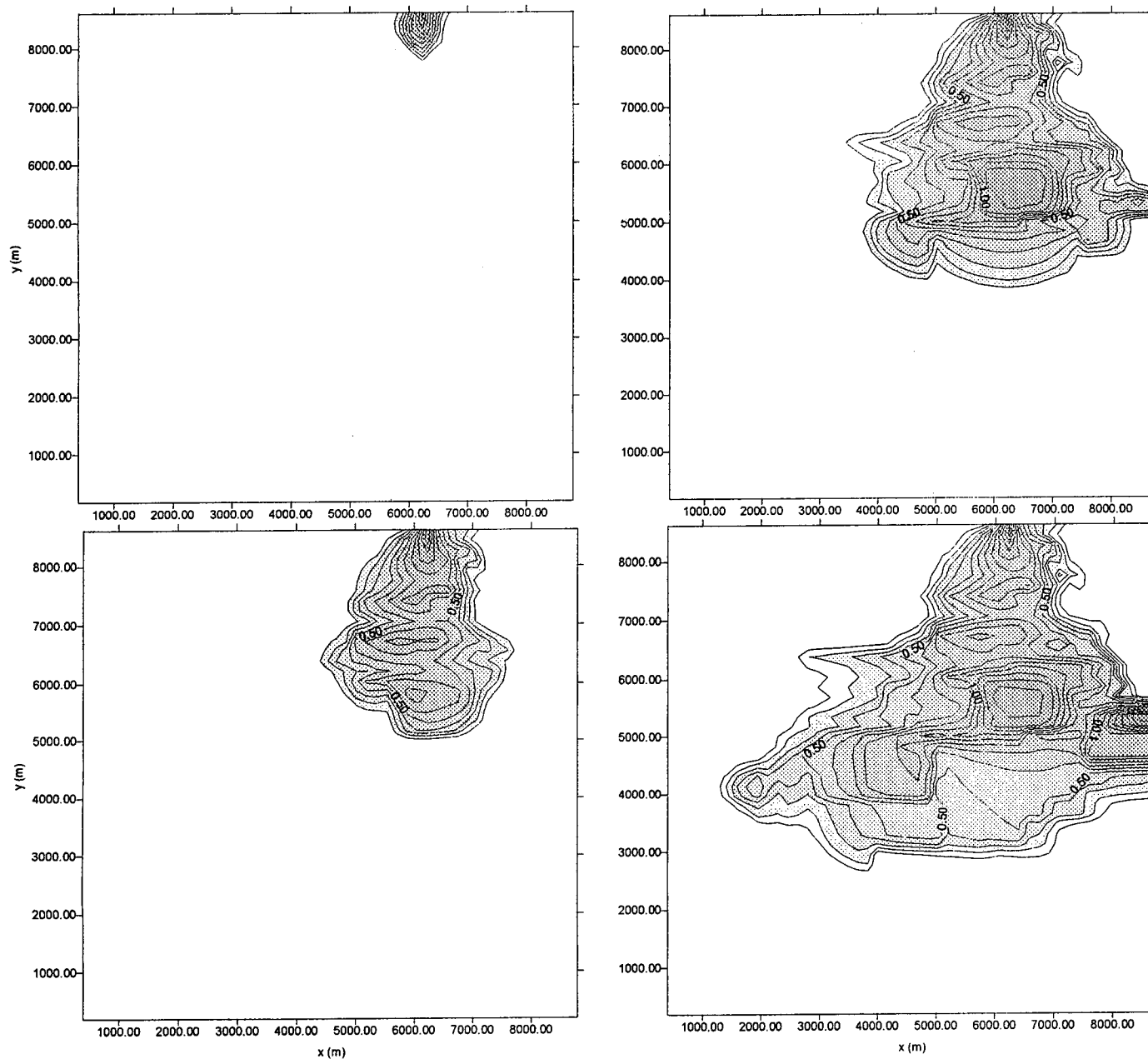


Fig.4.2.22a) Contour plot for run SR7. On the left: top t=8h, bottom t=10h; on the right: top t=12h, bottom t= 15 hours (scale in meter).

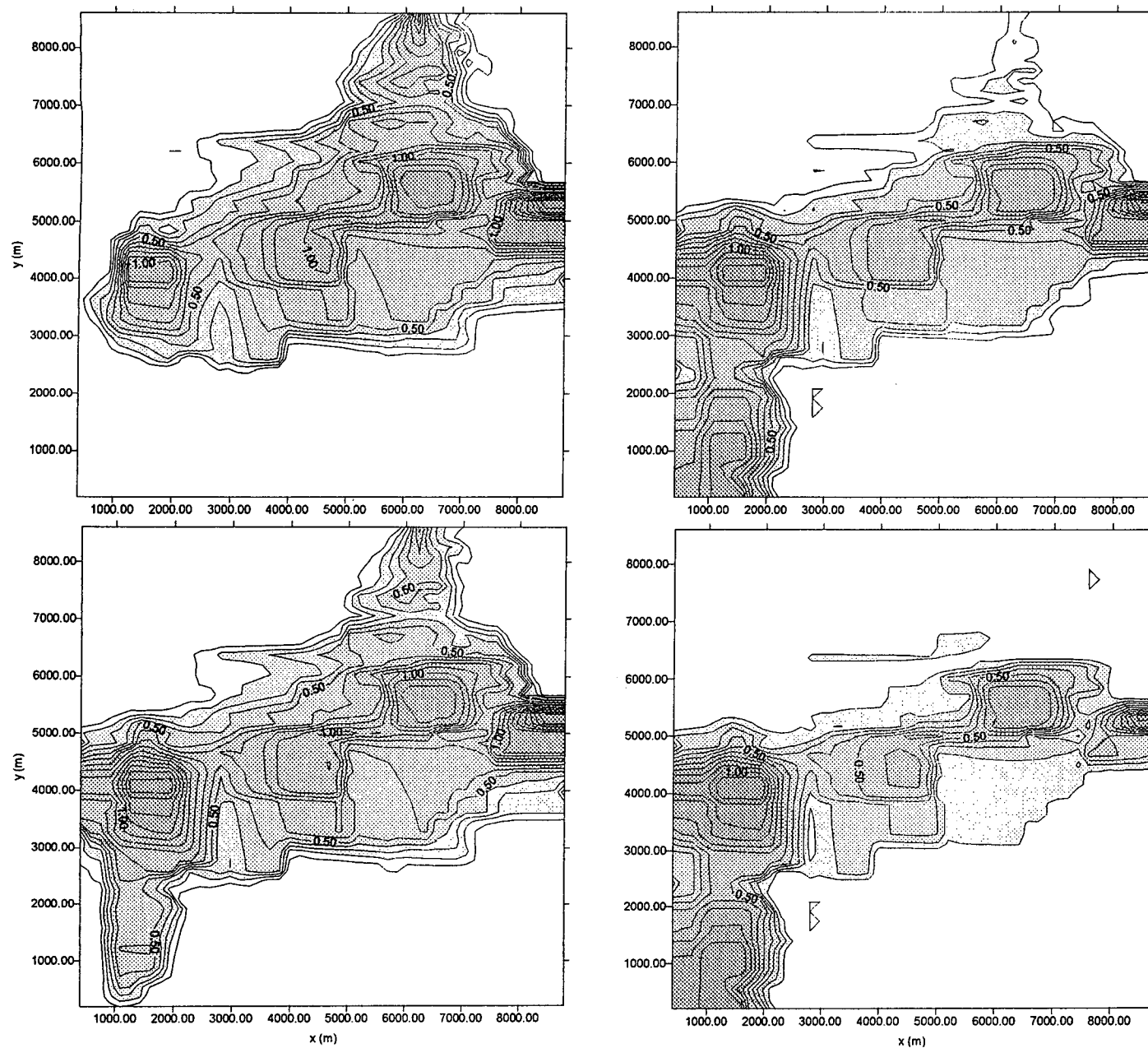


Fig.4.2.22b) Contour plot for run SR7. On the left: top $t=17h$, bottom $t=20h$; on the right: top $t=25h$, bottom $t=29h$ (scale in meter).

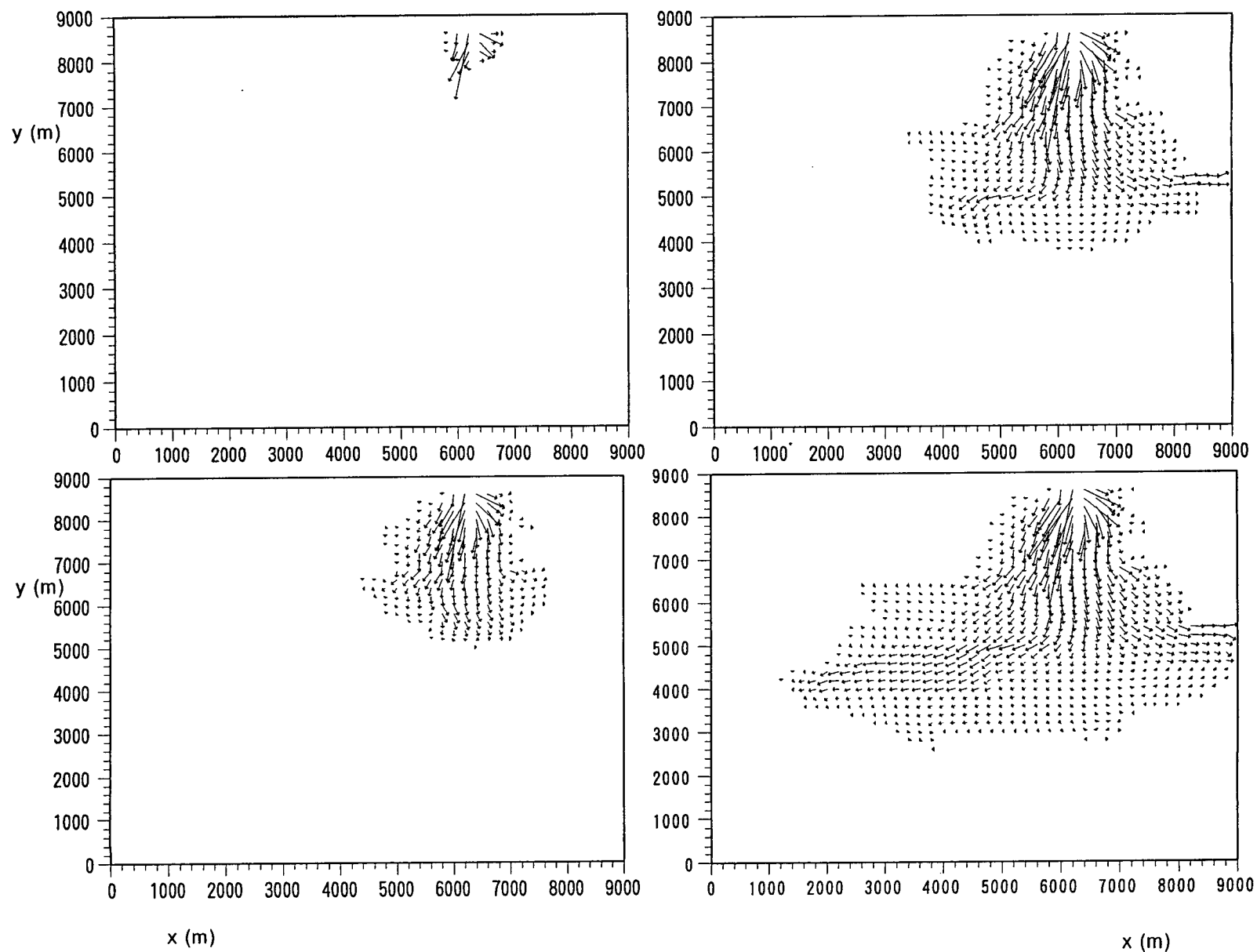


Fig.4.2.23a) Vector plot for run SR7. On the left: top $t=8h$, bottom $t=10h$; on the right: top $t=12h$, bottom $t=15$ hours. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

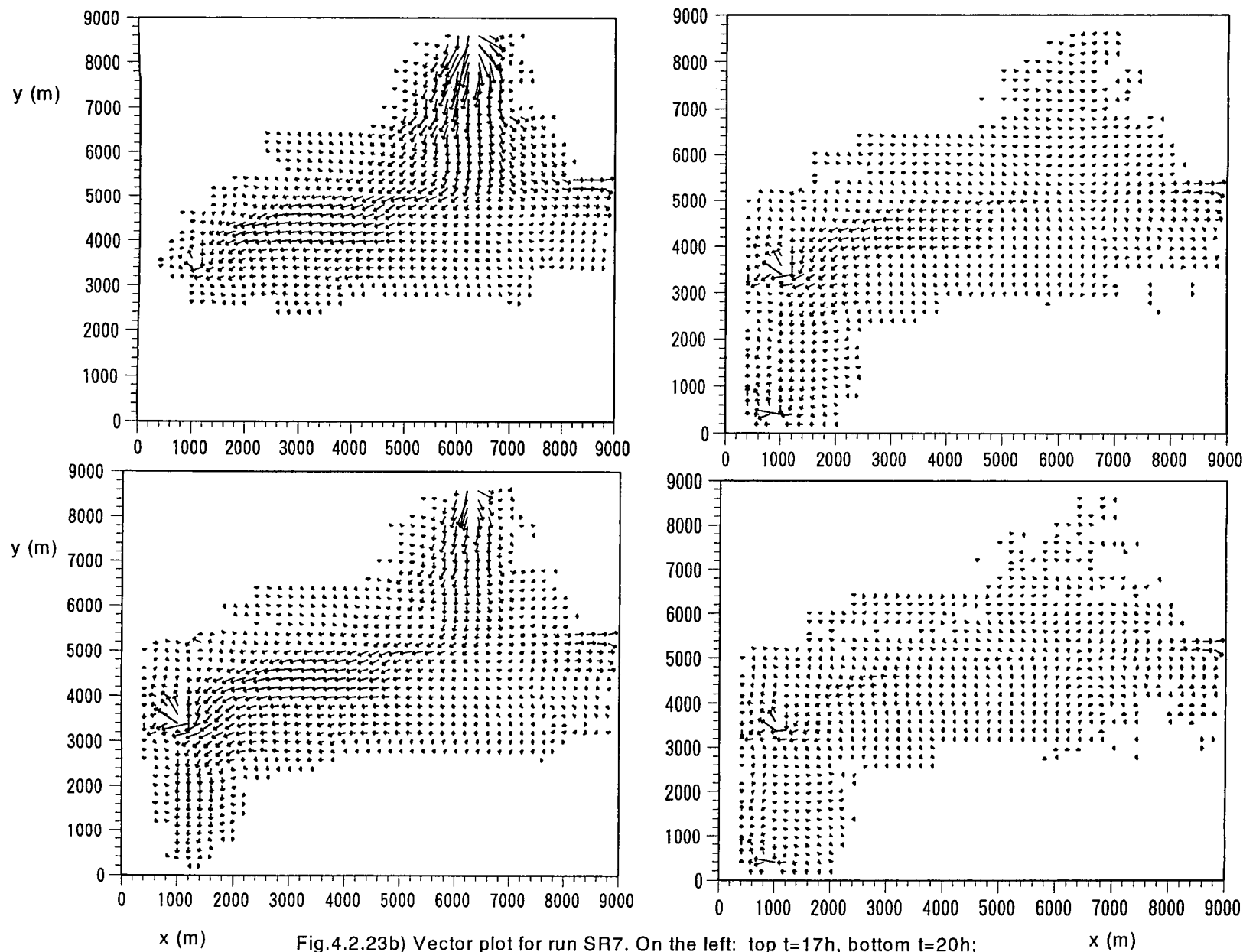


Fig.4.2.23b) Vector plot for run SR7. On the left: top $t=17\text{h}$, bottom $t=20\text{h}$; on the right: top $t=25\text{h}$, bottom $t=29\text{h}$. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

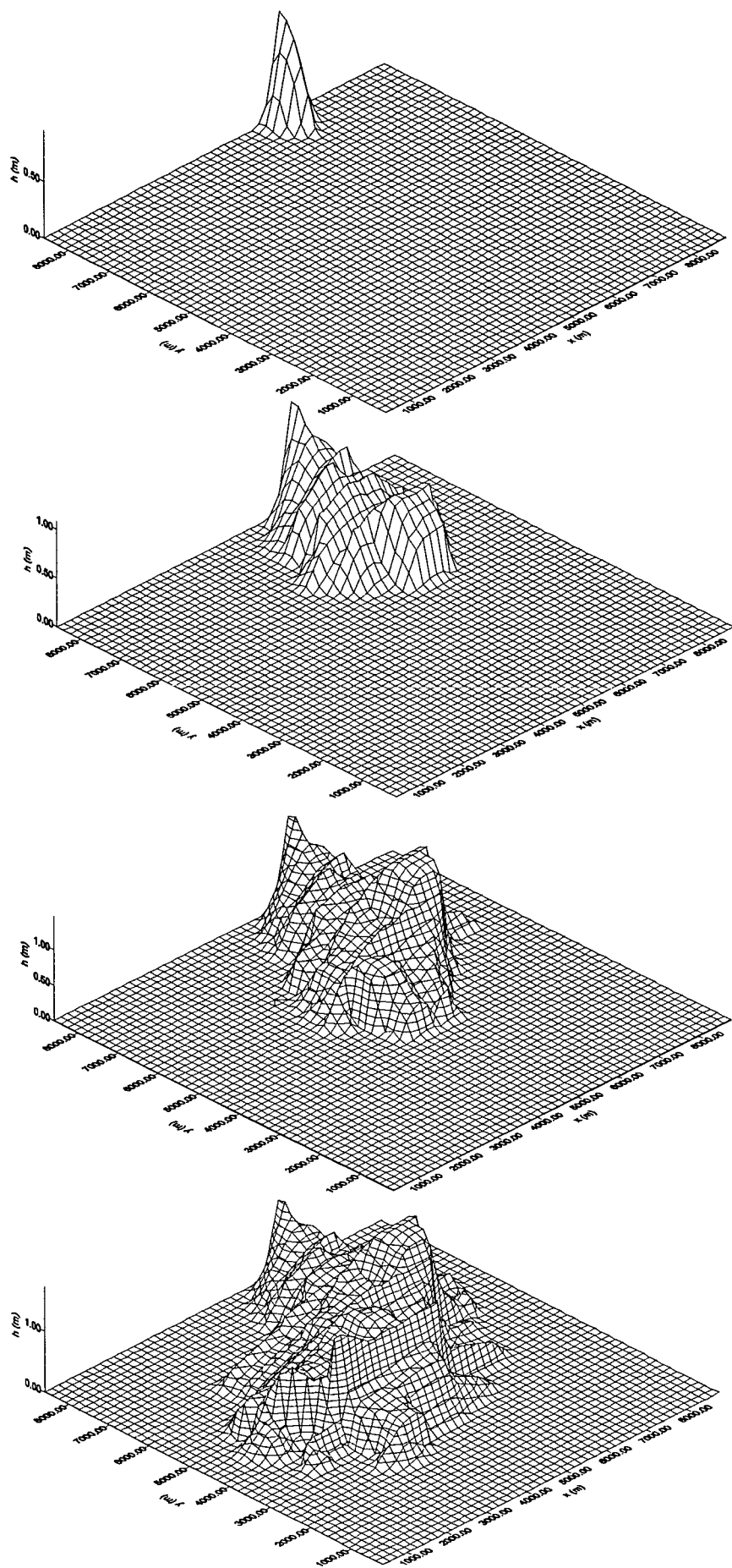


Fig.4.2.24a) Surface plot for run SR8. From top to bottom: $t=8h$, $t=10h$, $t=12h$ and $t=15h$ (x, y and z scale in meters).

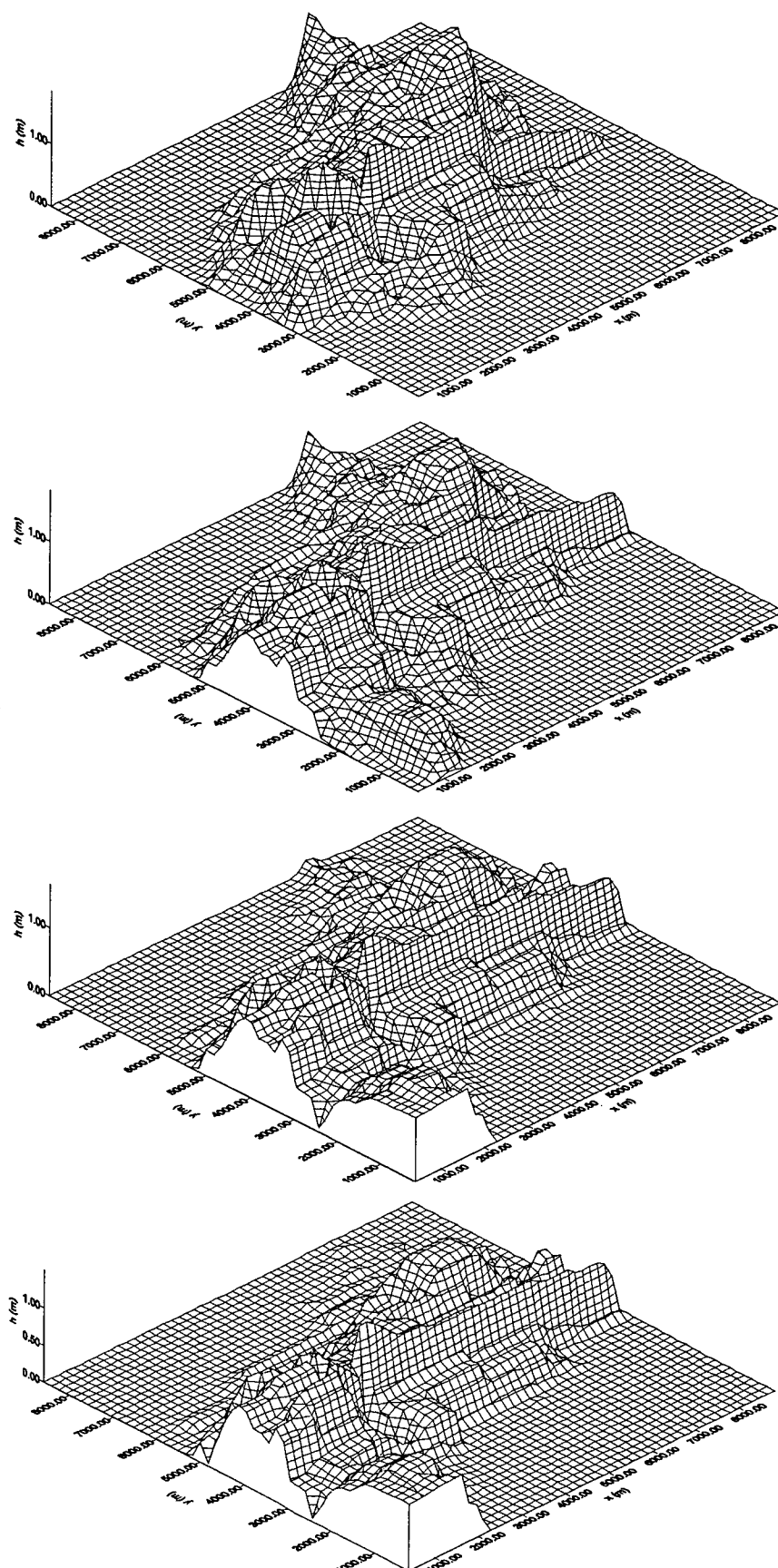


Fig.4.2.24b) Surface plot for run SR8. From top to bottom: $t=17h$, $t=20h$, $t=25h$ and $t=29h$ (x , y and z scale in meters).

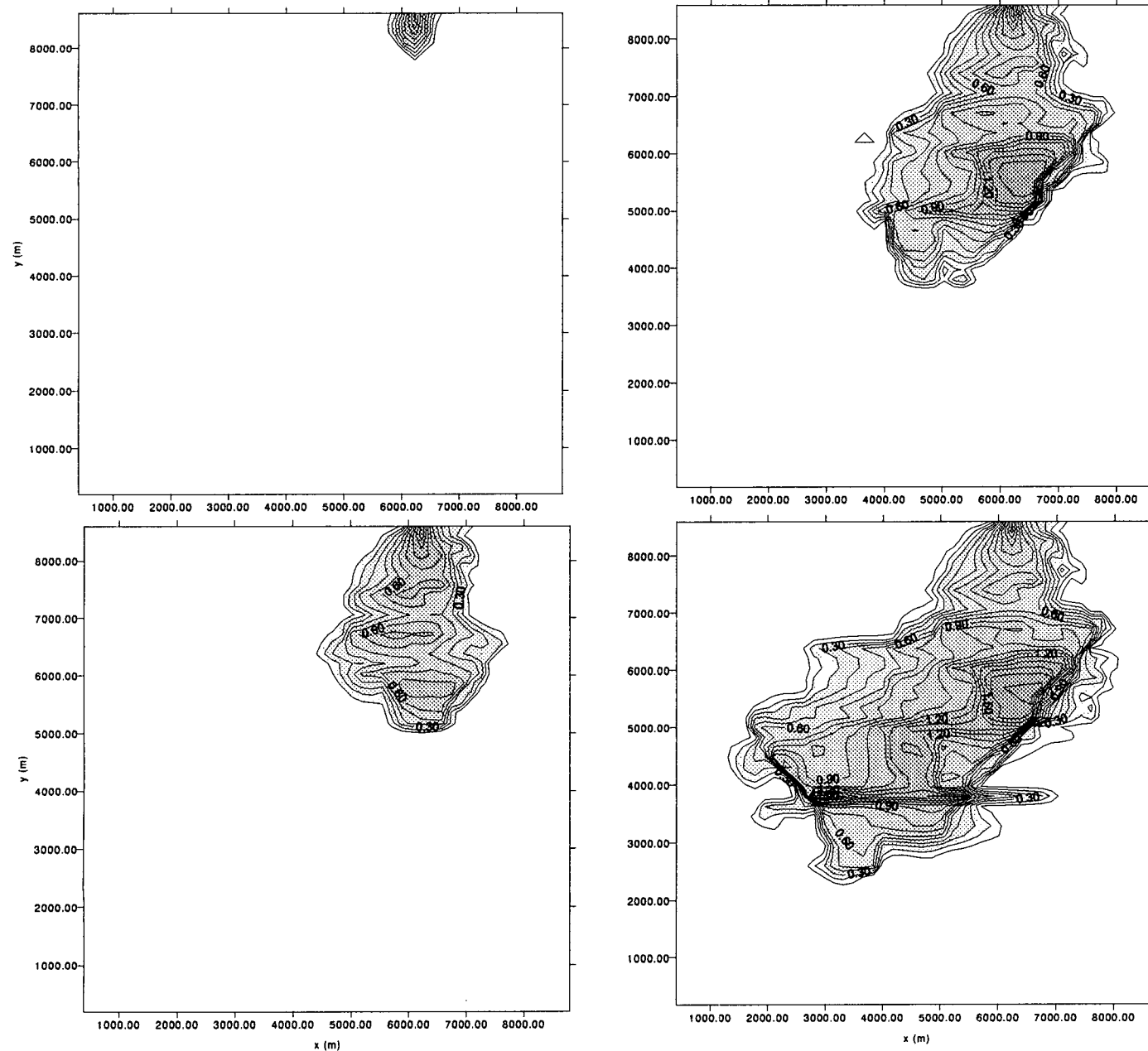


Fig.4.2.25a) Contour plot for run SR8. On the left: top $t=8h$, bottom $t=10h$; on the right: top $t=12h$, bottom $t=15h$ (scale in meter).

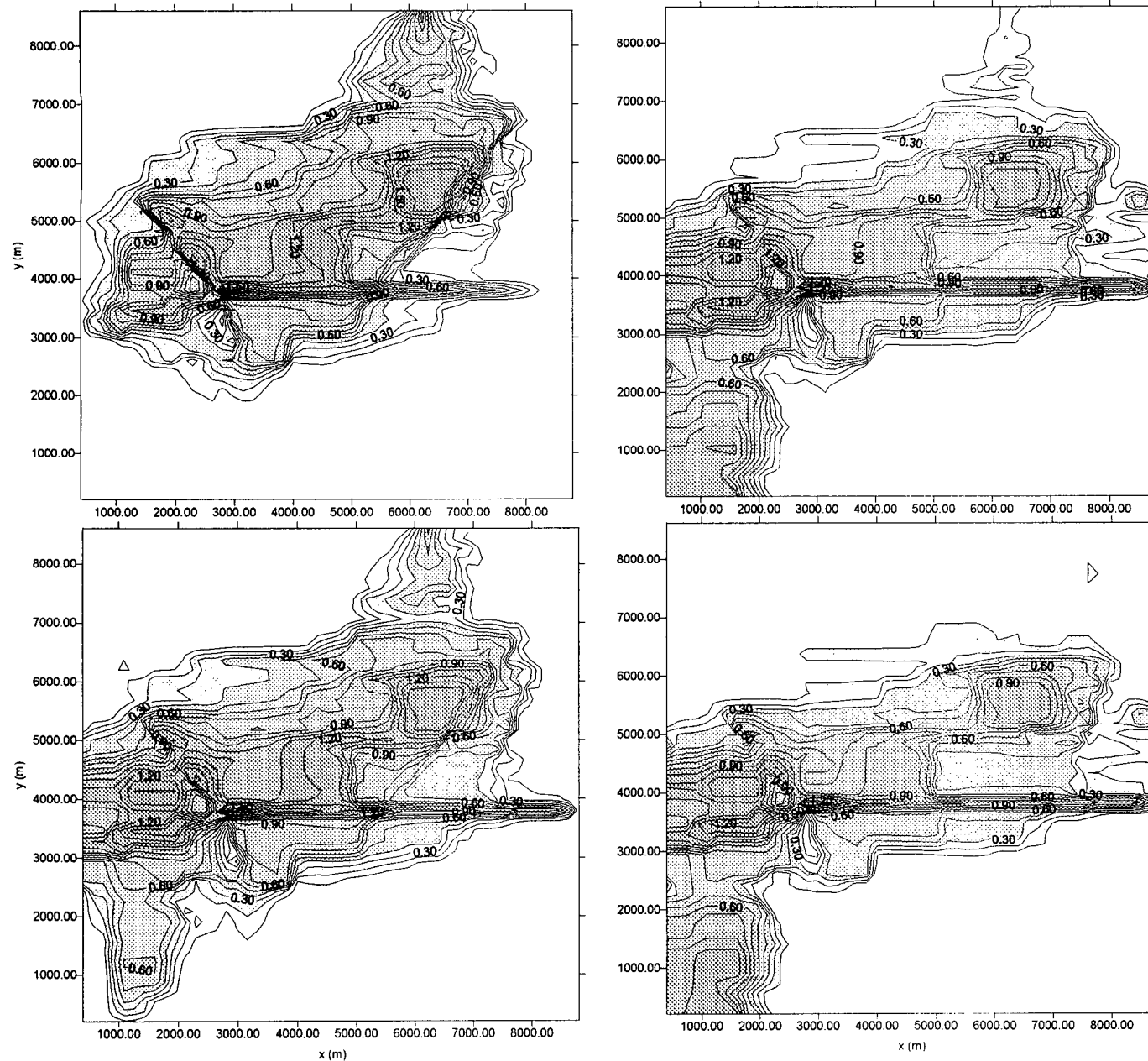


Fig.4.2.25b) Contour plot for run SR8. On the left: top t=17h, bottom t=20h; on the right: top t=25h, bottom t= 29 hours (scale in meter).

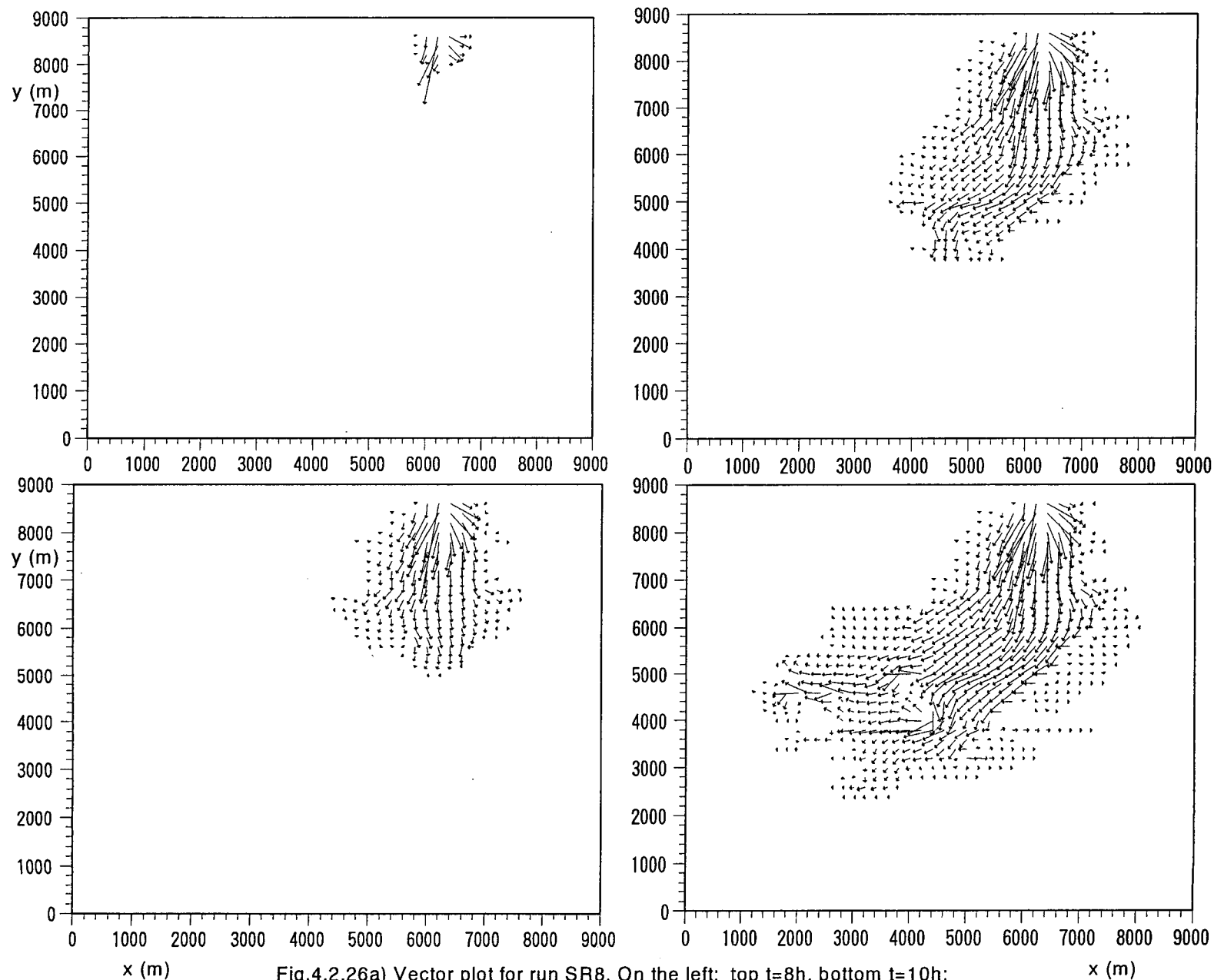


Fig.4.2.26a) Vector plot for run SR8. On the left: top $t=8h$, bottom $t=10h$; on the right: top $t=12h$, bottom $t=15$ hours. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

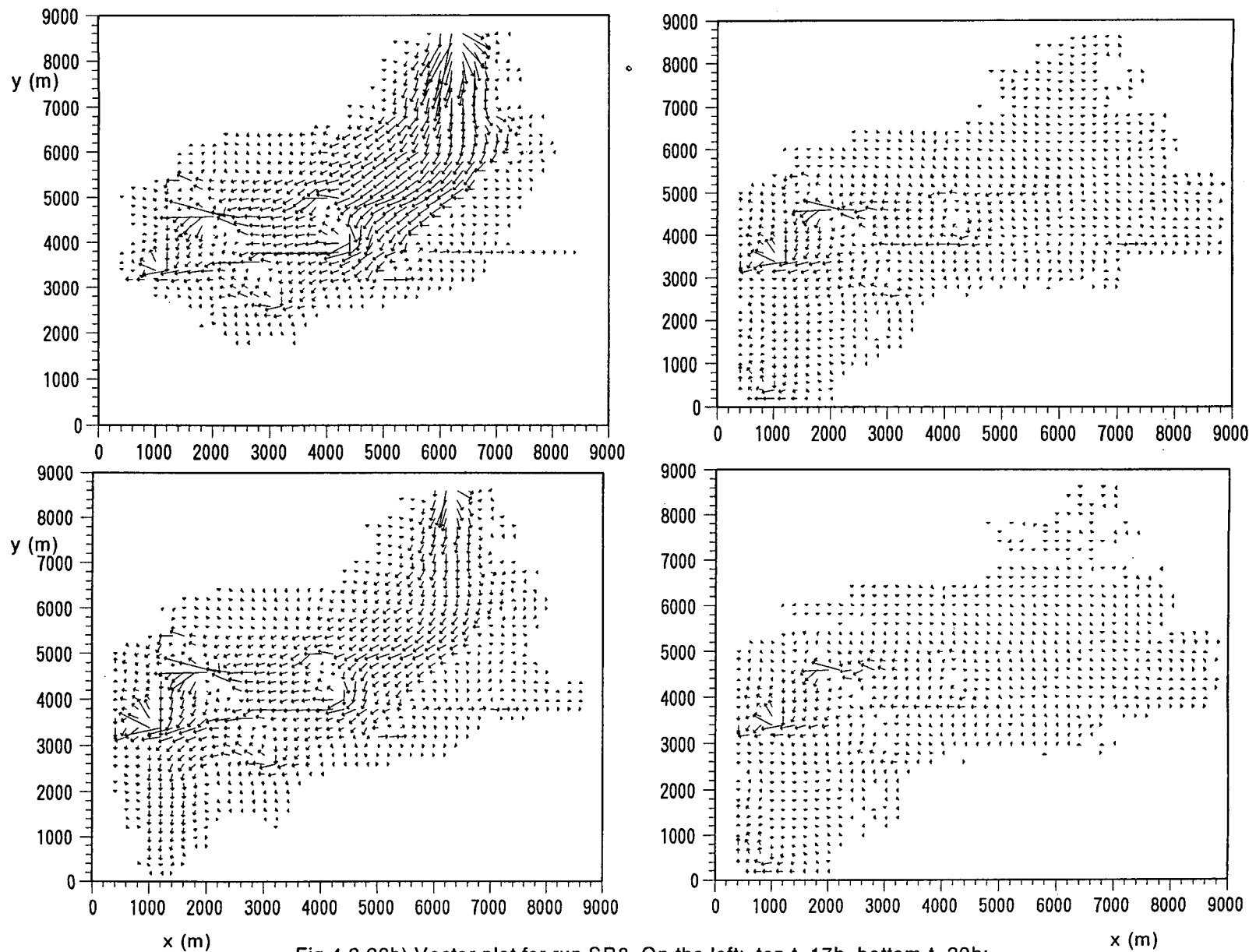


Fig.4.2.26b) Vector plot for run SR8. On the left: top $t=17h$, bottom $t=20h$; on the right: top $t=25h$, bottom $t=29h$ hours. The scale for the flux vector (m^2/s) is 1000 times the plot unit; x and y scale are in meters.

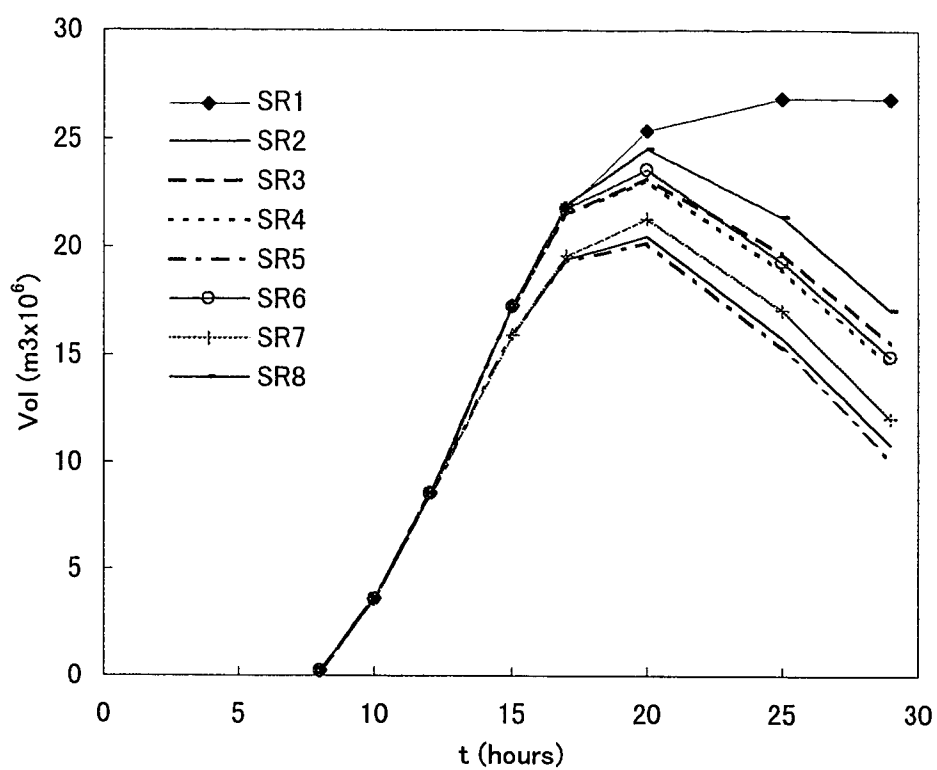


Fig.4.2.27 Volume of water inside the floodplain as a function of time

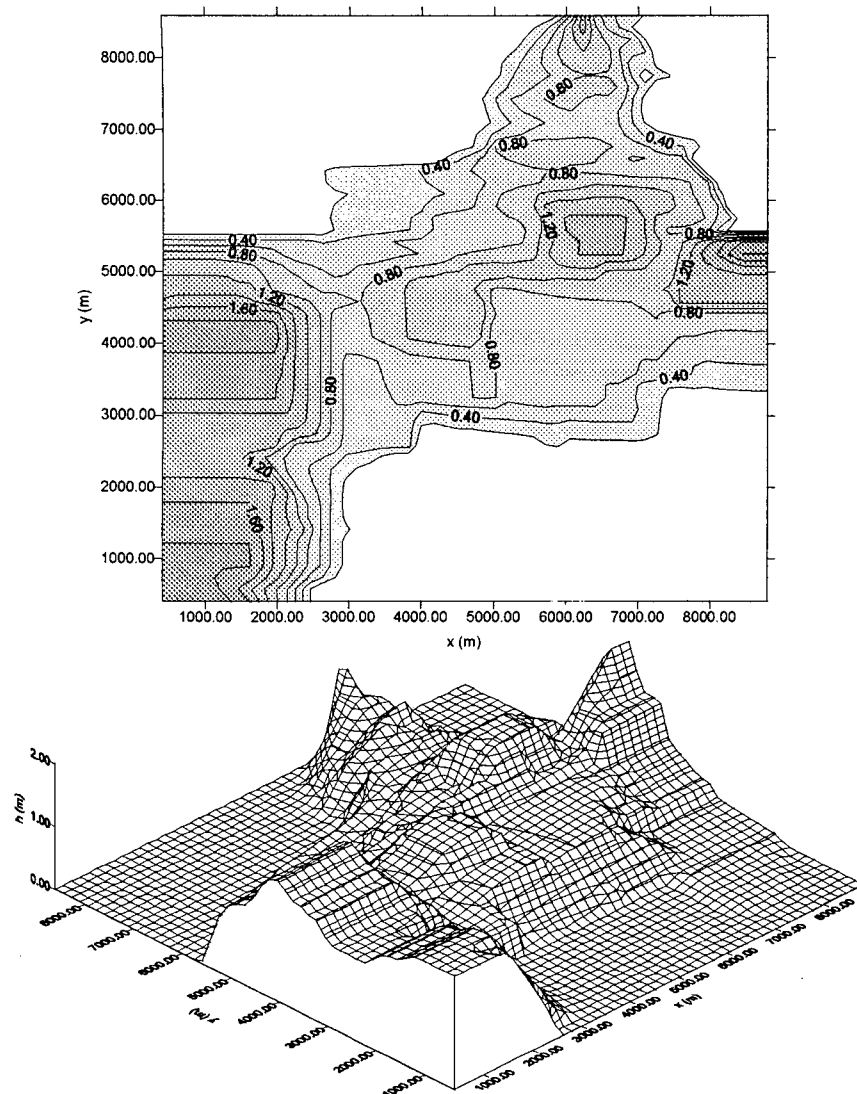


Fig.4.2.28a) Envelope of the maximum values of the water depth in the plane for run SR1 (contour and surface plot).

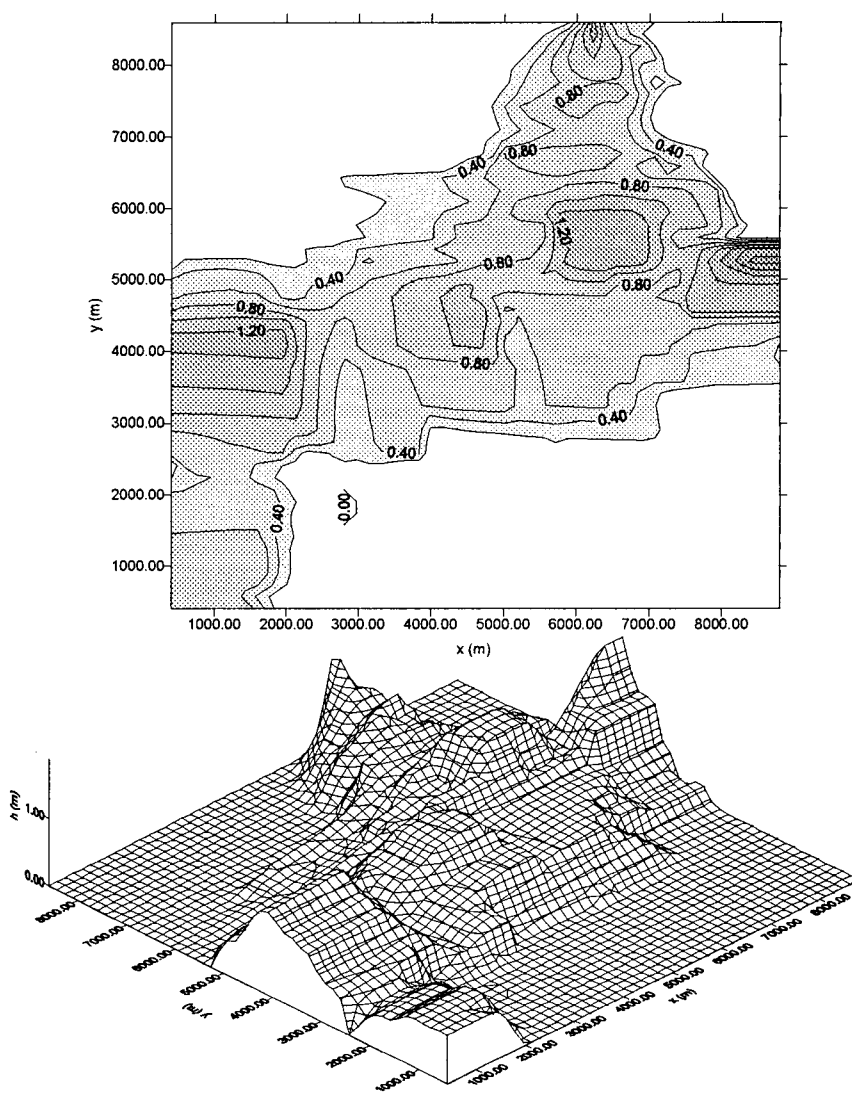


Fig.4.2.28b) Envelope of the maximum values of the water depth in the plane for run SR2 (contour and surface plot).

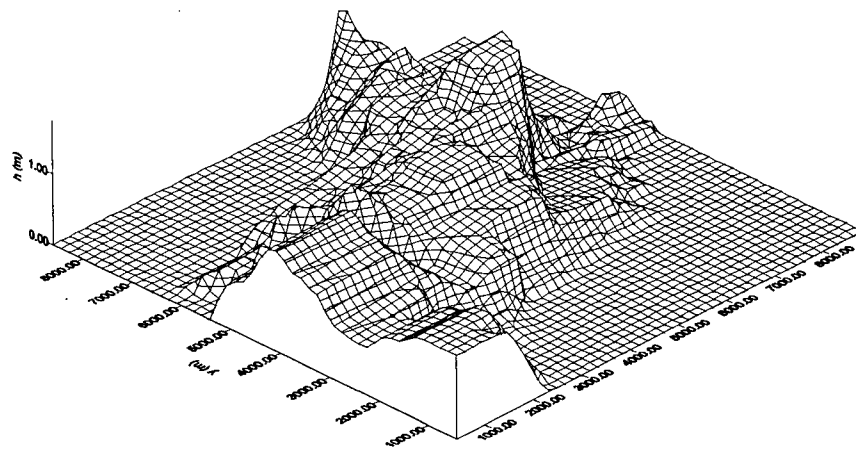
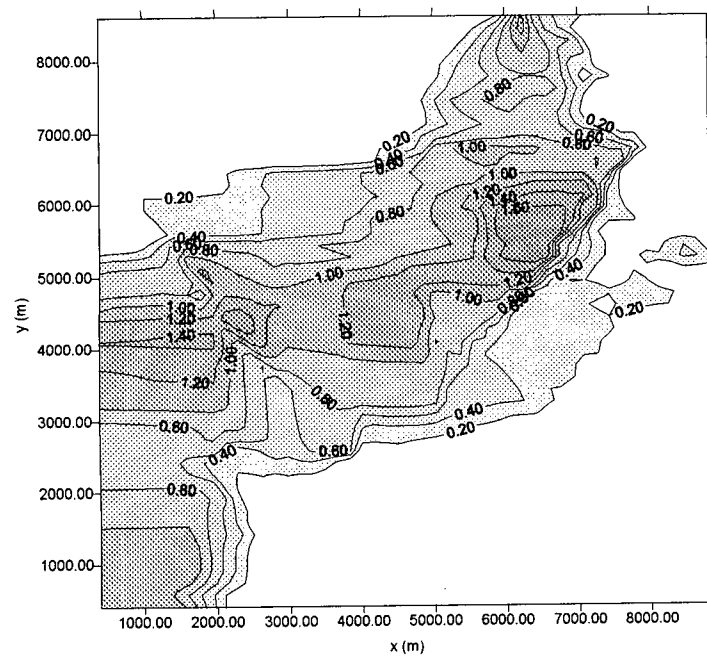


Fig.4.2.28c) Envelope of the maximum values of the water depth in the plane for run SR3 (contour and surface plot).

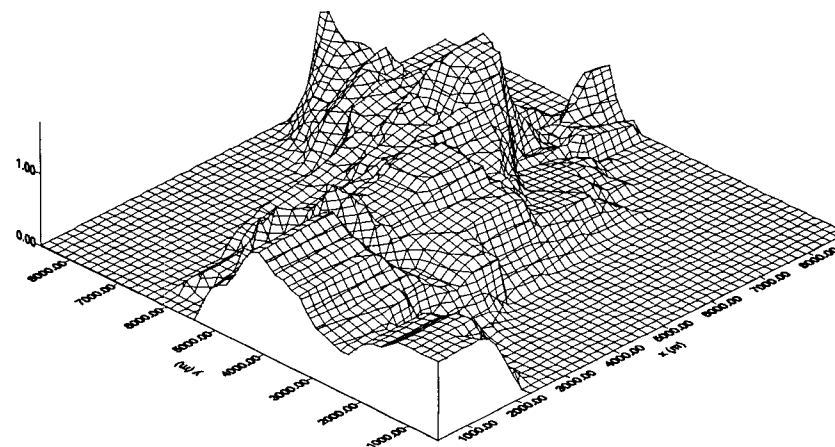
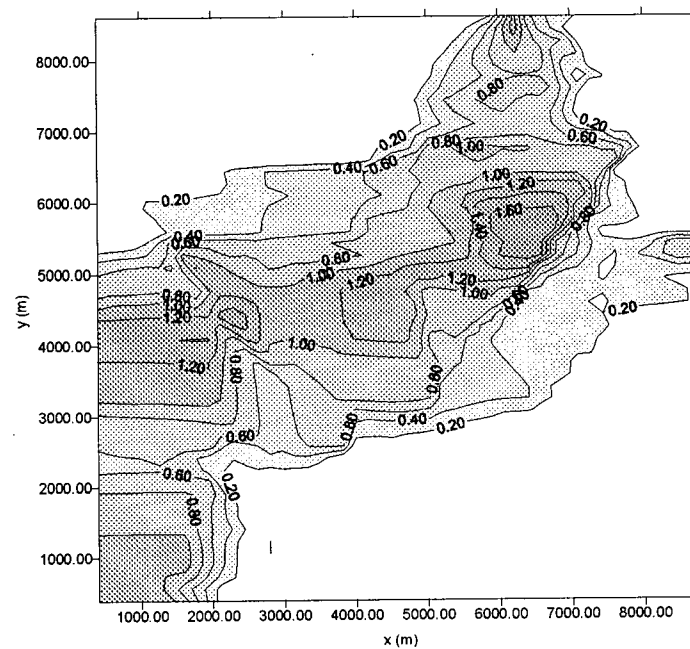


Fig.4.2.28d) Envelope of the maximum values of the water depth in the plane for run SR4 (contour and surface plot).

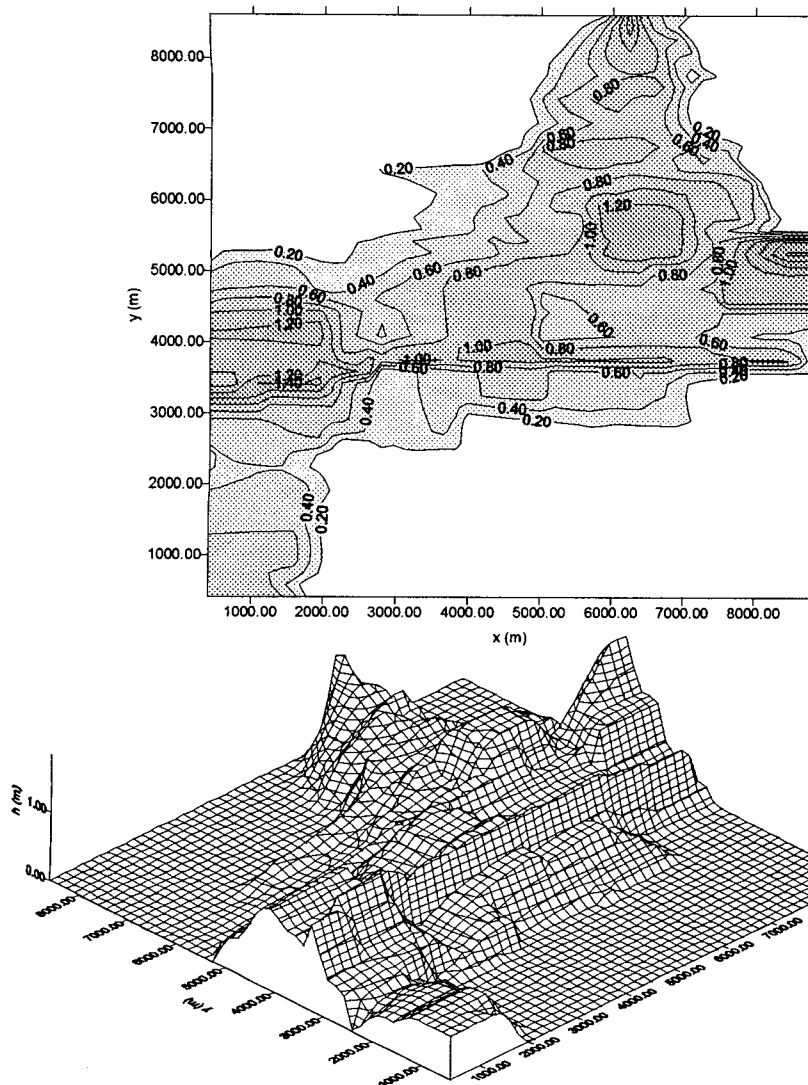


Fig.4.2.28e) Envelope of the maximum values of the water depth in the plane for run SR5 (contour and surface plot).

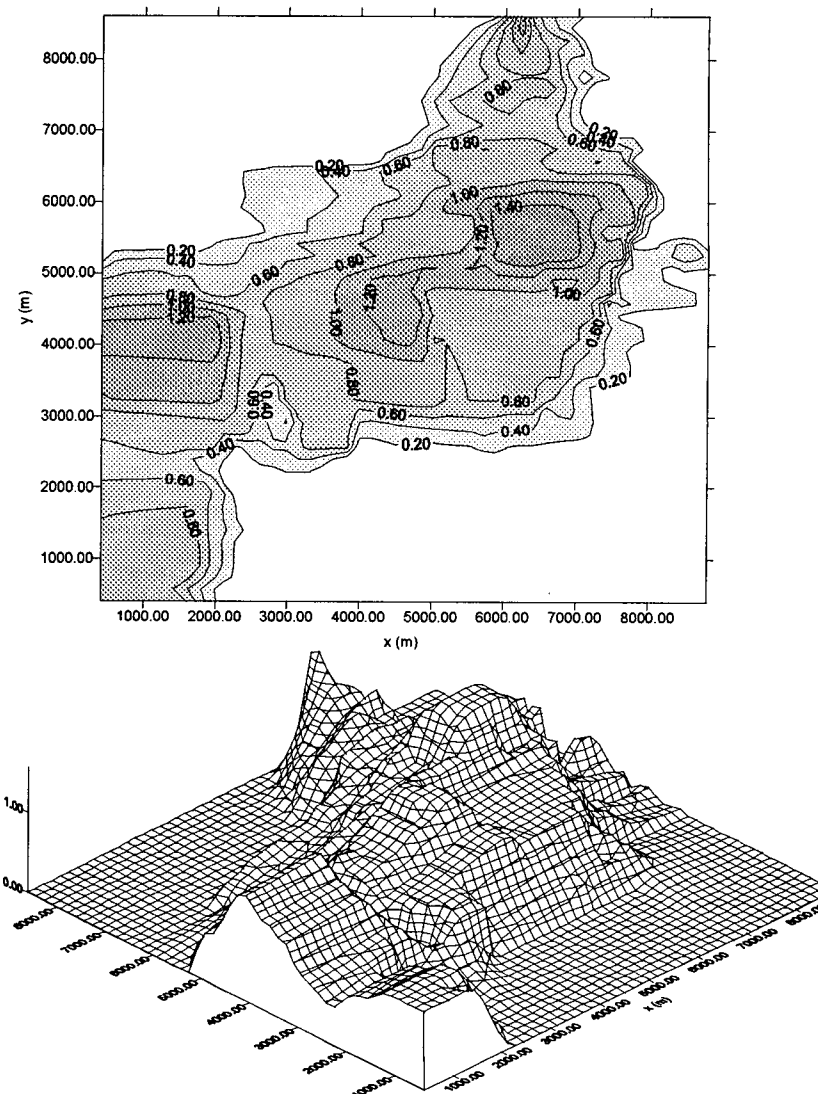


Fig.4.2.28f) Envelope of the maximum values of the water depth in the plane for run SR6 (contour and surface plot).

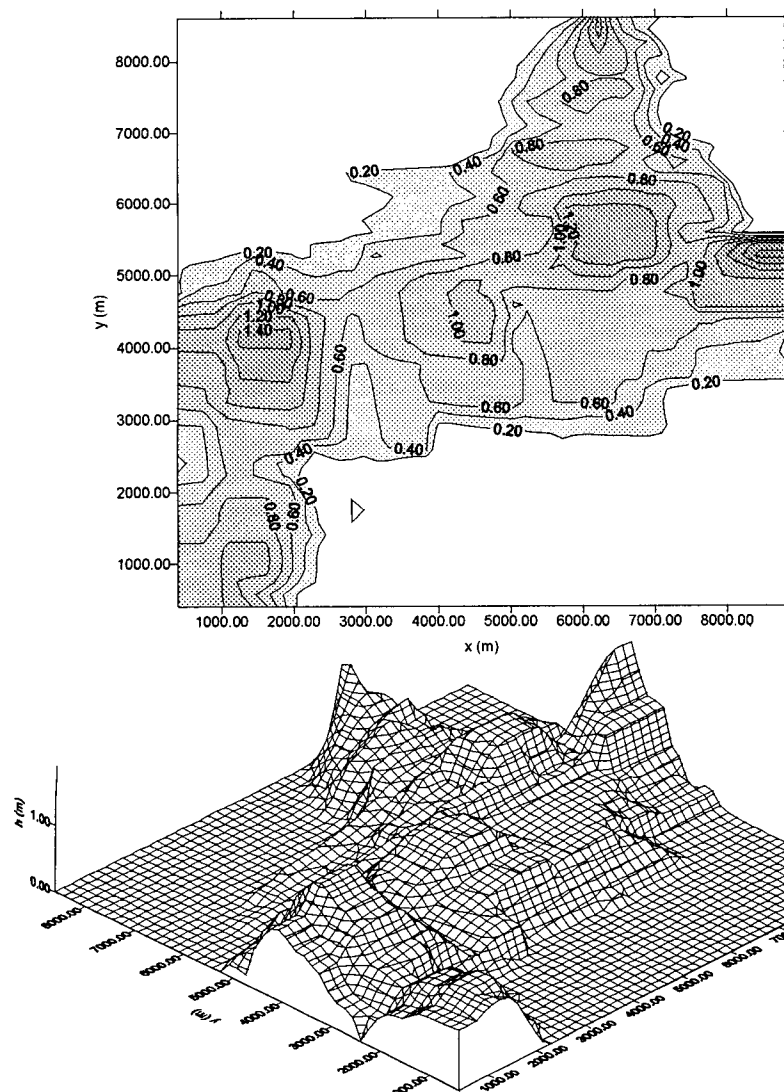


Fig.4.2.28g) Envelope of the maximum values of the water depth in the plane for run SR7 (contour and surface plot).

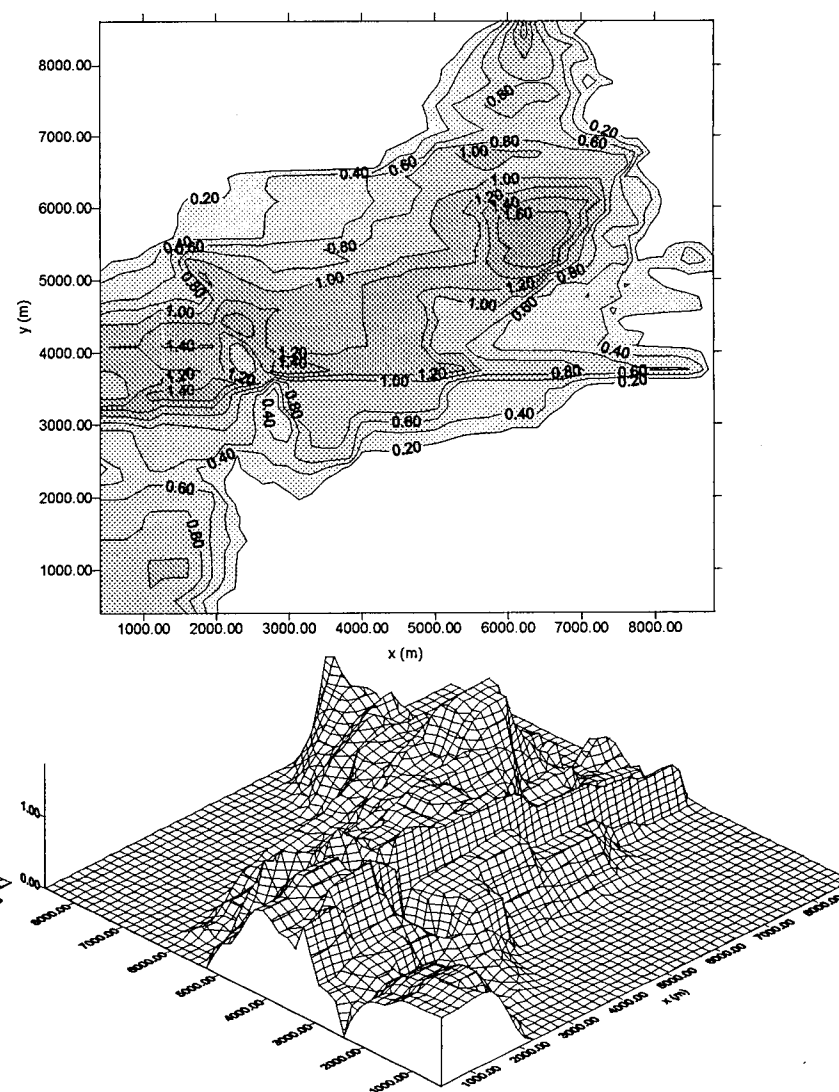


Fig.4.2.28h) Envelope of the maximum values of the water depth in the plane for run SR8 (contour and surface plot).

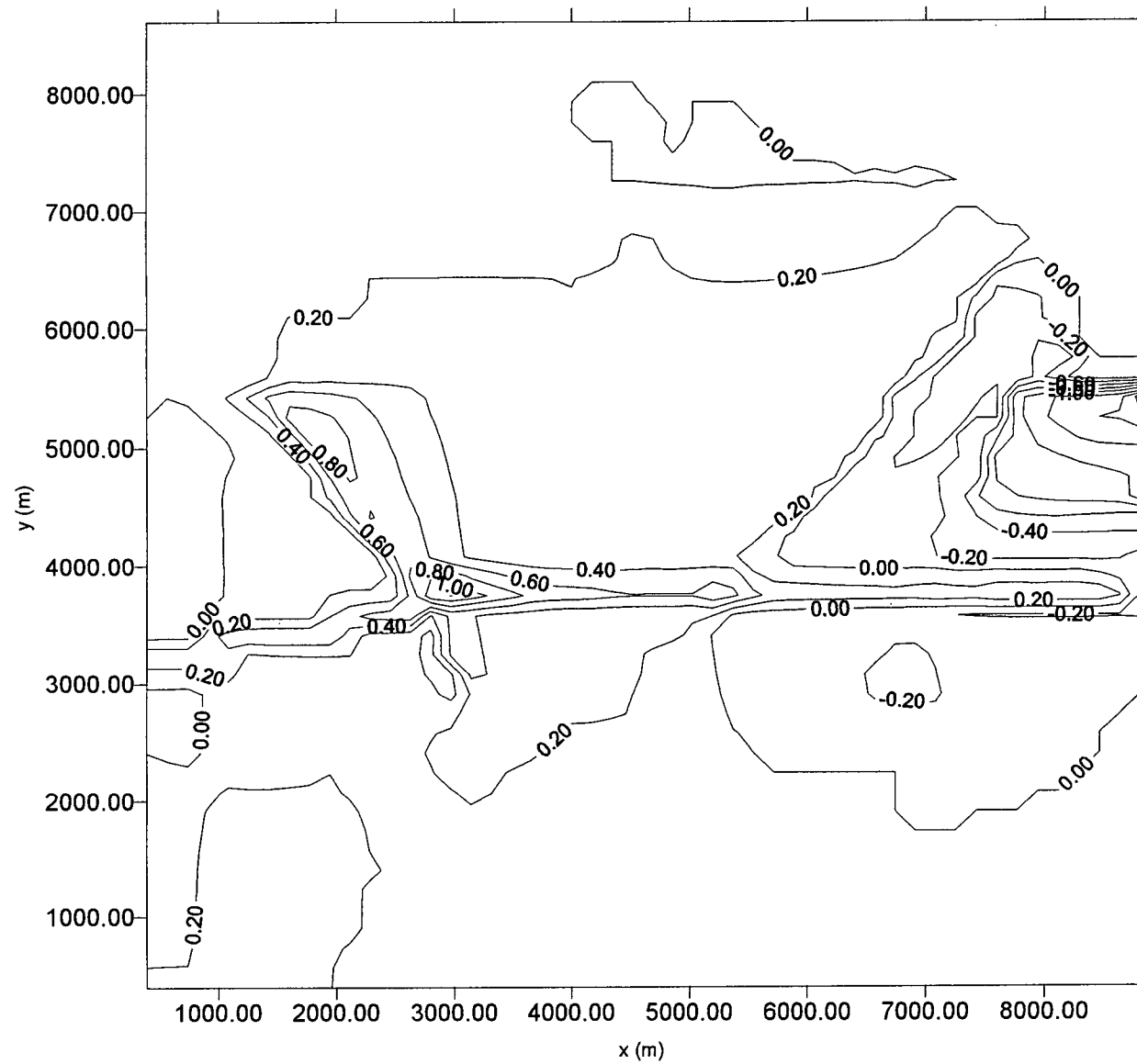


Fig.4.2.29 Differences of water depth between run SR8 (real situation) and SR2 (base condition)

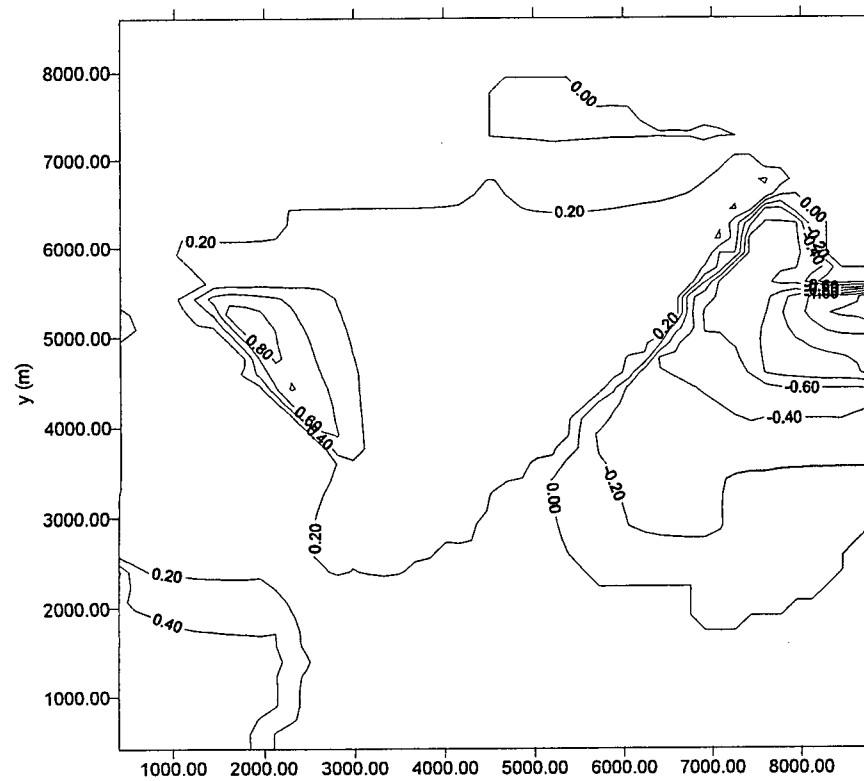


Fig.4.2.30a) Differences of water depth between run SR3 and SR2 (base condition)

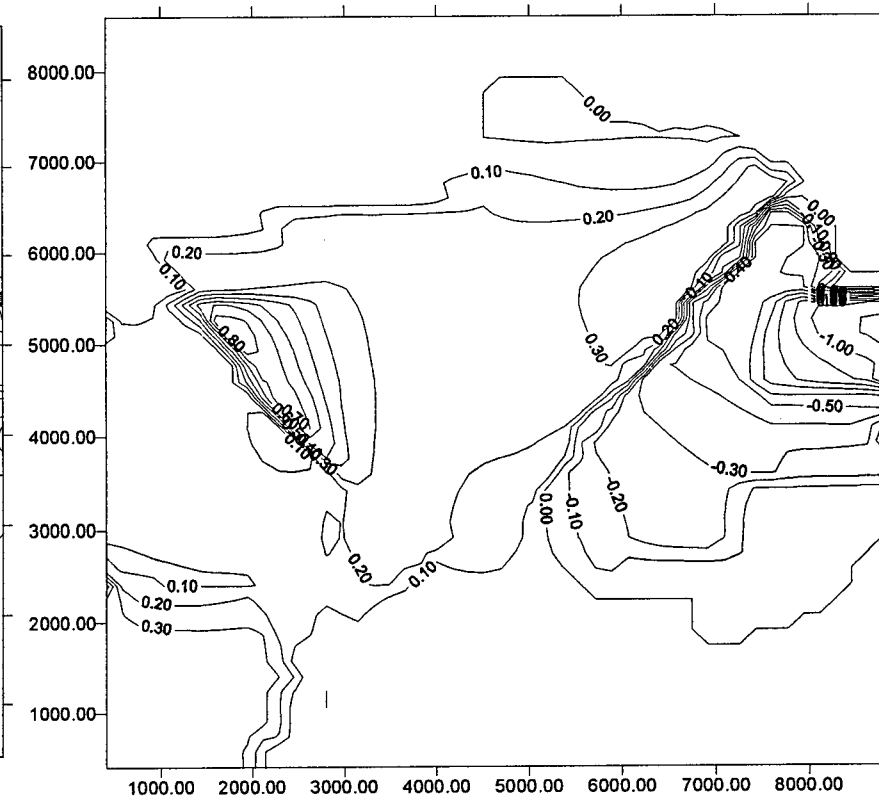


Fig.4.2.30b) Differences of water depth between run SR3 and SR2 (base condition)

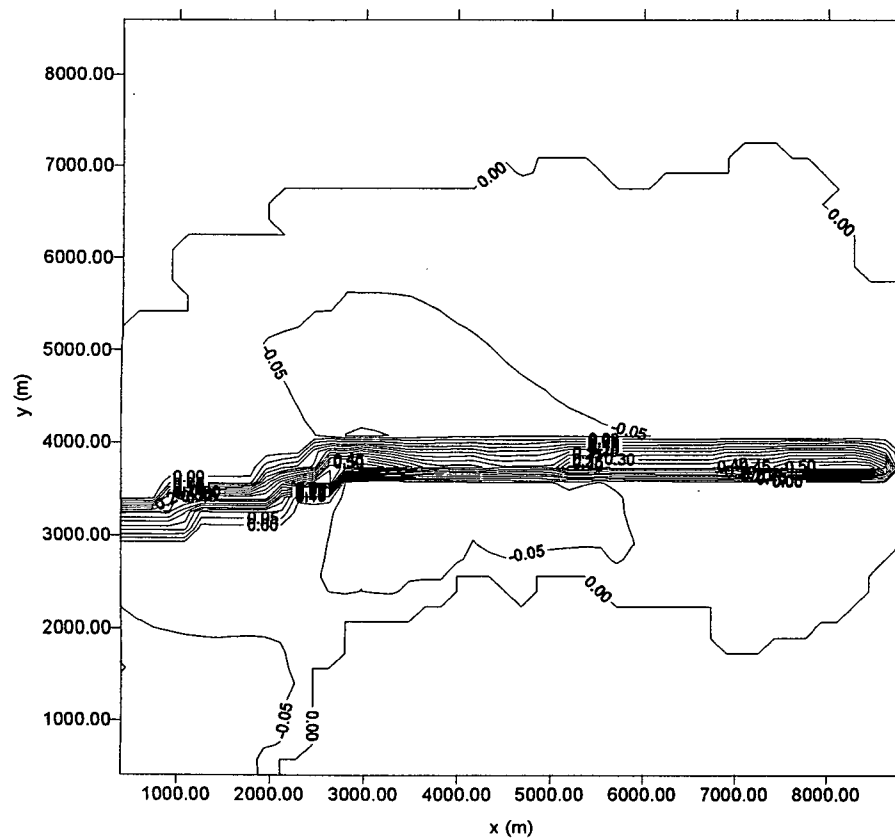


Fig.4.2.30c) Differences of water depth between run SR5 and SR2 (base condition)

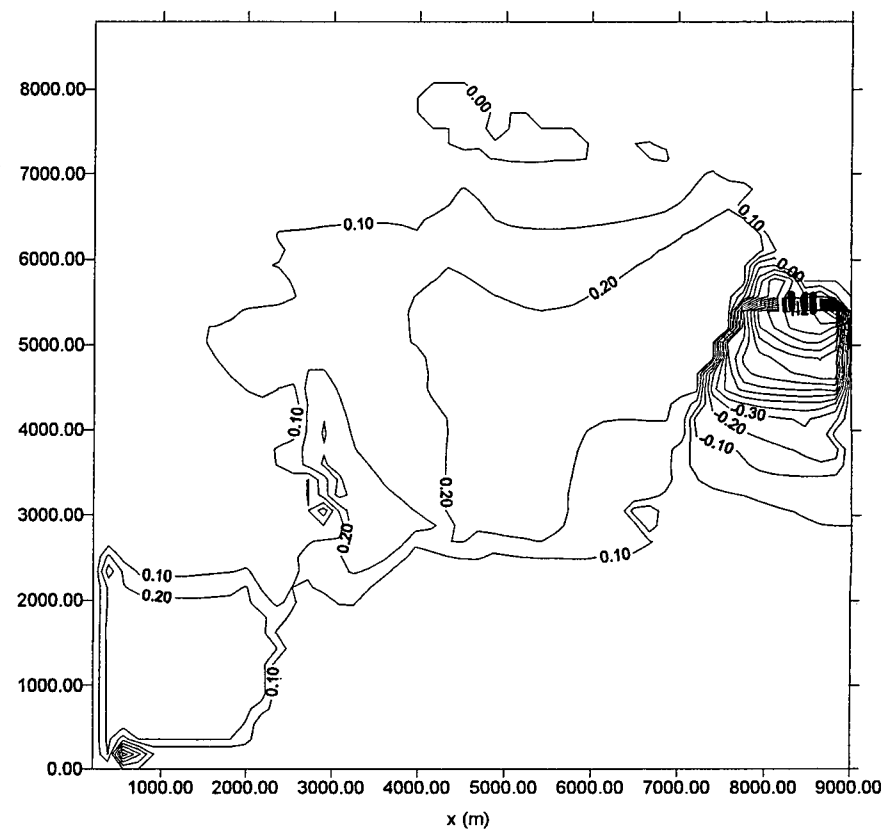


Fig.4.2.30d) Differences of water depth between run SR6 and SR2 (base condition)

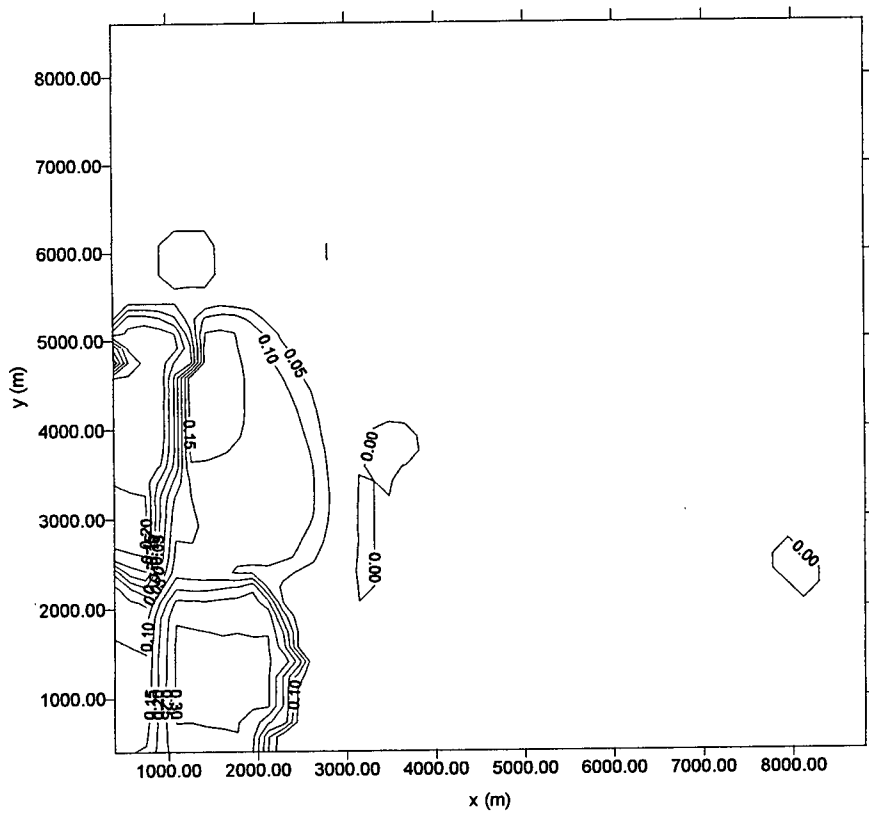


Fig.4.2.30e) Differences of water depth between run SR7 and SR2 (base condition)

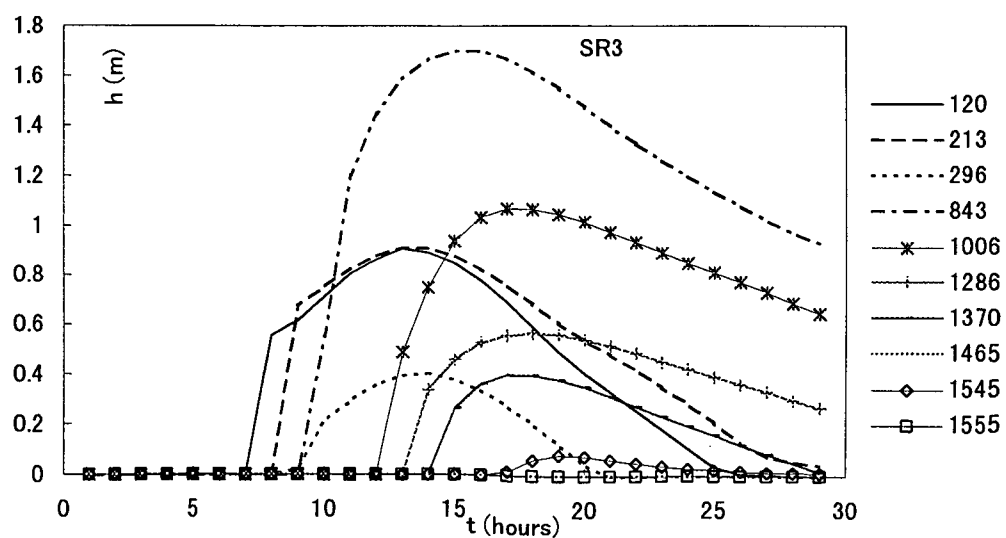
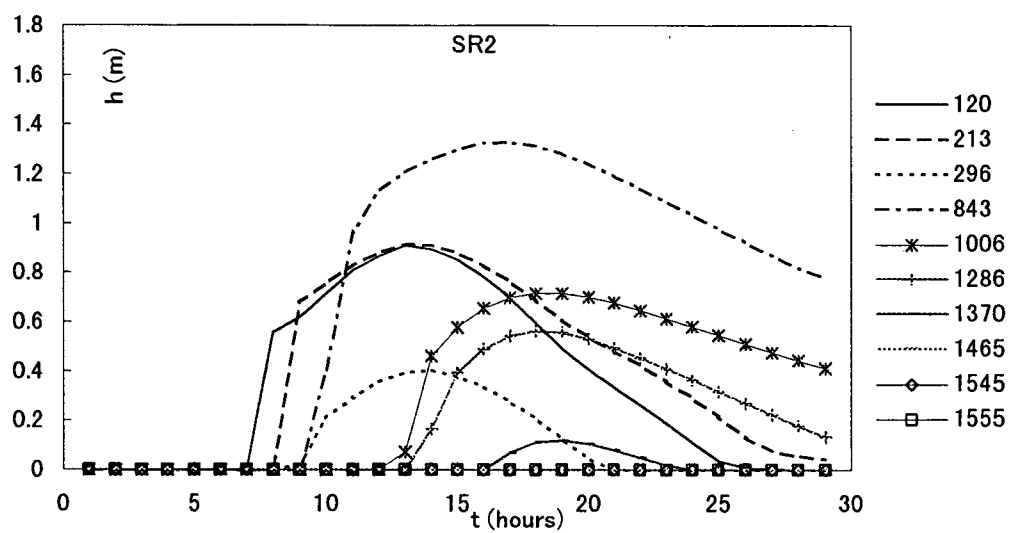
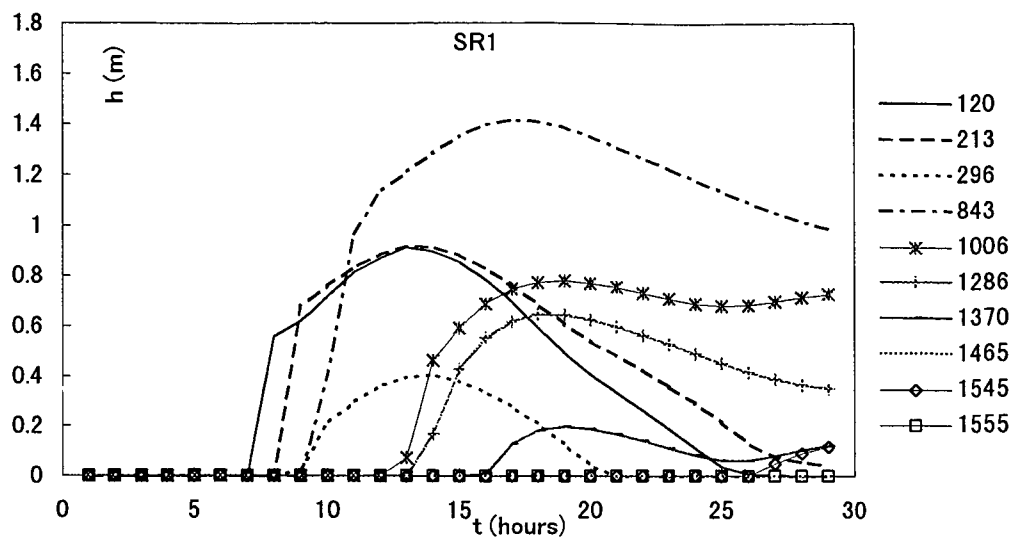


Fig.4.2.31 Water depth as a function of time for selected points

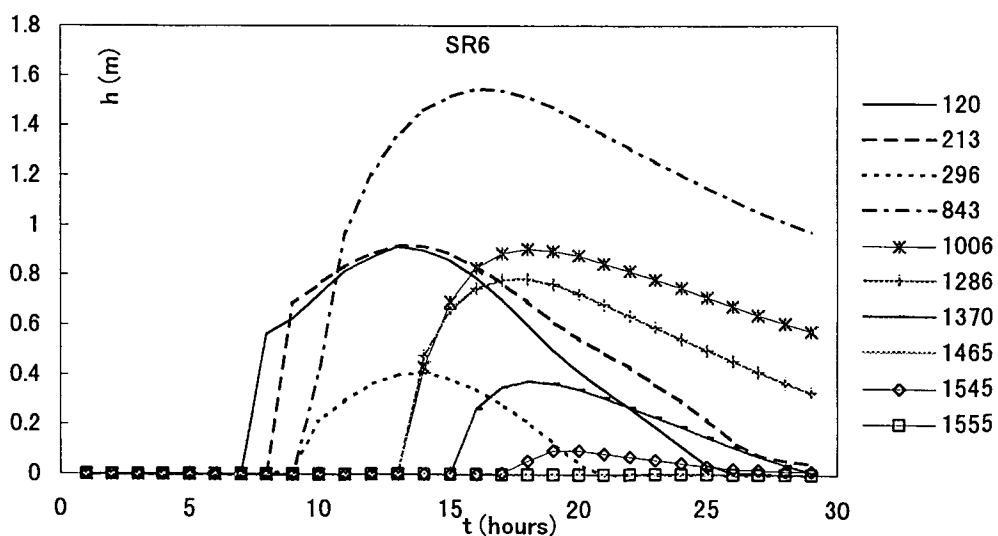
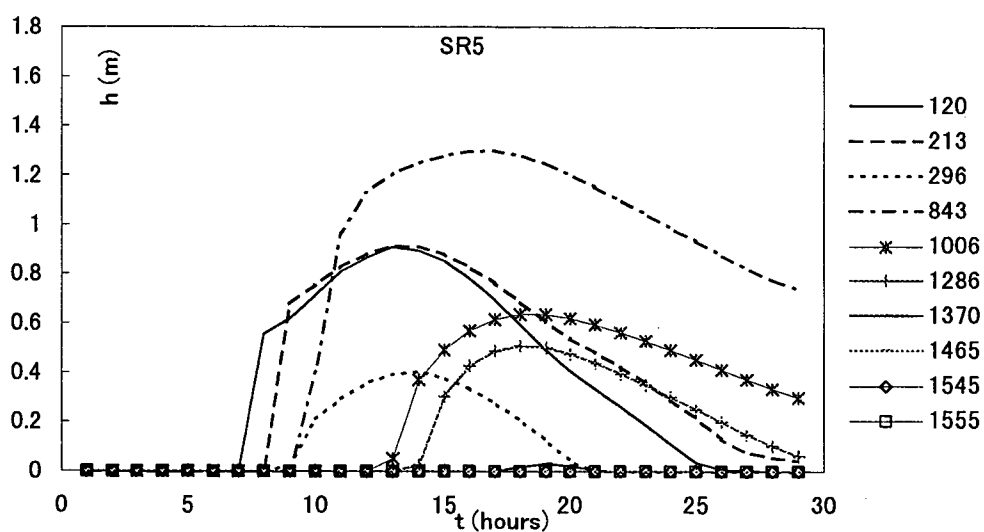
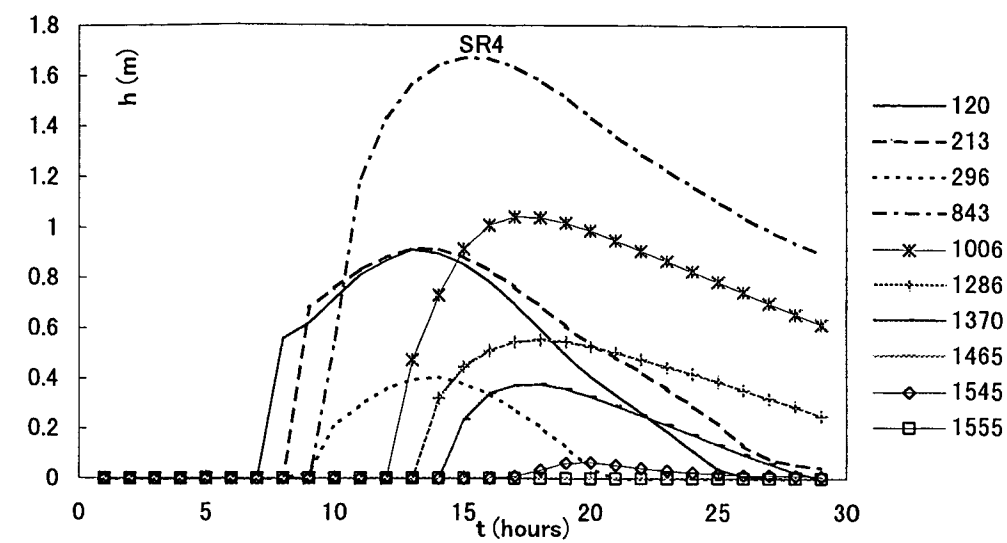


Fig.4.2.31 (continue)

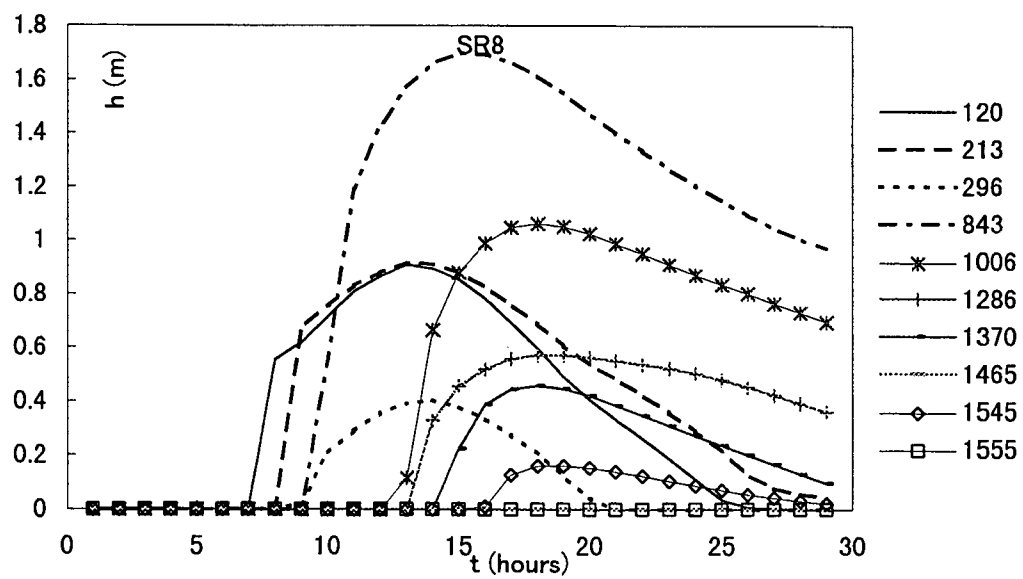
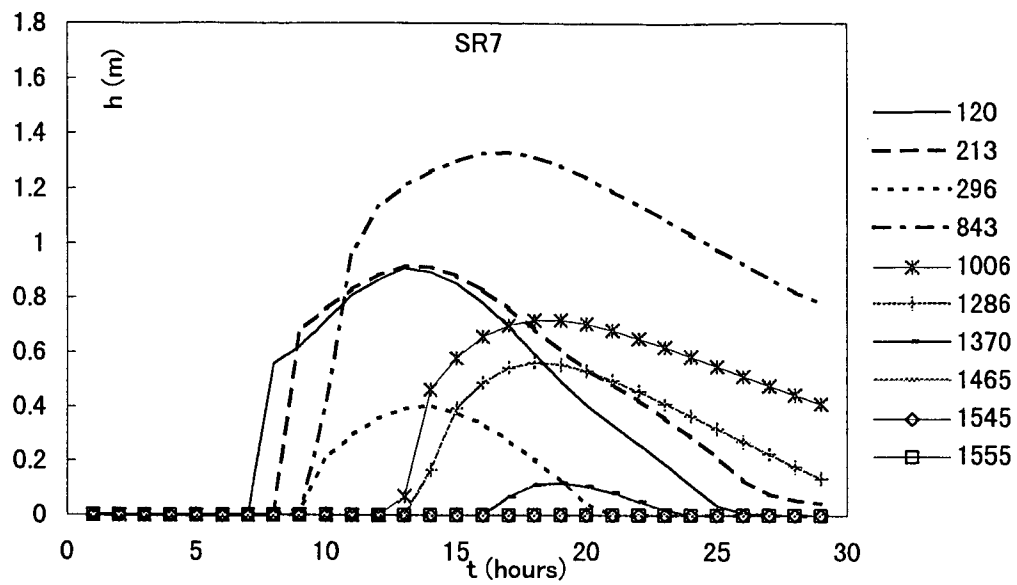


Fig.4.2.31 (continue)

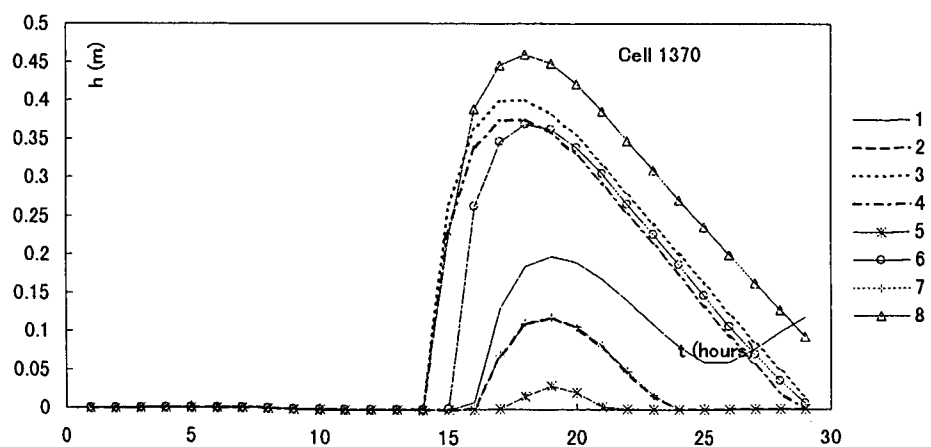
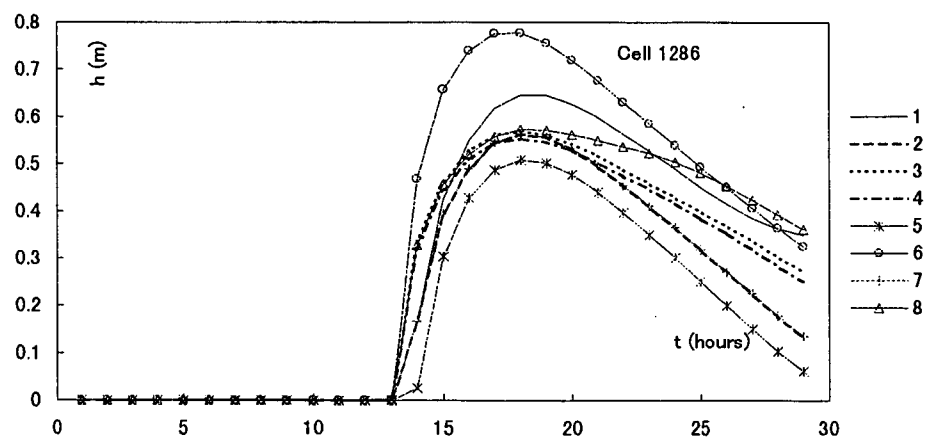
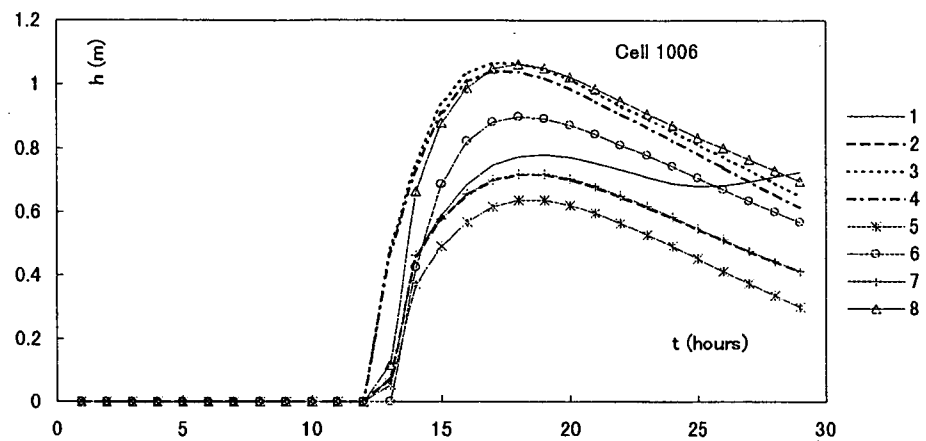
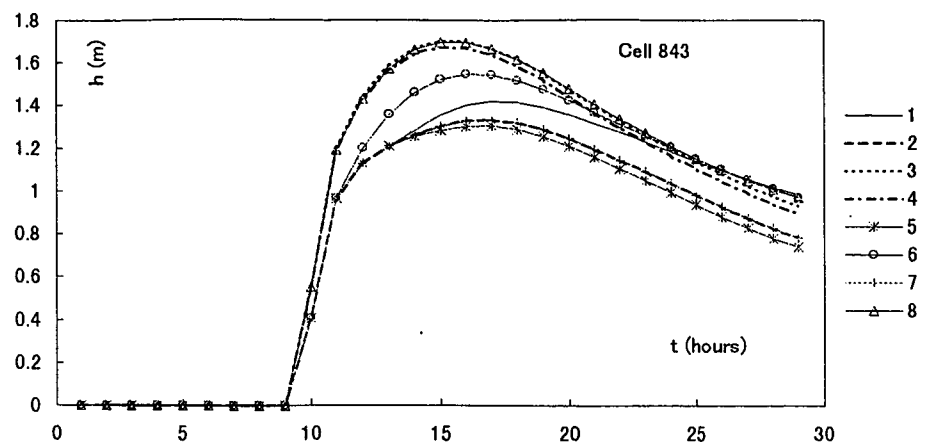


Fig.4.2.32 Depth of water for all the simulations for points 843, 1006, 1286 and 1370

CONCLUSIONS

Numerical simulations of simplified or real inundated plains help in understanding the complex phenomena of floodplain analysis. For this purpose, a two-dimensional unsteady flow model that account for the complete De Saint Venant equations has been used.

The simulations done in chapter three form the basis for a better knowledge of the influence of the various parameters that affect the flooding flow pattern in the case of a very simple and ideal plain. In subchapter 3.1 is reported a comparison between simulations for different values of the roughness coefficient and the urbanization ratio. Results show that the influence of this parameter is important in the propagation of the flood front. In subchapter 3.2, simulations that account for the change in the slope of the plain have been reported. Of course there are appreciable differences in the results also, for change in the slope in the order of 1/10 percent. This is probably the most important parameter to consider in terms of civil protection to quantify the time of arriving of the flooding flow. Subsequently the case in which various banks are present in the plain has been examined. The effect of banks can be important and a key parameter to evaluate a bank effect on the flow propagation is the ratio between the inflow hydrograph and the storage volume due to the presence of the bank itself. The presence of different channels has been analyzed in subchapter 3.4. Results show that a channel that flows perpendicular to the flood direction is the most efficient in terms of drainage of the flooded area and protection of the downstream part. Different shape of the input hydrograph (uniform or triangular in the specific case) has very different effect on the propagation of the flood. In section 3.5 the effects of the mesh size has been reported. The results are practically the same for the different mesh sizes analyzed and this is comforting in case of simulation of large areas in terms of computer resources and simulation time. As a consequence the size of the mesh is constrained only by the correct simulation of structures like roads, banks and channels. Finally, the interaction between river and floodplain accounting for the type of break and the eventual presence of submergence due to the high elevation of the floodplain itself has been analyzed. The importance of a levee that will not break when overtopped is stressed in this part of the work due to the high differences in terms of damage between the two cases.

In Chapter four, a step forward in the real world has been made, by the simulation of a real floodplain in which a levee break causes a flood hydrograph of approximately thirty millions

of cubic meters. The attempt done is to simulate the floodplain between the Serchio river and the city of Pisa in central Italy. The presence, in the inundated plane, of structures like roads, channels, railways and banks of different type complicate the flow pattern. The different simulations analyze the flooding flow each time accounting for the presence of only one structure and finally for the contemporary presence of all the structures.

The results, furnish valuable information about the role that each structure plays in modifying the flooding flow pattern. The worst case, in terms of water depth in the zone is resulted the real one, in which each structure seems to create an obstacle to the flow from the point of view of the protection of urban areas. Some graphs reporting the water depth envelope of the flooded zone are reported for each case examined.

The stress of the work is on the importance of a correct floodplain simulation. This is useful in terms of planning studies and civil protection purposes. In fact each structure that interferes with the floodplain, can change the flow pattern considerably and the effect must be correctly simulated in order to obtain a reliable evaluation of the flooding propagation.

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