“Multidisciplinary approach to karstwater protection strategy”

UNESCO «Erdélyi Mihály» School of Advanced Hydrogeology, Eötvös Loránd University (ELTE)

Short Course, 22-27 August 2005, Budapest (Hungary)

A brief introduction to modeling groundwater flow in karst aquifers

(or how to talk back to models and to modelers…)

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Preliminary remarks

In this short introduction we will not have time to deal with many important technical details. The "absolute beginner" is advised to read the old, but excellent book of Wolfgang Kinzelbach: Groundwater Modelling (Elsevier 1986).

For the more interested persons I put a few papers and some PhD theses on an anonymous ftp site: ftp://sitelftp.unine.ch/Kiraly/Papers Missing references, figures, etc. will be put onto the same site. If you cannot download the files, ask your assistant for a CD-Rom.

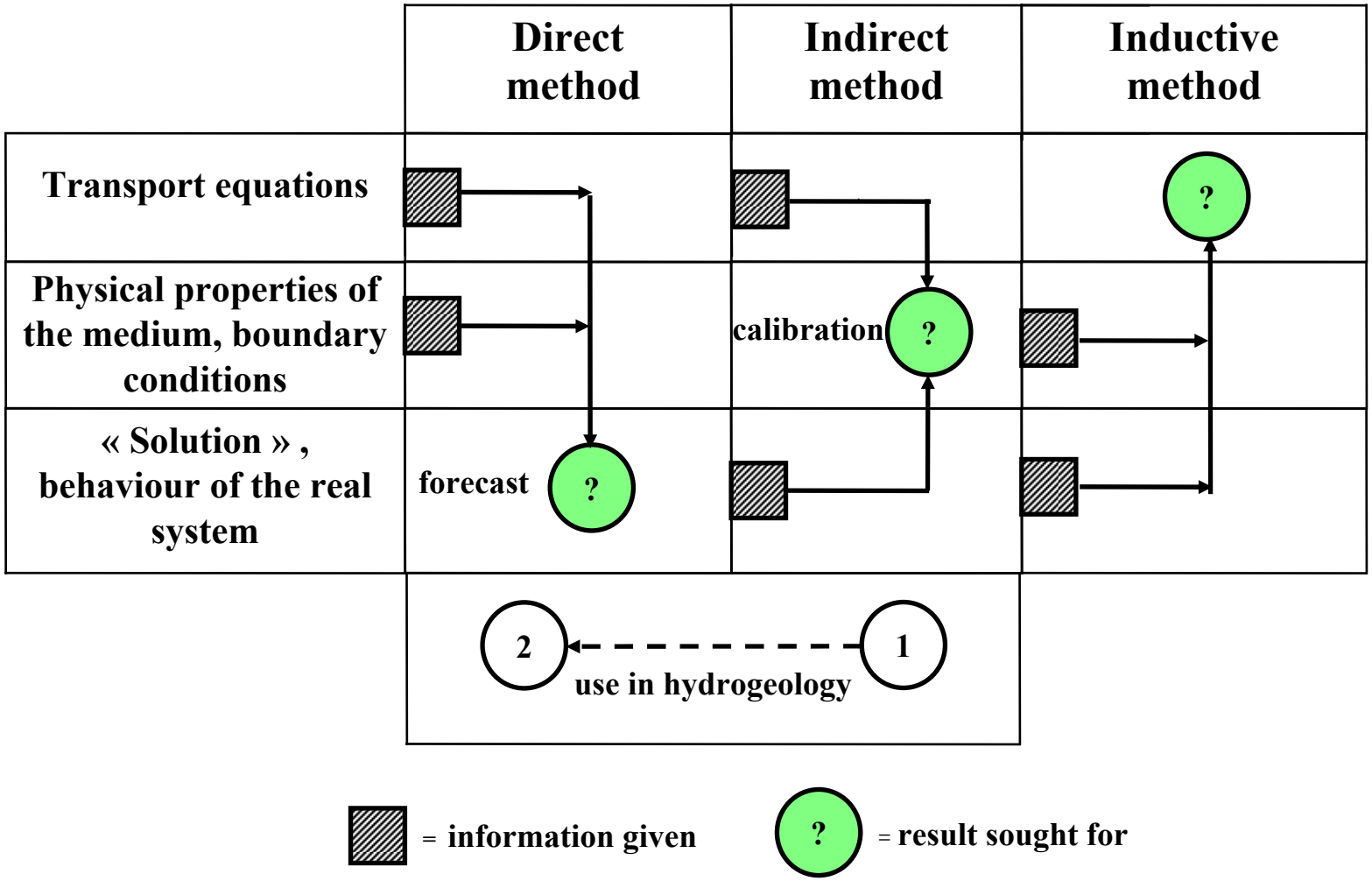
Some interesting papers can be found on the speleogenesis website: http://www.speleogenesis.info

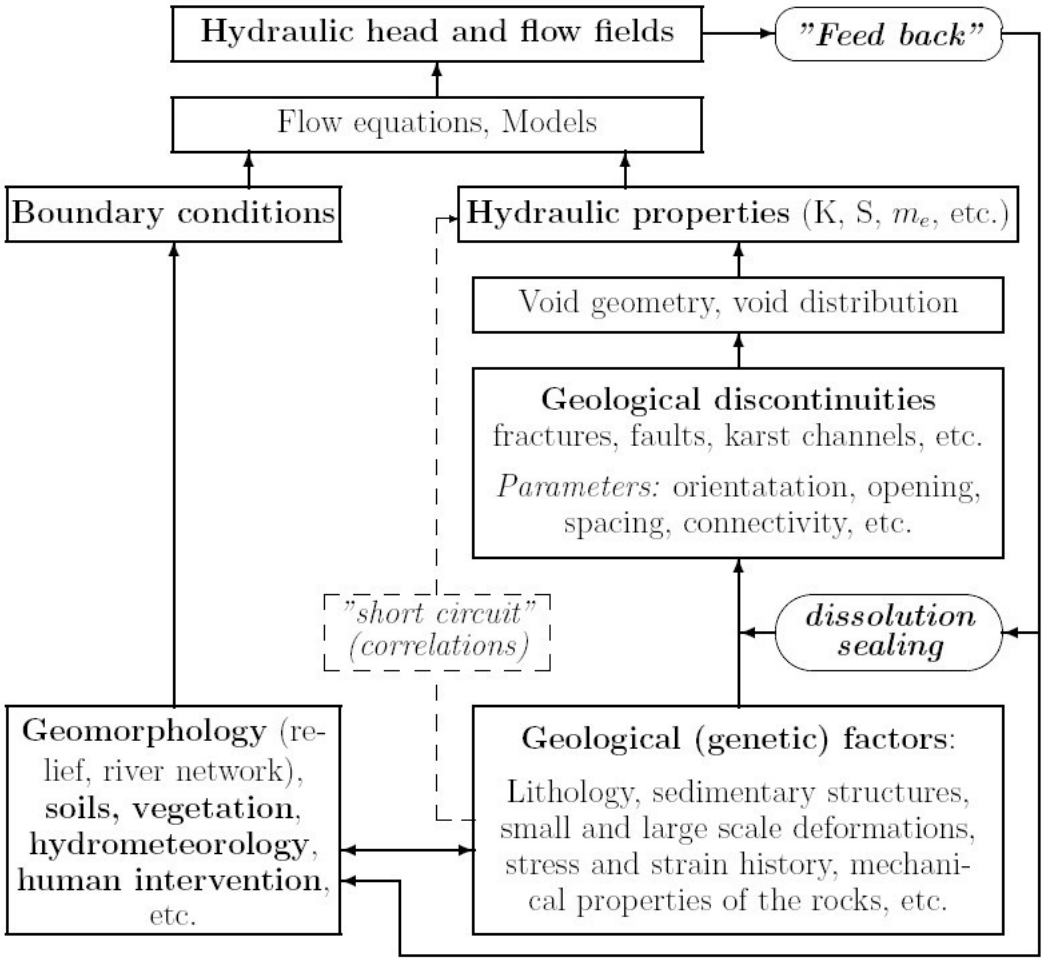
Use of hydrodynamic models from a pragmatic point of view

« TEACHING »	**COMMUNICATION OF THE KNOWLEDGE IN A SYNTHETIC, NON-VERBAL FORM; DEMONSTRATION OF THE CONSEQUENCES OF HYDRAULIC LAWS**
« RESEARCH »	**« UNDERSTANDING » THE BEHAVIOR OF HIGHLY HETEROGENEOUS AQUIFERS (KARST, FRACTURED ROCKS); CHECKING HYPOTHESES ON FLOW, TRANSPORT OR KARST GENETIC PROCESSES**
« PRACTICE »	**FORCASTING FLOW AND TRANSPORT UNDER NATURAL CONDITIONS AND UNDER HUMAN INTERVENTION; SOLVING GROUNDWATER MANAGEMENT PROBLEMS**

« Karst models » are used mainly in teaching and research. Lack of information on the real karst channel network greatly hinders their use for real-world problems

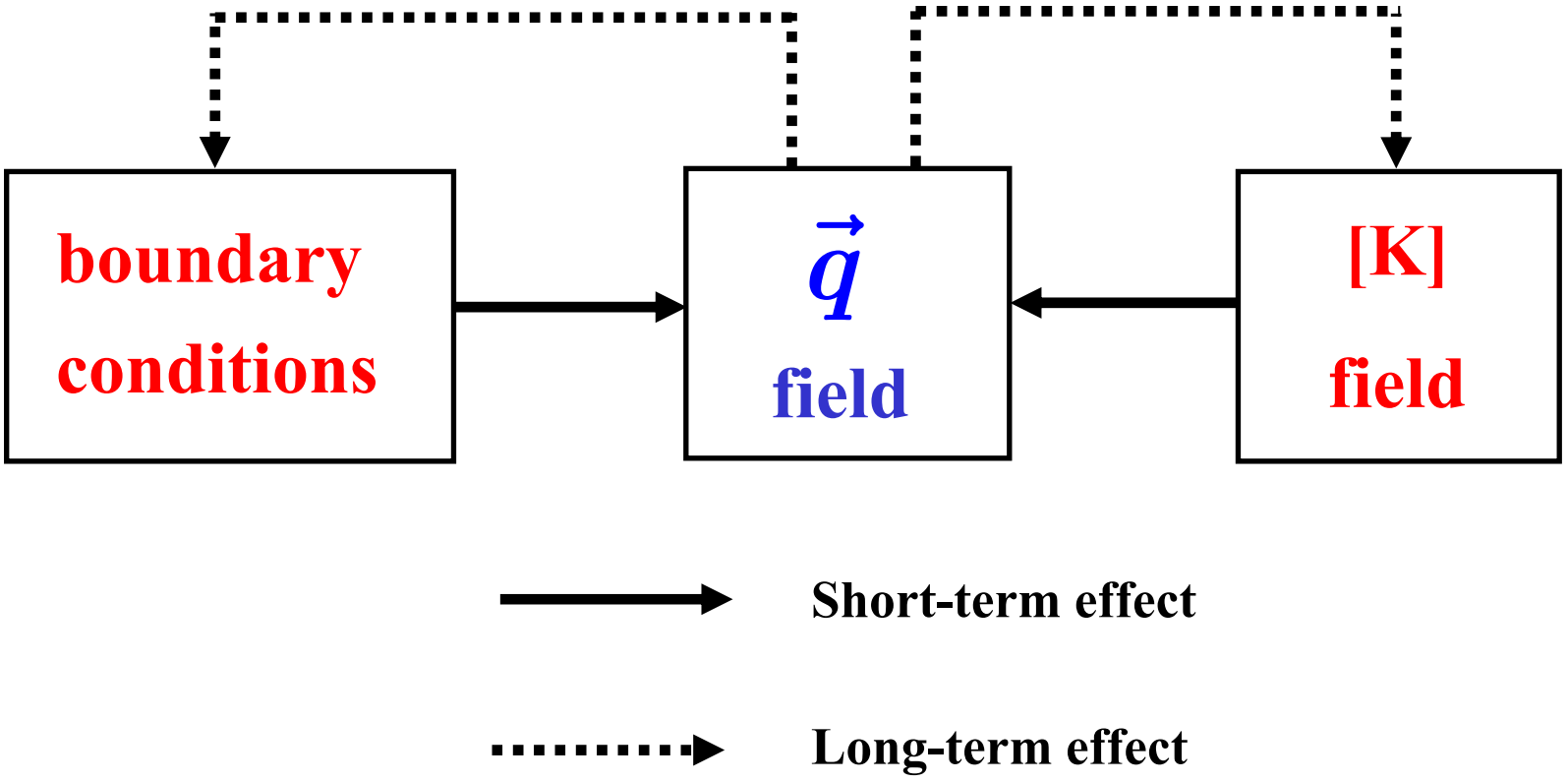
Direct, indirect and inductive use of models (after Szűcs E. 1971)





Karst aquifer as a partly self-organizing system: feed-back of the flow field on the hydraulic parameter fields and the boundary conditions

« Selfregulation » in karst aquifers



Representation of the principal problems in modelling groundwater flow

ABSTRACT SCHEME

$$S\,\frac{\partial h}{\partial t} + div\,(-[K]\;\vec{grad}\,h) + Q = 0$$

Equations representing the "abstract scheme" of the groundwater flow. Generally, their validity depends on a number of restrictive hypotheses in a more general theoretical framework. The complete statement of the flow problem requires the definition of the following data fields (they represent the "abstract scheme" of a particular aquifer):

Geometry
Define the limits of the region to be modelled

K field
Give to each point of the region a value of K

S field
Give to each point of the region a value of S

Imposed conditions
Impose to each point of the region either $h(t)$ or $Q(t)$

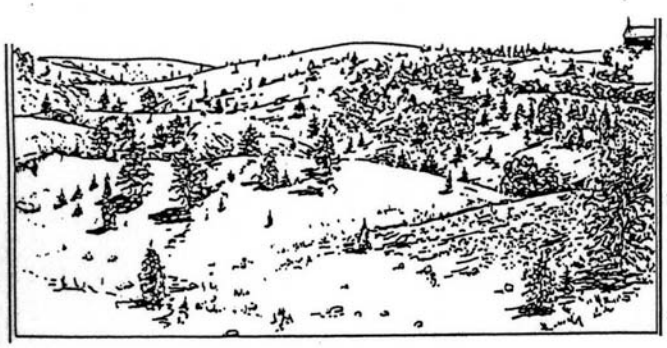
Initial conditions
Give to each point of the region a value of h at time $t = t_0$

Abstraction

Realization ??

Realization

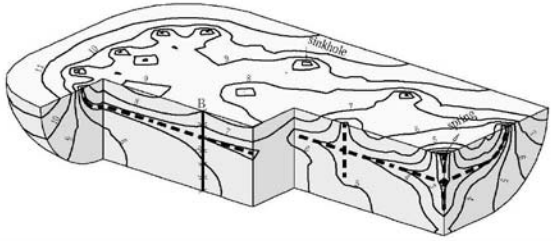
REAL SYSTEM



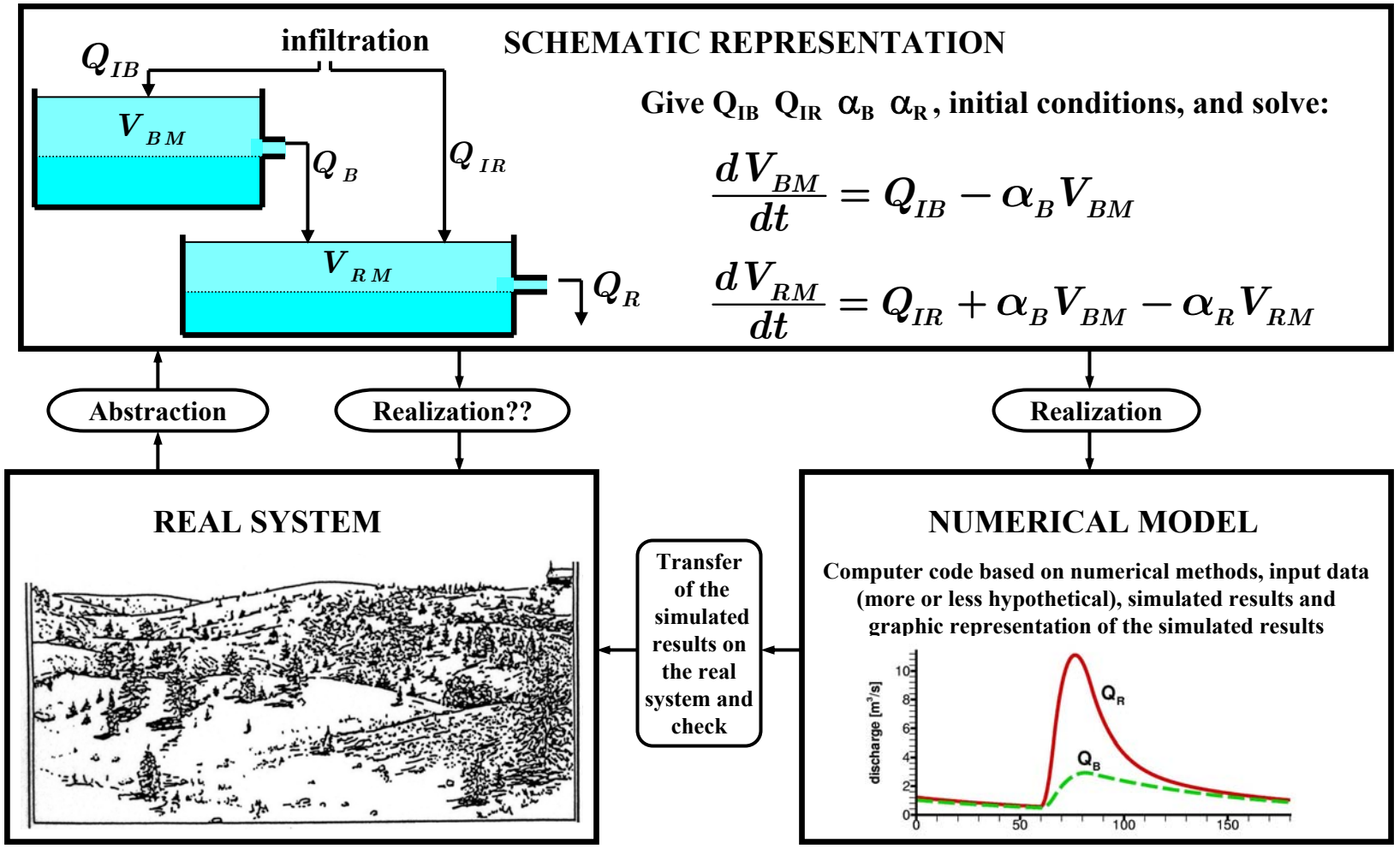
Transfer of the simulated results on the real system and check

NUMERICAL MODEL

- Computer code (based on numerical methods)
- Input data (mainly hypothetical due to interpolation)
- Simulated results (consequences of the input data)
- Graphic representation of the simulated results



Representation of the principal problems in modeling groundwater flow



Depending on the problem to solve, the same real system may be represented by very different schematic representations

We are free to invent any inevitably hypothetical and schematic representation of the real system, which helps to solve a problem (this a question of inspiration)

But then we have to:

1. **Deduce the verifiable consequences of the assumed hypotheses**
2. **Check the consistency of the schematic representation in a larger theoretical framework (do learn physics and some math!)**
3. **Check by direct or indirect experimental methods whether the real system may (or may not) be considered as a realization of the proposed scheme (do not forget the field work!)**

(this requires perspiration)

Transfer of the simulated results onto the real system

Strictly speaking, the simulated results are not "valid" but in the highly simplified numerical model. Their meaningful transfer onto the real system requires that simplifying assumptions and uncertainties on the data explicitly do appear as uncertainties on the results. This could help to avoid such ridiculous situations as trying to simulate observed piezometric heads to within a few centimeters, even though the simplified hydraulic conductivity field in the model "ignores" the strong local heterogeneities existing in the real system.

The transfer is possible if both the numerical model and the real system may be considered as being, to some extent and from a certain point of view, the realizations of the same schematic representation. The central role played by the schematic representation might seem surprising, but it is the only thing we really know, because we have created it.

Modelling is not just curve fitting!!

FOR A GOOD MATHEMATICAL MODEL IT IS NOT ENOUGH TO WORK WELL

IT MUST WORK WELL FOR THE RIGHT REASONS!! (V. Klemes, 1986)

What are the « right reasons » a model should respect when simulating flow and transport in karst aquifers?

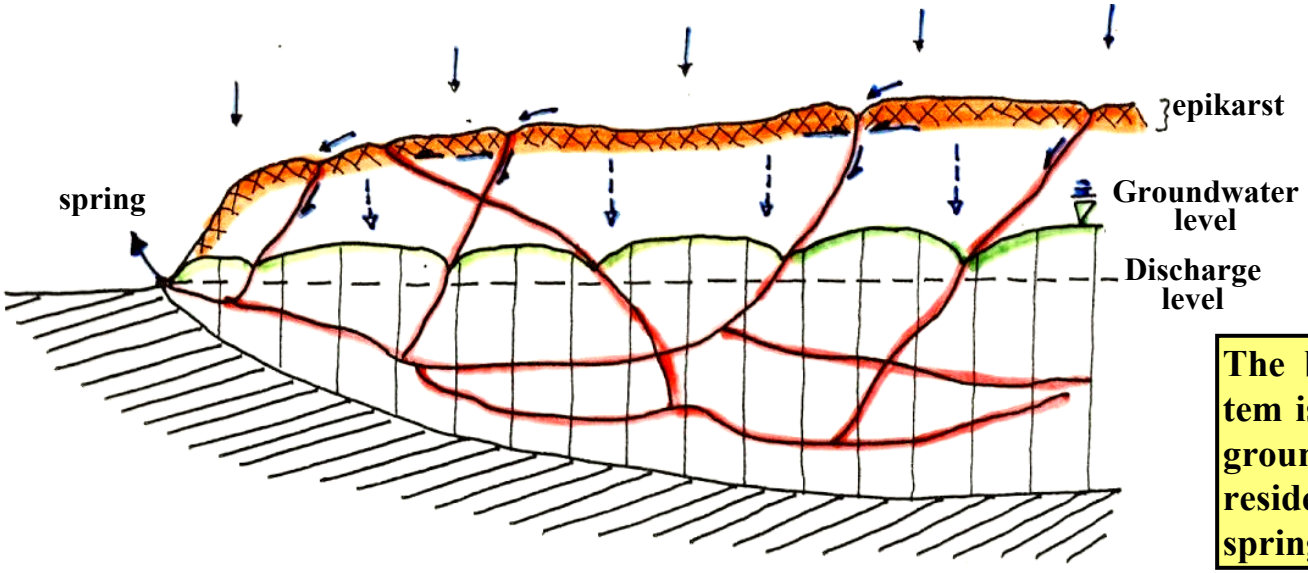
The DUALITY of karst (effect on permeability, infiltration, discharge)

The NESTED STRUCTURE OF DISCONTINUITIES with « meshes » of different order of magnitudes.

The SCALE EFFECT on the HYDRAULIC CONDUCTIVITY

The typical KARSTIC HYDROGRAPHS of karst springs

« DUALITY » OF KARST



The behaviour of the whole system is determined by this duality: groundwater level, flow velocities, residence times, head distribution, spring hydrograph, chemistry, etc.

PERMEABILITY

1. High permeability karstic network « immersed » in
2. Low permeability fractured rock volumes

INFILTRATION

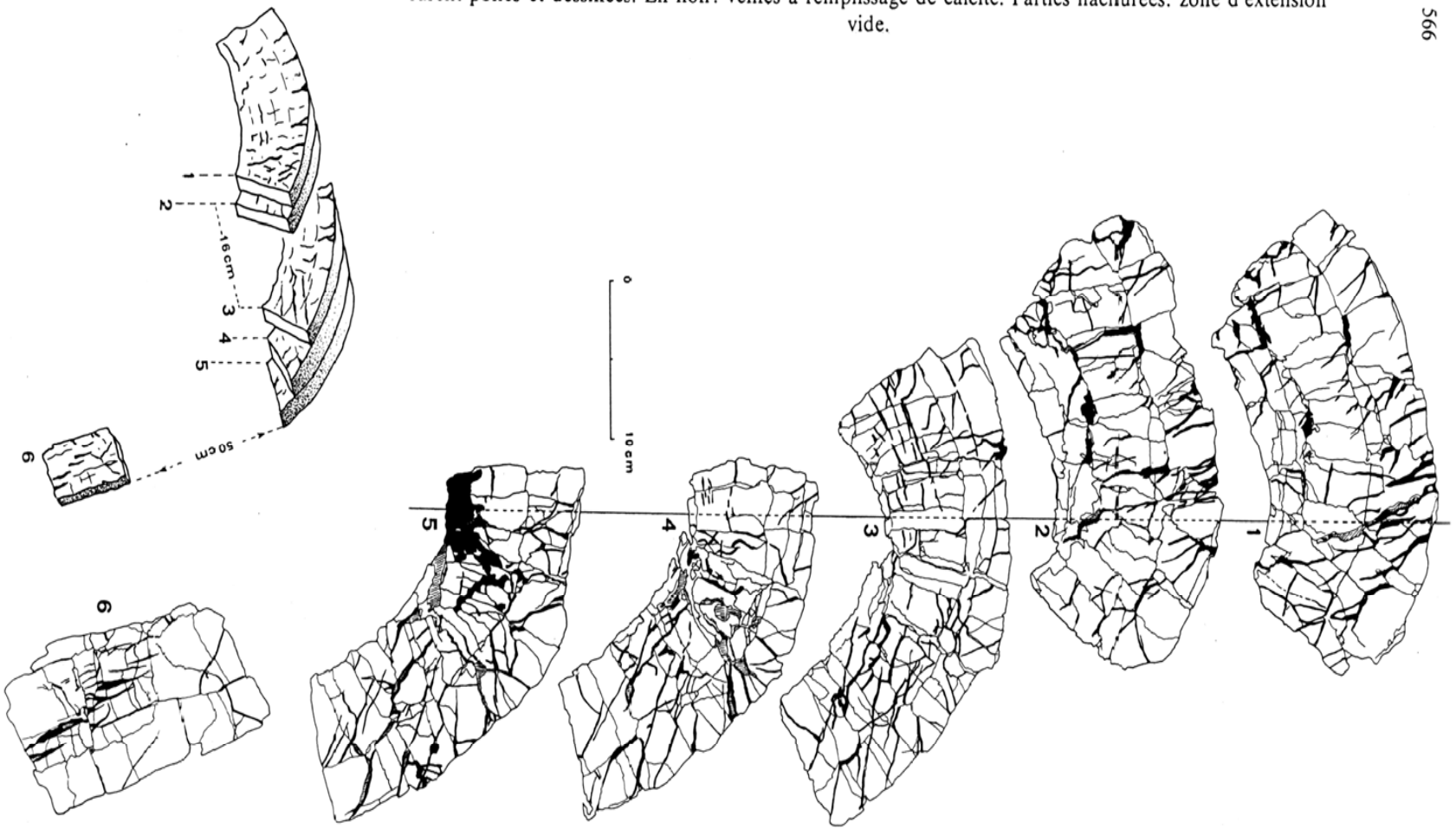
1. High intensity (« concentrated ») input into the karstic network (dolines, drainage in the epikarst zone)
2. Low intensity (« diffuse ») percolation through the low permeability fractured volumes

DISCHARGE

1. « Concentrated » from the channel network at karst springs
2. « Diffuse » from the low permeability volumes

Nested network of discontinuities of different magnitude

Fig. 13. Plis dans calcaire micritique de la base de l'Argovien, région «Vorpet» (coord. 544.975/212.780).
Le pli d'entraînement a été scié en tranches de 2 à 3 cm d'épaisseur. Un certain nombre de surfaces furent polies et dessinées. En noir: veines à remplissage de calcite. Parties hachurées: zone d'extension vide.



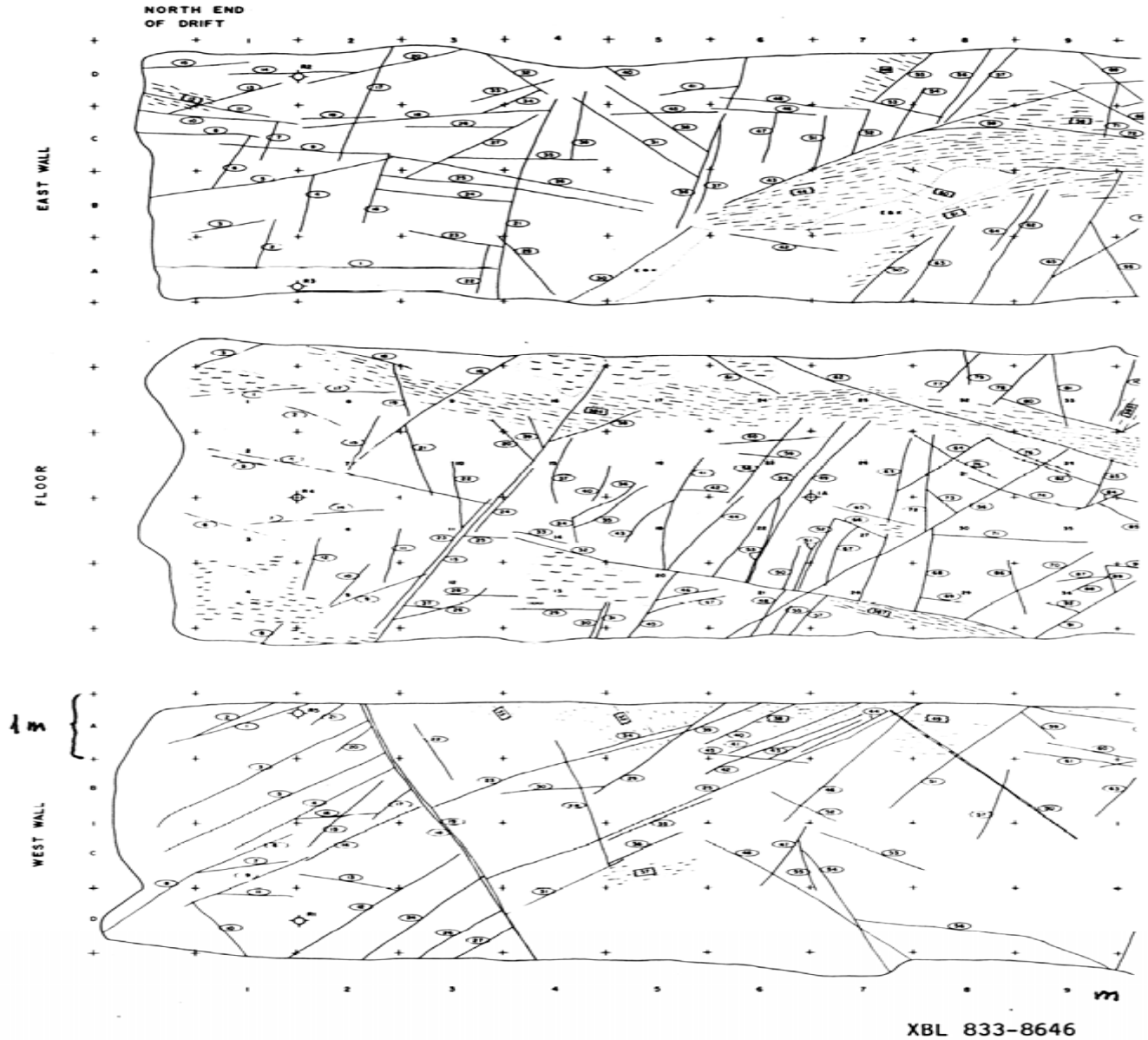


Fig. 2.1 Fracture map B - north end of drift

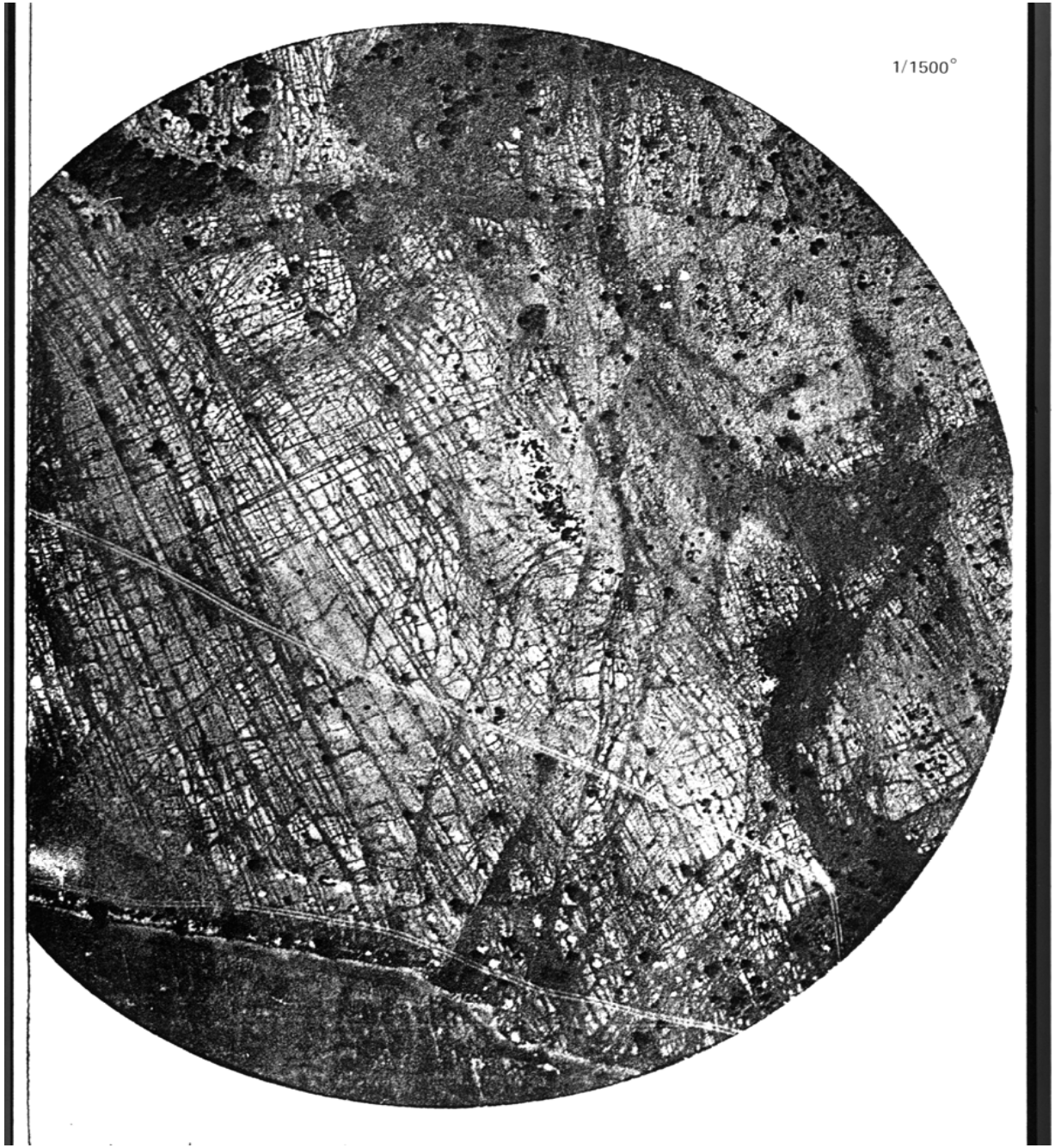
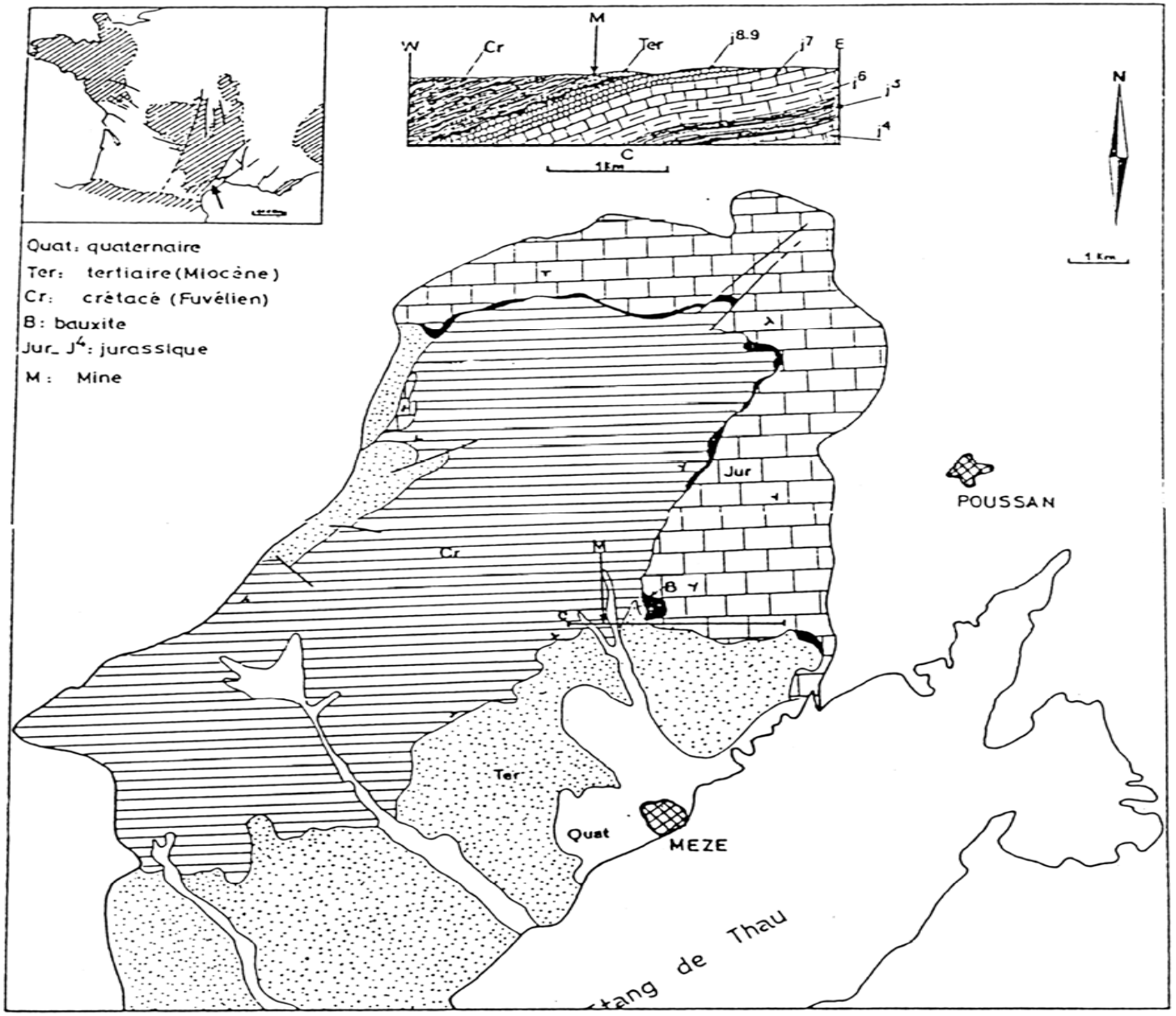
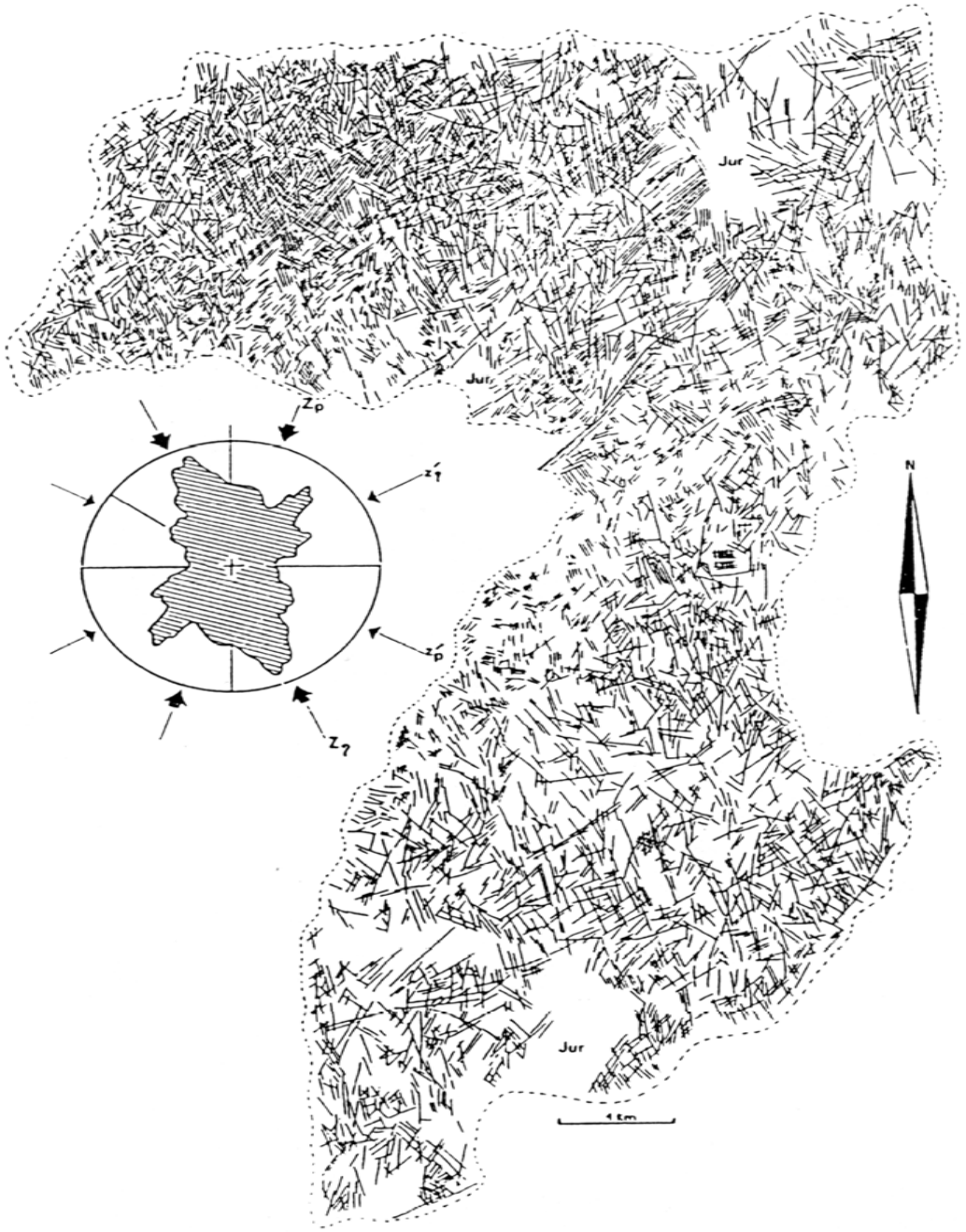
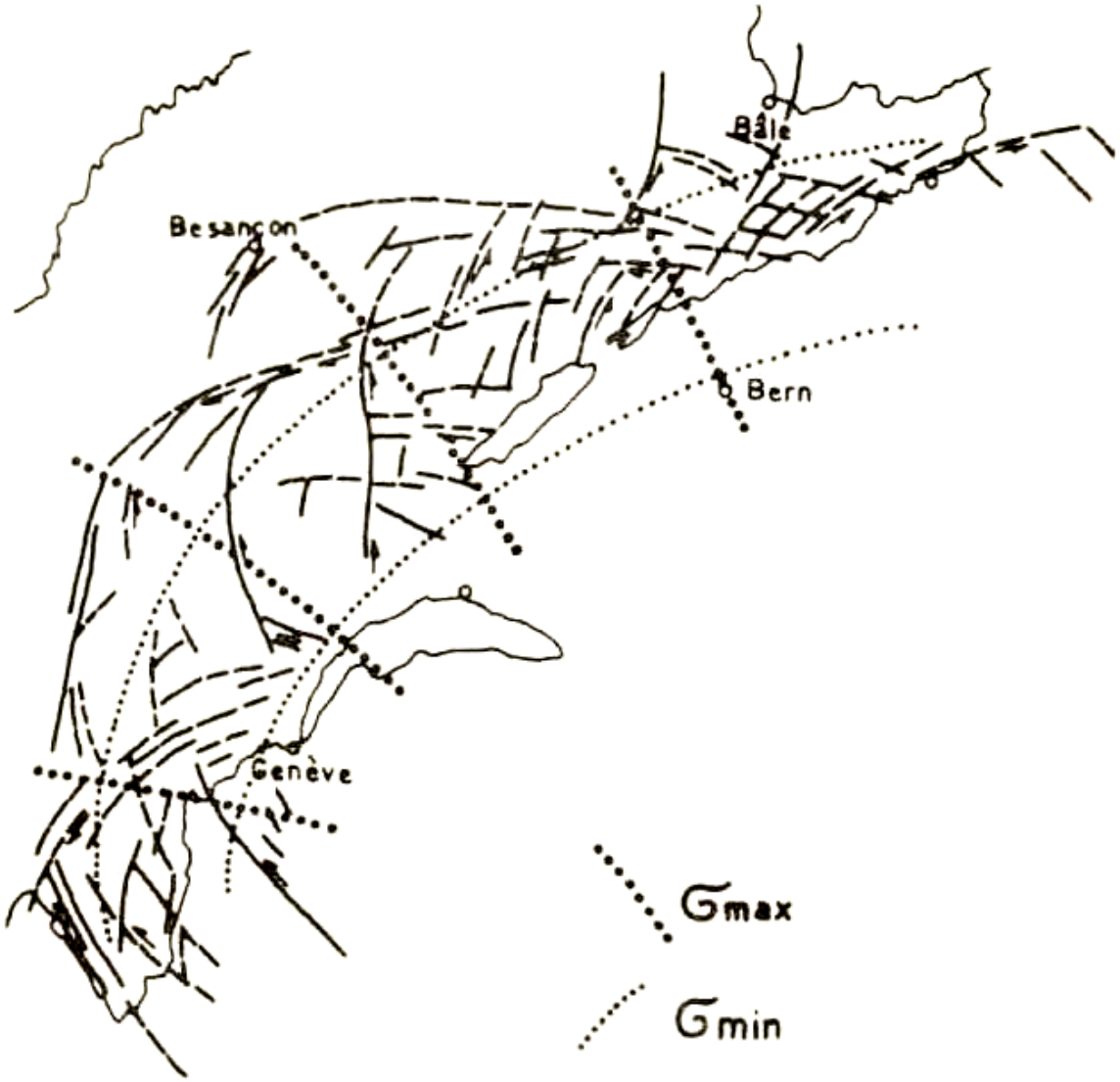

1/1500°

FIGURE 6–2 Vertical aerial view showing joints in the flat-lying Cedar Mesa Sandstone (Permian) in Canyonlands National Park, Utah. The two sets of systematic joints intersect with an angle of 70° and crosscut each other without deflection. A rose diagram of the orientations of the systematic joints is shown. The nonsystematic joints do not crosscut the systematic joints, but abut them at a high angle, approaching 90°. The area of the photograph is about 500 m by 700 m. (Photograph by George E. McGill.)


M
W
Cr
Ter
j8.9
j7
E
j6
j5
j4
C
1 km
N
1 km
Quat: quaternaire
Ter: tertiaire (Miocène)
Cr: crétacé (Fuvélien)
B: bauxite
Jur_ J4: jurassique
M: Mine
Jur
POUSSAN
Cr
M
B
Ter
Quat
MEZE
Thau

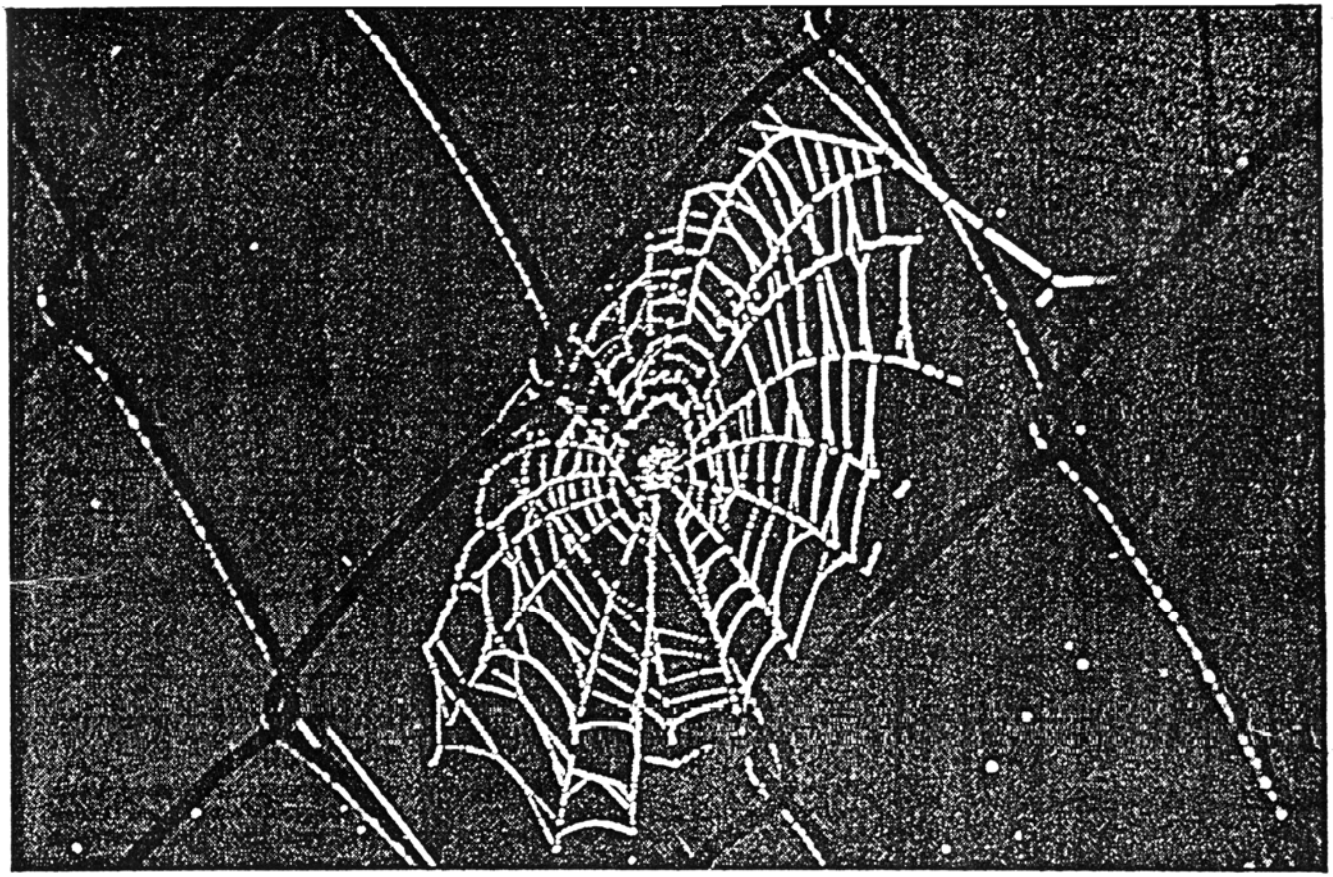

Jur
Jur
Jur
Zp
Z'T
Z'p
ZT
N
1 km



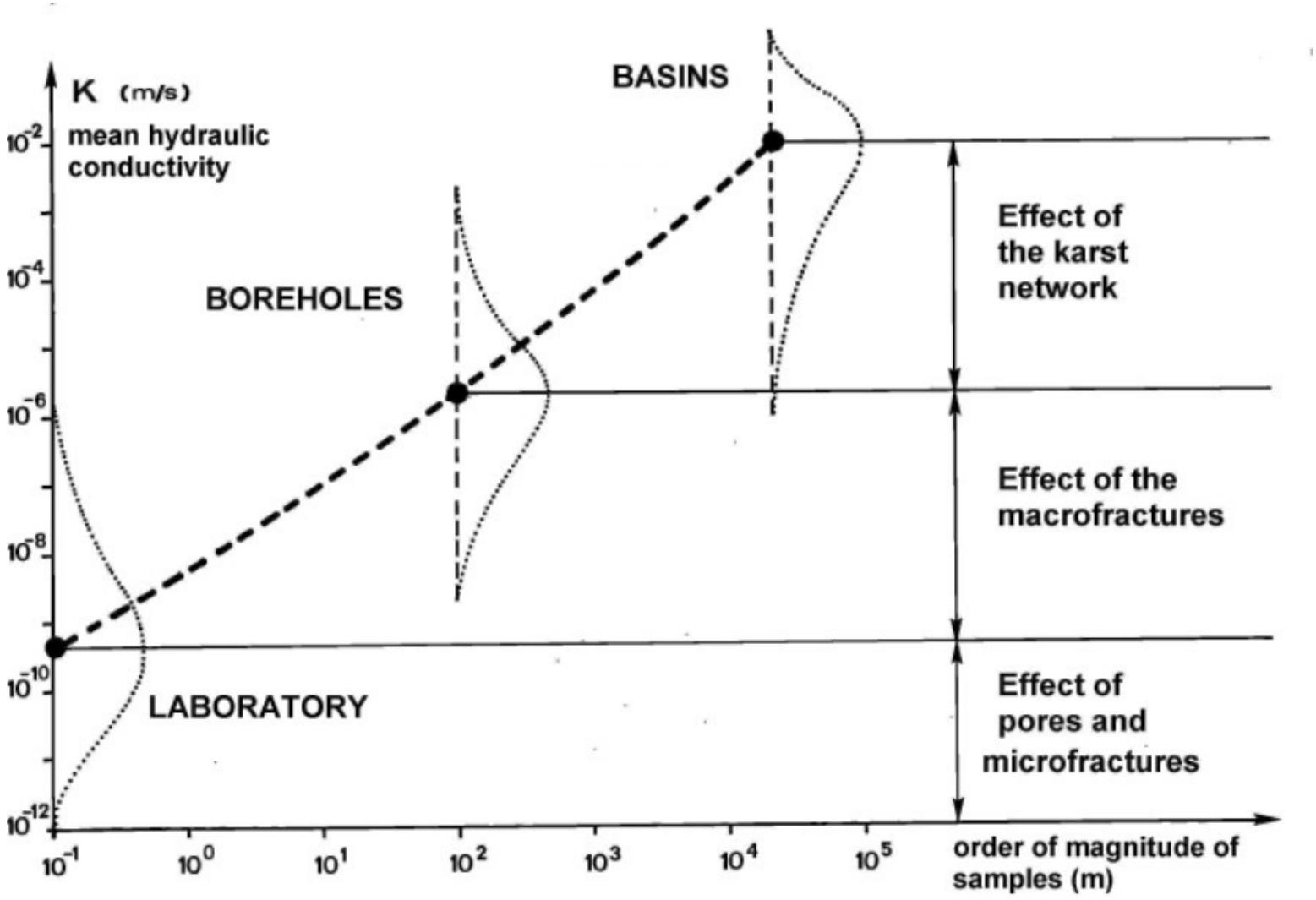
Trajectoires hypothétiques des contraintes principales dans le Jura d'après les grands cisaillements dextres et senestres. Plan de décrochements : d'après N. PAVONI, 1961.

Nested network of discontinuities of different magnitude

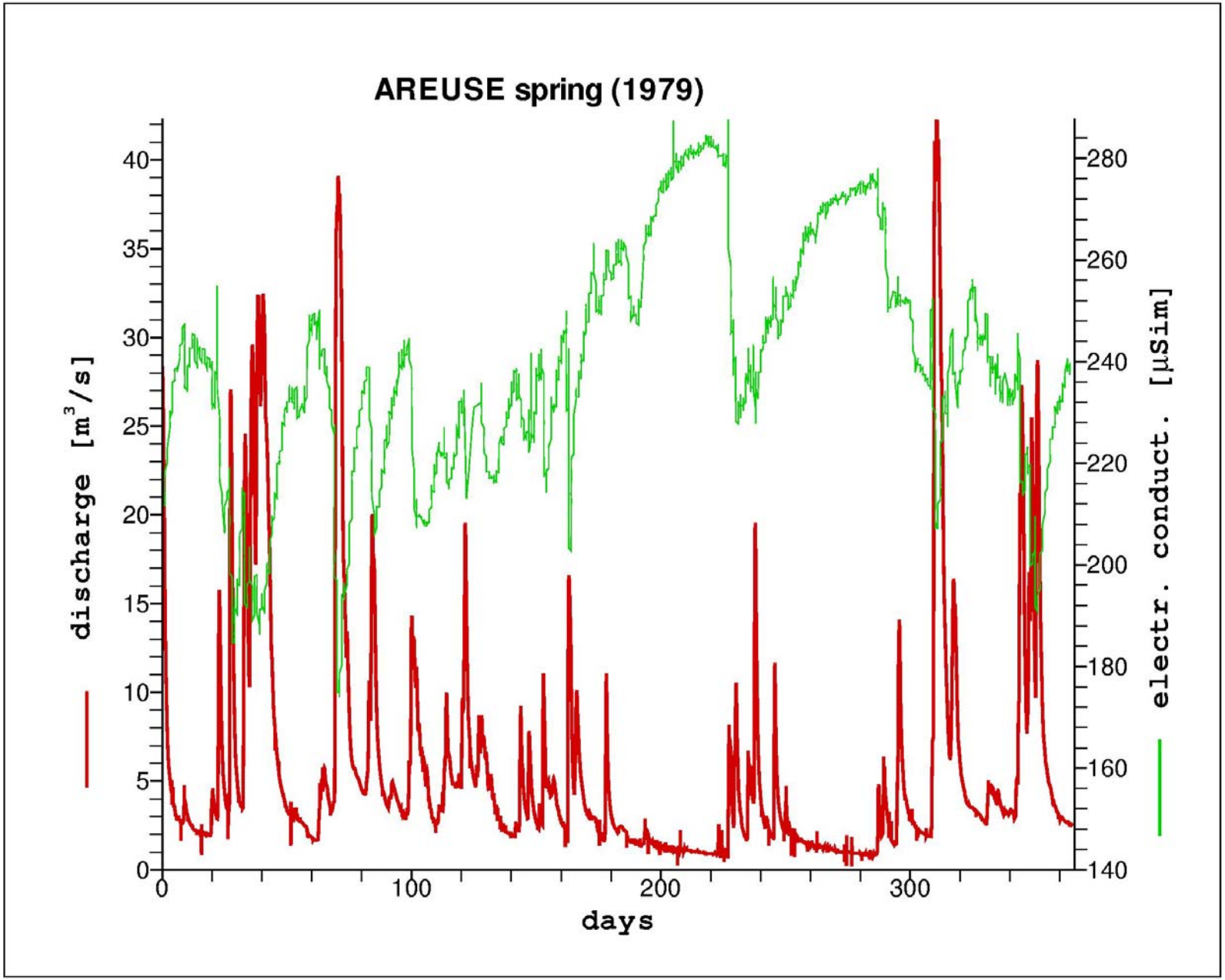
Petites et grosses mailles

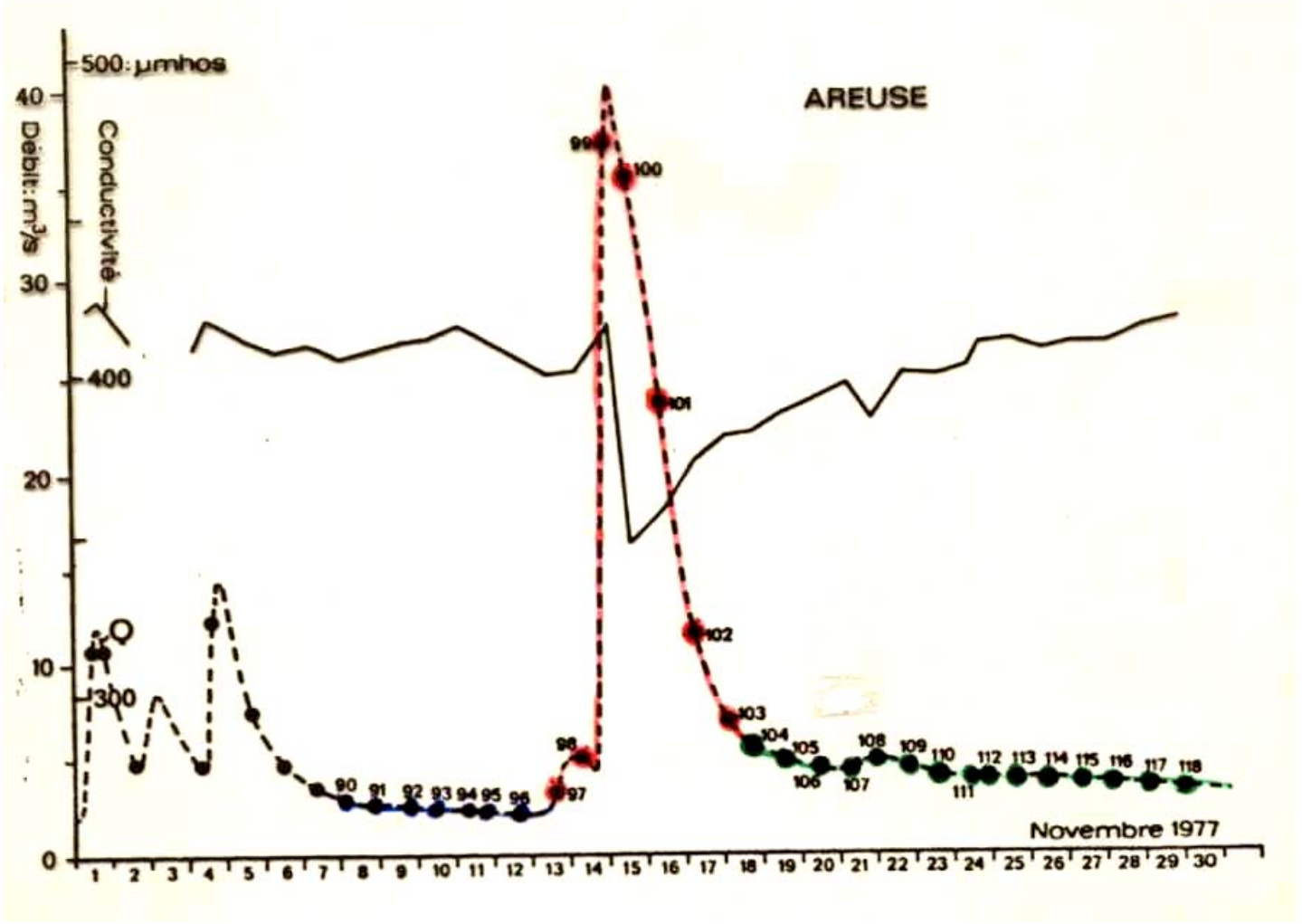


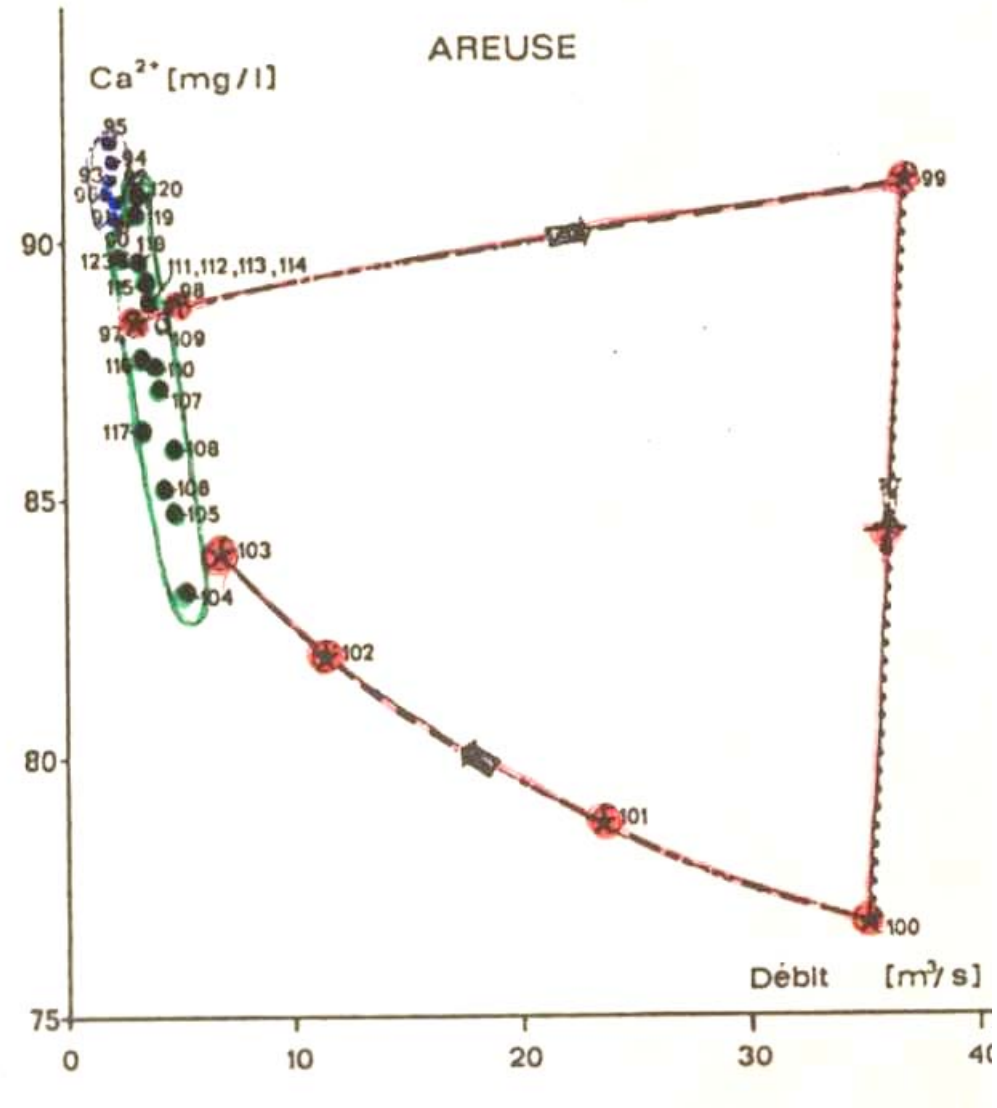
Scale effect on the hydraulic conductivity

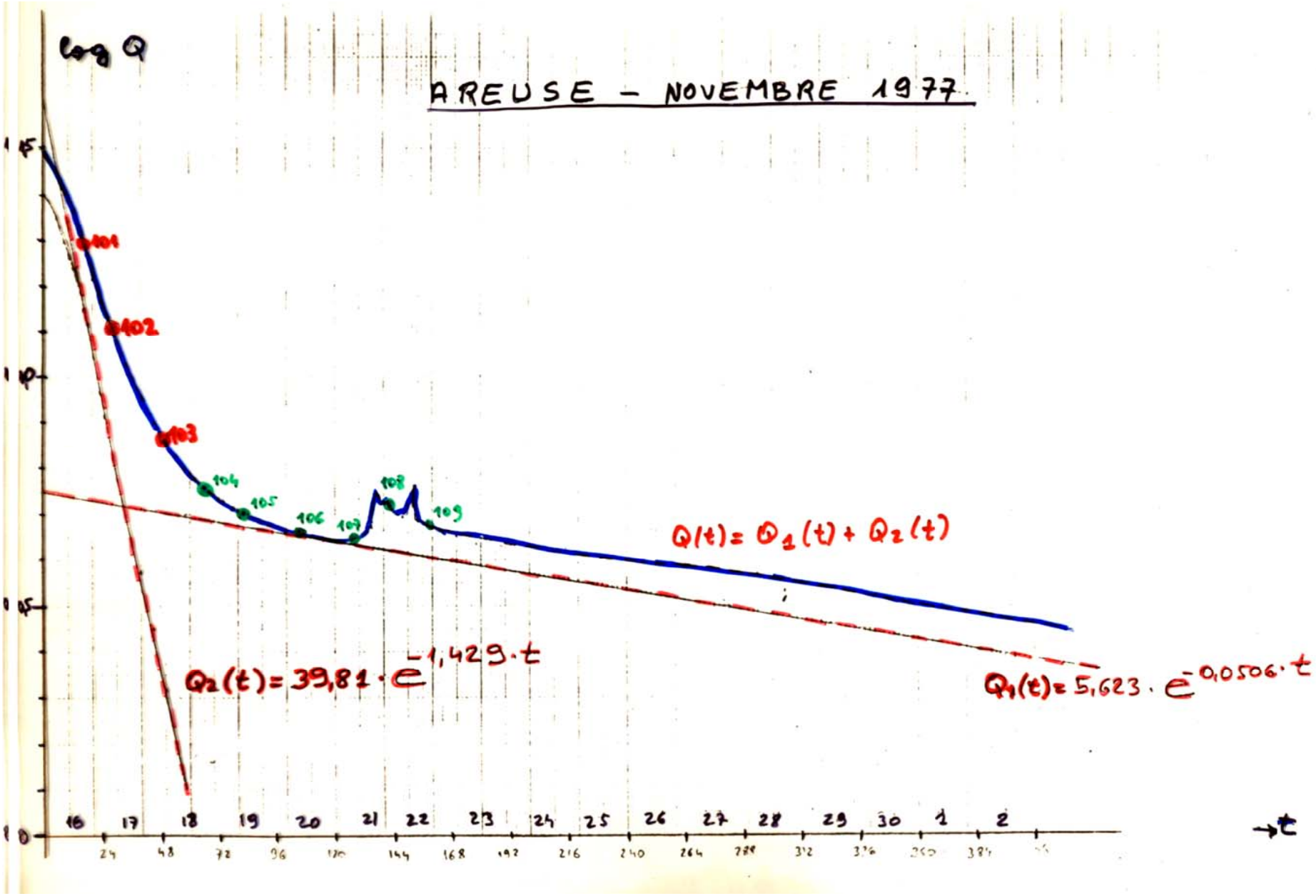


(after Kiraly 1973)

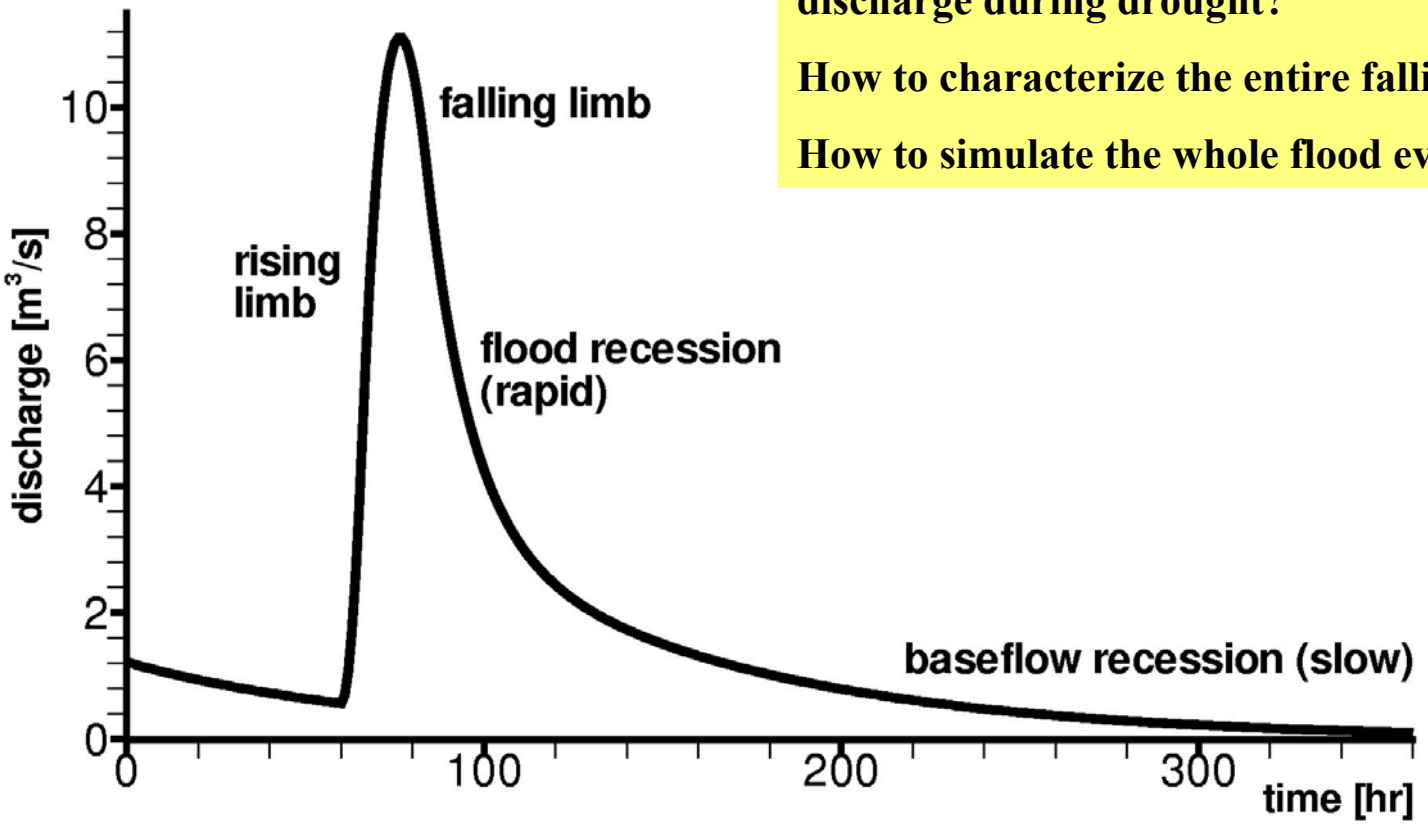

AREUSE spring (1979)
discharge [m³/s]
electr. conduct. [µSim]
days
0
5
10
15
20
25
30
35
40
140
160
180
200
220
240
260
280
0
100
200
300


AREUSE
500 µmhos
Conductivité
Débit: m³/s
40
30
20
10
0
400
300
Novembre 1977
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118


AREUSE
Ca2+ [mg/l]
90
85
80
75
0
10
20
30
Débit [m3/s]
99
100
101
102
103
104
105
106
107
108
109
110
111,112,113,114
98
97
117
116
115
123
119
120


Log Q
AREUSE – NOVEMBRE 1977
101
102
103
104
105
106
107
108
109
$Q(t) = Q_1(t) + Q_2(t)$
$Q_2(t) = 39{,}81 \cdot e^{-1{,}429 \cdot t}$
$Q_1(t) = 5{,}623 \cdot e^{-0{,}0506 \cdot t}$
16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 1 2
24 48 72 96 120 144 168 192 216 240 264 288 312 336 360 384
→t

Analysis of a single flood event

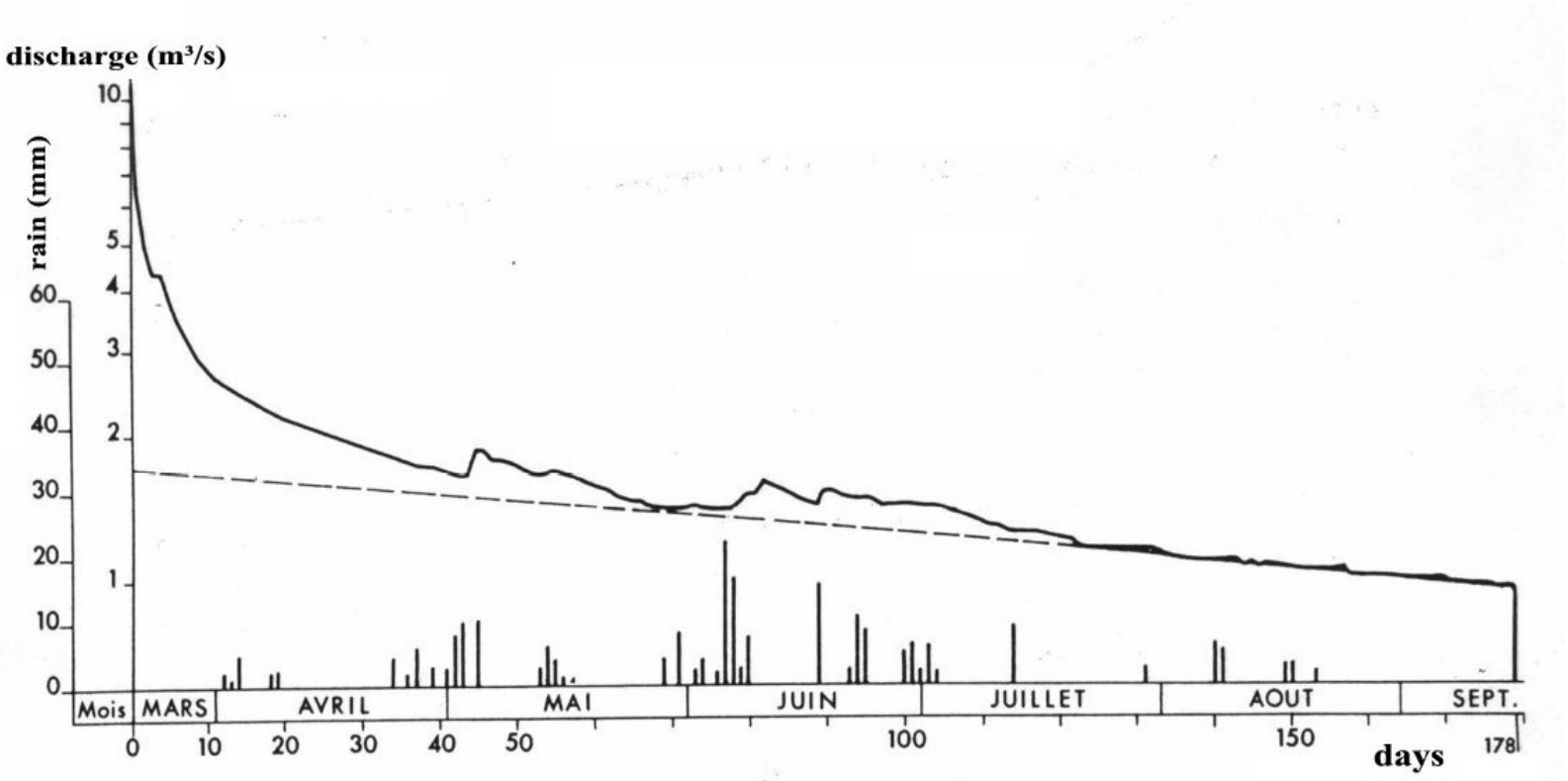


How to characterize the depletion (the baseflow recession) curve? How to forecast the spring discharge during drought?

How to characterize the entire falling limb?

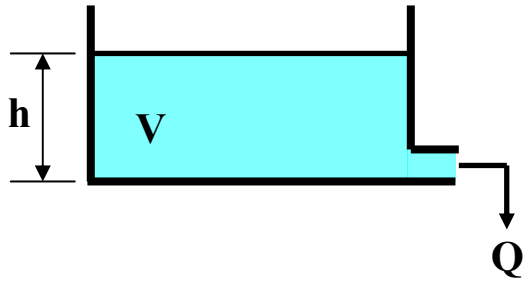
How to simulate the whole flood event?

Basics for the “global” models (1)



Basics for the "global" models (2)

Emptying of a reservoir:



If n=1, the recession of Q is exponential:

$$\frac{dV}{V} = -\alpha dt$$ and the integral gives

$$V(t) = V_0\, e^{-\alpha t}$$

$$Q(t) = Q_0\, e^{-\alpha t}$$

Hypotheses

volume V is proportional to h and discharge Q is proportional to a power of h (→ V)

$$Q = -\frac{dV}{dt} \qquad Q = KV^n$$

$$\alpha = Q/V$$ and we have

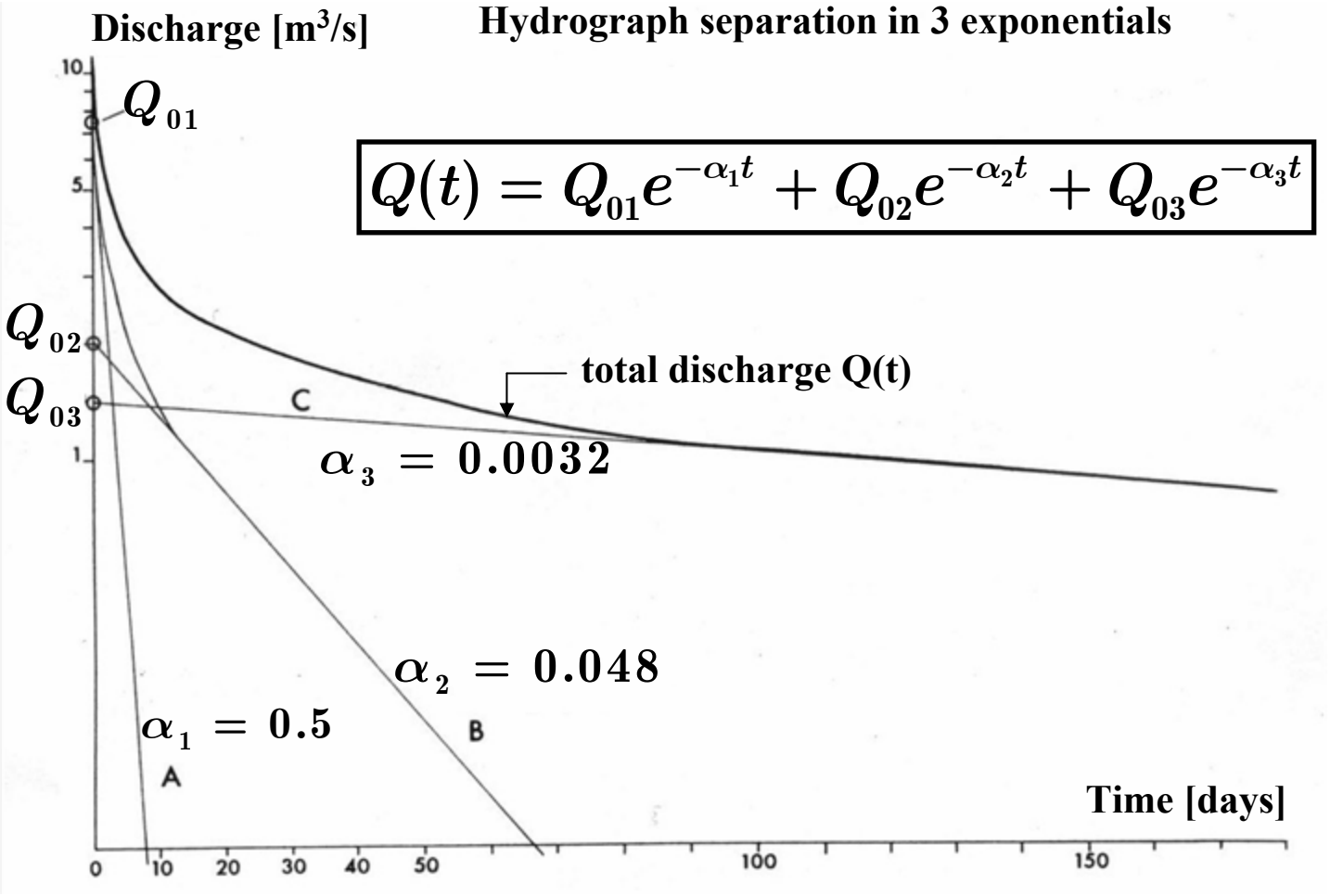
$$\frac{dV}{dt} + KV^n = 0$$ for emptying

In a diagram *ln Q* versus *t* the exponential part of the recession hydrograph appears as a straight line. If we know two points (Q_1, t_1) and (Q_2, t_2) on the exponential part, we can determine α by:

$$\alpha = \frac{1}{t_2 - t_1} \ln \frac{Q_1}{Q_2}$$

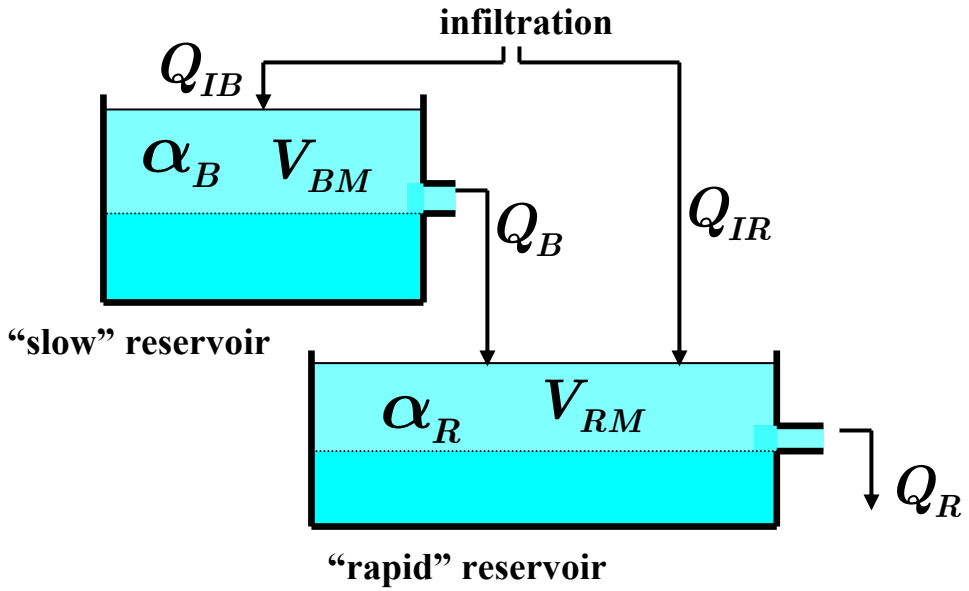
The hydrograph Q(t) and α allow to estimate the volume V by V(t)=Q(t) / α. Caution if Q is given in [m^3/s] and α is given in [1/day]: 1 day = 86400 seconds.

Basics for the "global" models (3)



(Forkasiewicz and Paloc, 1967)

Basics for the "global" models (4)



$$\frac{dV_{BM}}{dt} = Q_{IB} - \alpha_B V_{BM}$$

$$\frac{dV_{RM}}{dt} = Q_{IR} + \alpha_B V_{BM} - \alpha_R V_{RM}$$

Double reservoir model

Q_R = spring discharge

Q_B = baseflow component

α_R = recession coefficient for the rapid reservoir

α_B = recession coefficient for the slow reservoir

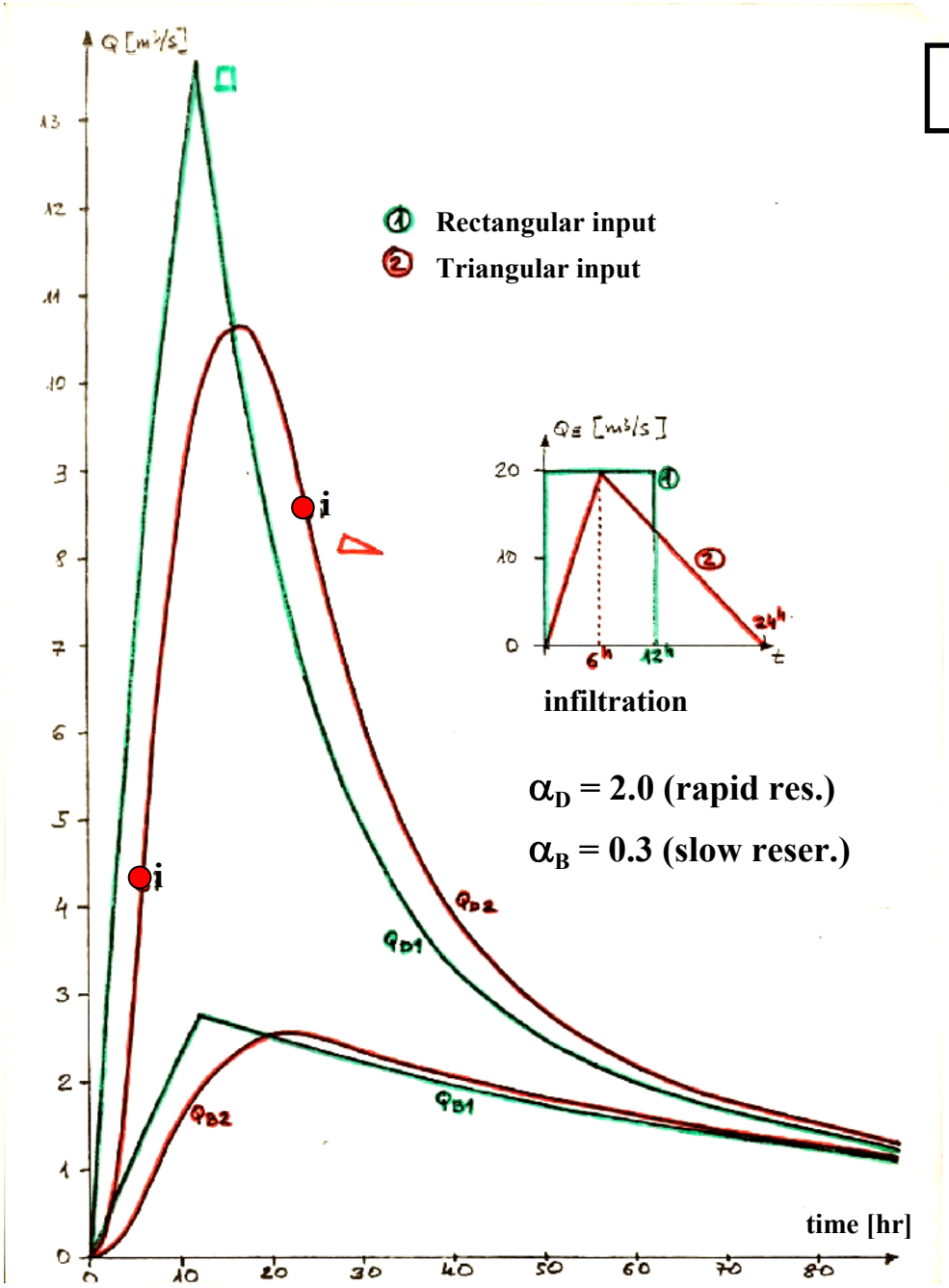
Q_{IB} = diffuse infiltration into the slow reservoir

Q_{IR} = direct infiltration into the rapid reservoir

V_{BM} = "mobile" volume of the slow reservoir

V_{RM} = "mobile" volume of the rapid reservoir

Basics for the "global" models (5)



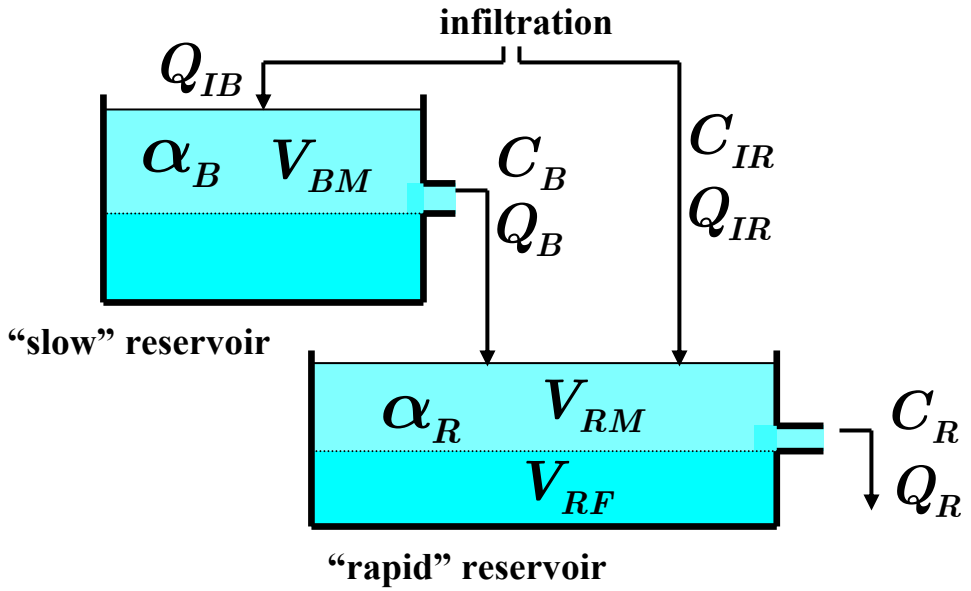
Spring hydrographs obtained by the double-reservoir model: effect of the form of input functions on the hydrographs

If you can avoid, do not use rectangular input functions

Observe the 2 inflexion points "i" on the curve Q_{D2} obtained by the triangular input function. The first inflexion point is at 6 hr (infiltration has its maximum value) and the second is at 24 hr (the infiltration is ceased).

Observing the inflexion points on real spring hydrographs would perhaps allow to make a guess on the real input function.

Basics for the "global" models (6): dilution effect at the spring



Q_R : spring discharge

Q_B : baseflow component

α_R : recession coefficient for the rapid reservoir

α_B : recession coefficient for the slow reservoir

Q_{IB} : diffuse infiltration into the slow reservoir

Q_{IR} : direct infiltration into the rapid reservoir

V_{BM} : "mobile" volume of the slow reservoir

V_{RM} : "mobile" volume of the rapid reservoir

V_{RF} : "fixed" volume of the rapid reservoir

C_B : concentration in baseflow

C_R : concentration in spring

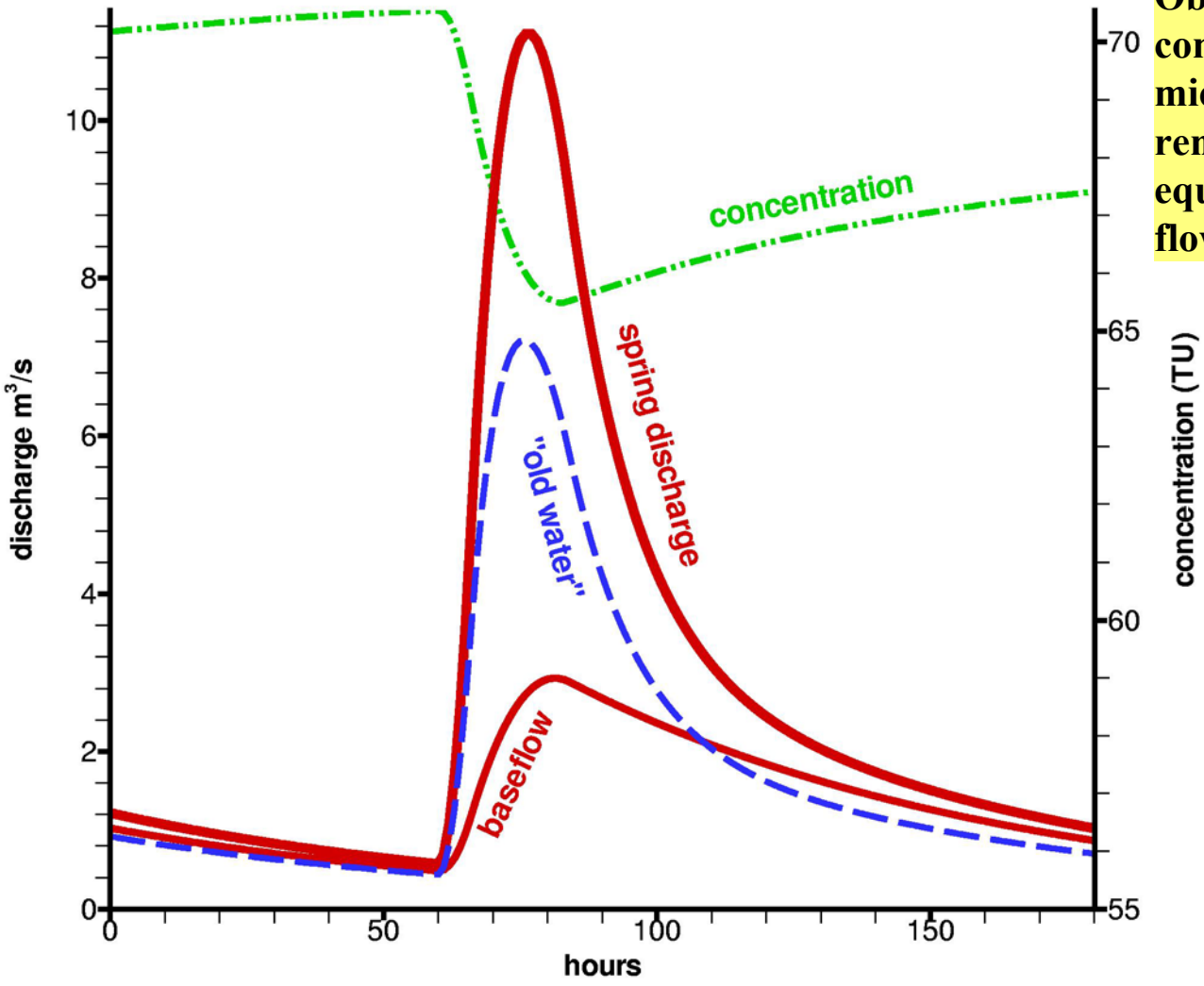
C_{IR} : concentration in direct input

$$\frac{dV_{BM}}{dt} = Q_{IB} - \alpha_B V_{BM}$$

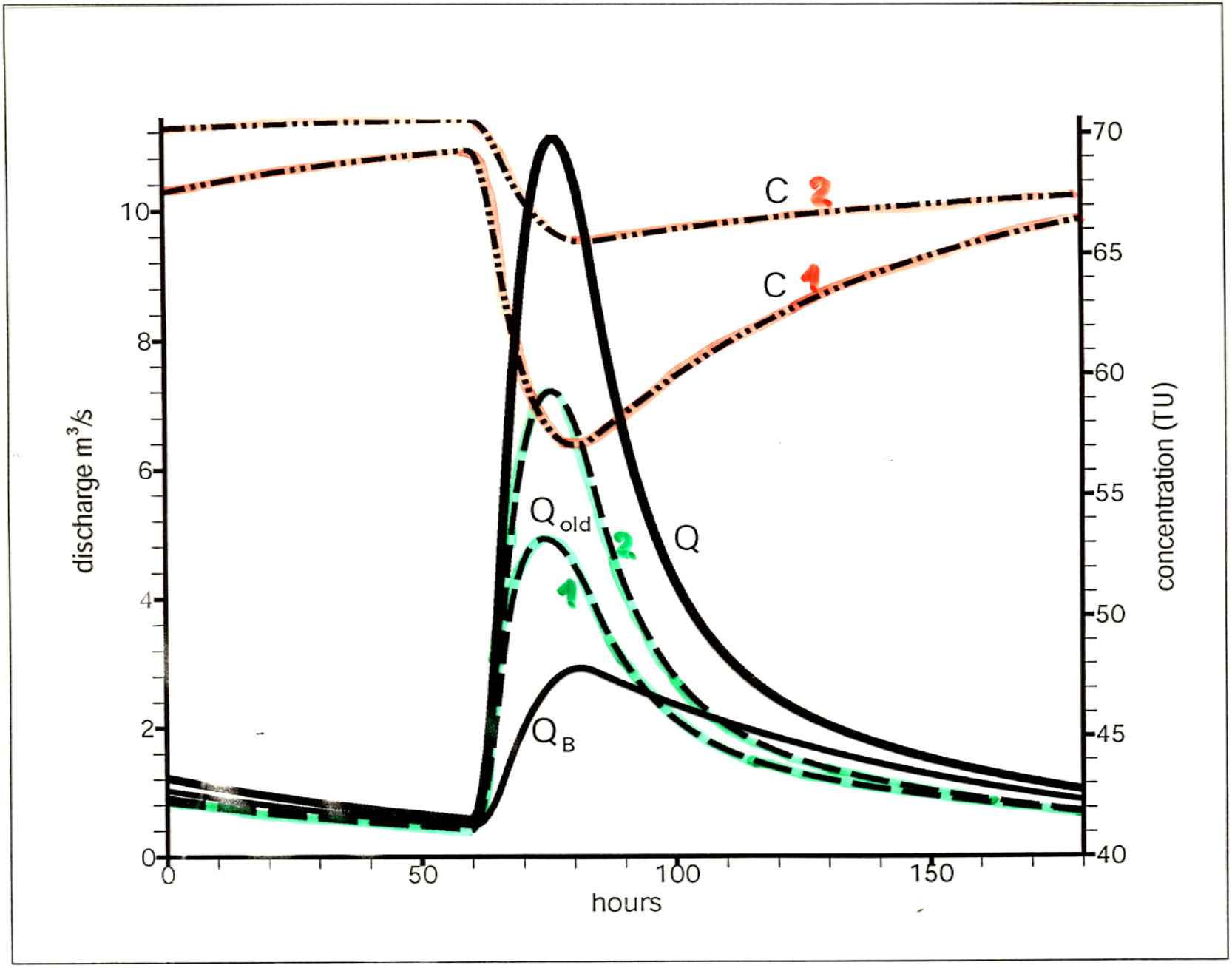
$$\frac{dV_{RM}}{dt} = Q_{IR} + \alpha_B V_{BM} - \alpha_R V_{RM}$$

$$\frac{dC_R}{dt} = Q_B \frac{(C_B - C_R)}{(V_{RM} + V_{RF})} + Q_{IR} \frac{(C_{IR} - C_R)}{(V_{RM} + V_{RF})}$$

Basics for the "global" models (7): dilution effect at the spring



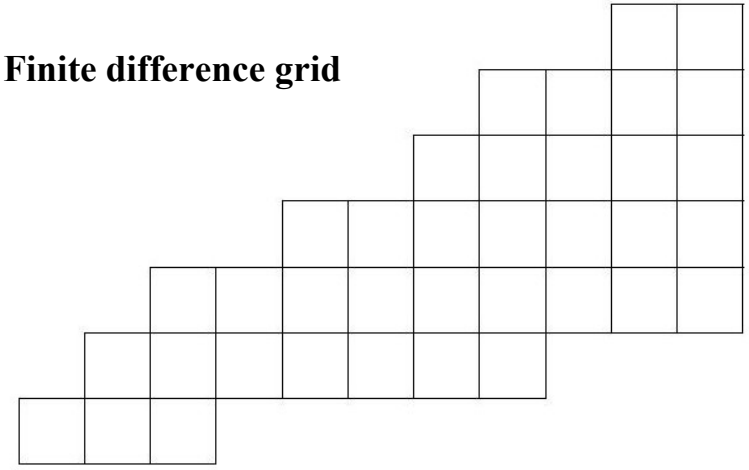
Observe that "old water" component and hydrodynamic baseflow are two different concepts!!! Do not equate "old water" to "baseflow"!!


discharge m³/s
concentration (TU)
hours
0
50
100
150
0
2
4
6
8
10
40
45
50
55
60
65
70
C 2
C 1
Q old 2
Q old 1
Q
Q B

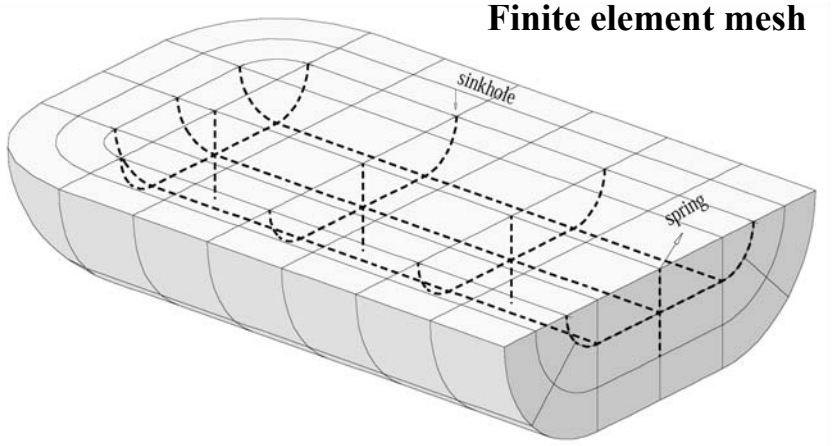
DISTRIBUTIVE MODELS

In the distributive models the flow problem is solved in a (generally great) number of "discrete" points ("nodes" or nodal points) which allow to interpolate the results over the whole region under consideration. The two most common techniques are represented by the Finite Difference models and by the Finite Element models. In both cases the exact, but unknown solution of the governing partial differential equation will be approximated by a simpler function of known type in the finite difference cells or over the finite elements (for example, constant head value in the cells and linear, quadratic or cubic function over the finite elements) which allow to obtain a (generally linear) equation for each node of the model. The system of simultaneous linear equations is then solved by iterative or direct numerical methods. Data necessary for the distributive models and how to obtain them?

Finite difference grid



Finite element mesh



Representation of the principal problems in modelling groundwater flow

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Equations representing the "abstract scheme" of the groundwater flow. Generally, their validity depends on a number of restrictive hypotheses in a more general theoretical framework. The complete statement of the flow problem requires the definition of the following data fields (they represent the "abstract scheme" of a particular aquifer):

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S field
Give to each point of the region a value of S

Imposed conditions
Impose to each point of the region either $h(t)$ or $Q(t)$

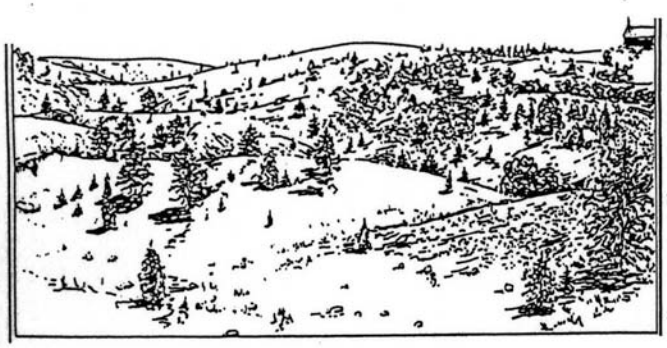
Initial conditions
Give to each point of the region a value of h at time $t = t_0$

Abstraction

Realization ??

Realization

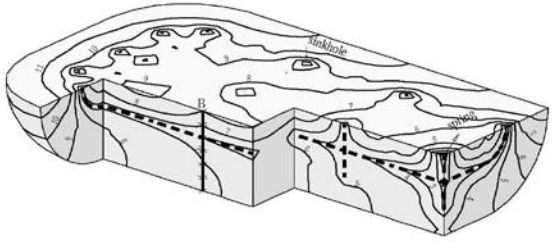
REAL SYSTEM

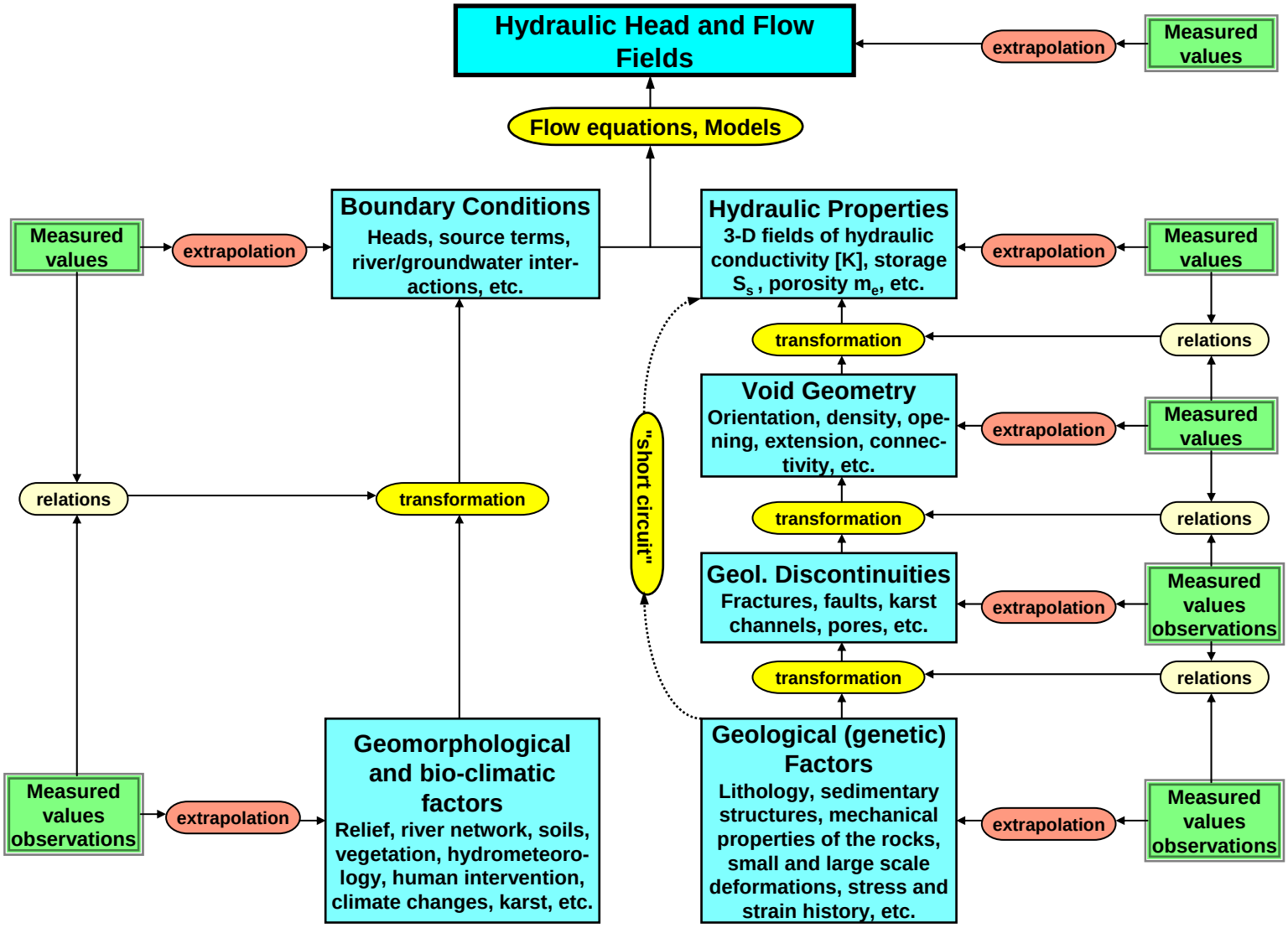


Transfer of the simulated results on the real system and check

NUMERICAL MODEL

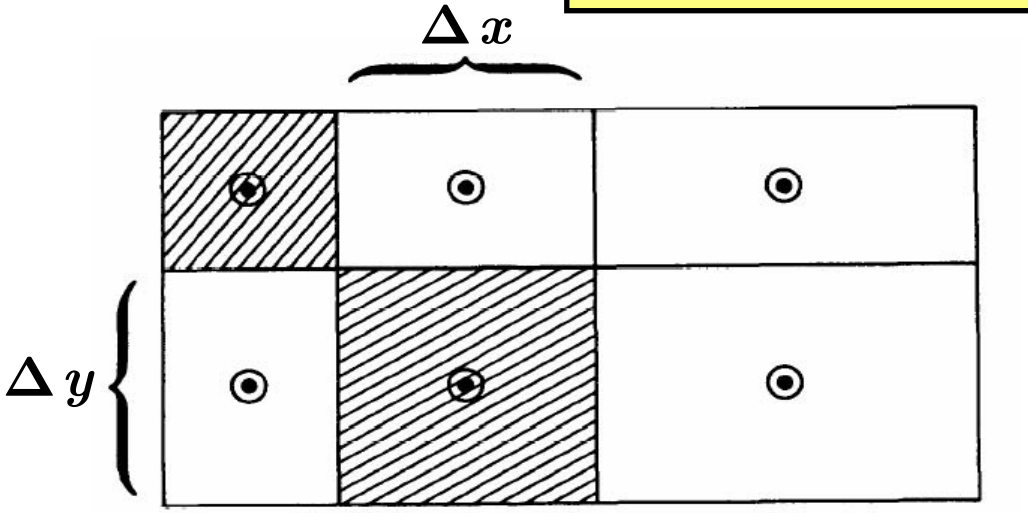
- Computer code (based on numerical methods)
- Input data (mainly hypothetical due to interpolation)
- Simulated results (consequences of the input data)
- Graphic representation of the simulated results





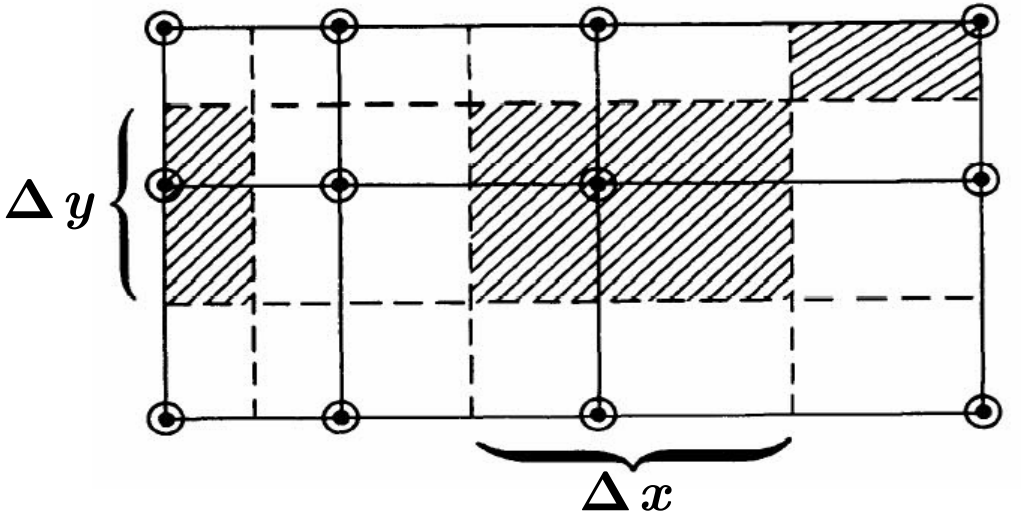
Problems related to the indirect reconstruction of the hydraulic parameter fields and boundary conditions (interpolation or extrapolation of the measured values or observations is <u>unavoidable!!</u>)

Finite difference models



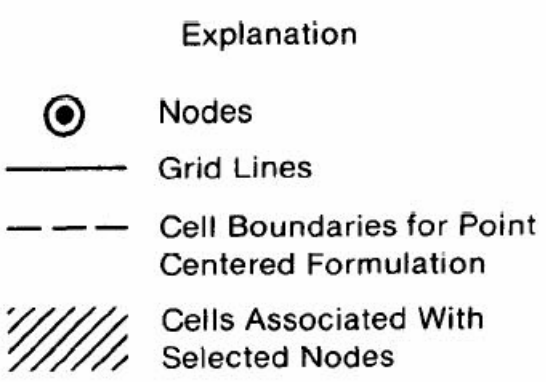
Block-centered Grid System

Point-centered Grid System



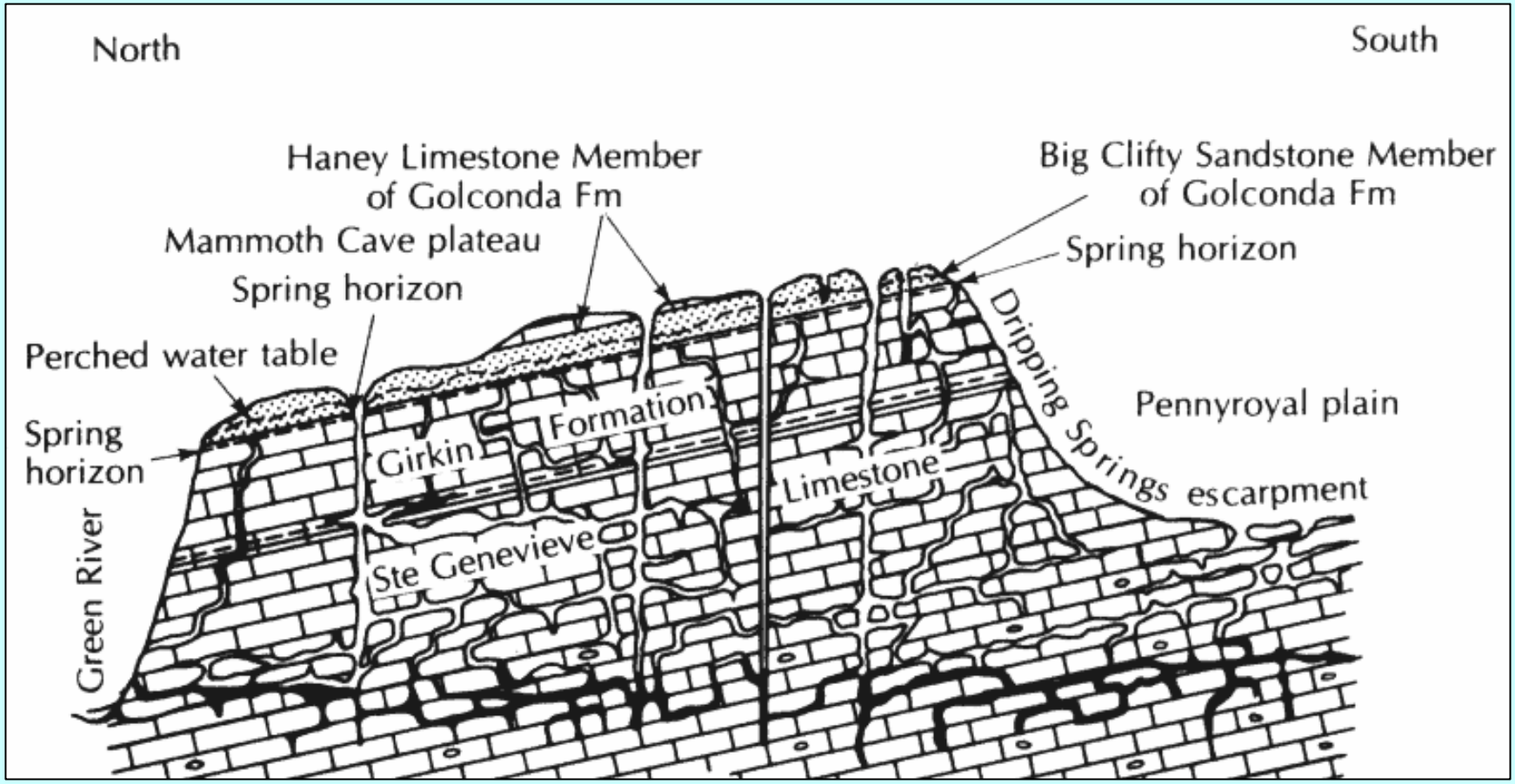
Block-centered and point-centered grid systems for Finite Difference models

Note that in each cell the hydraulic head is considered as being constant!! If possible, do not use Finite Difference models to simulate karst aquifers: Finite Element models are better for solving karst problems.



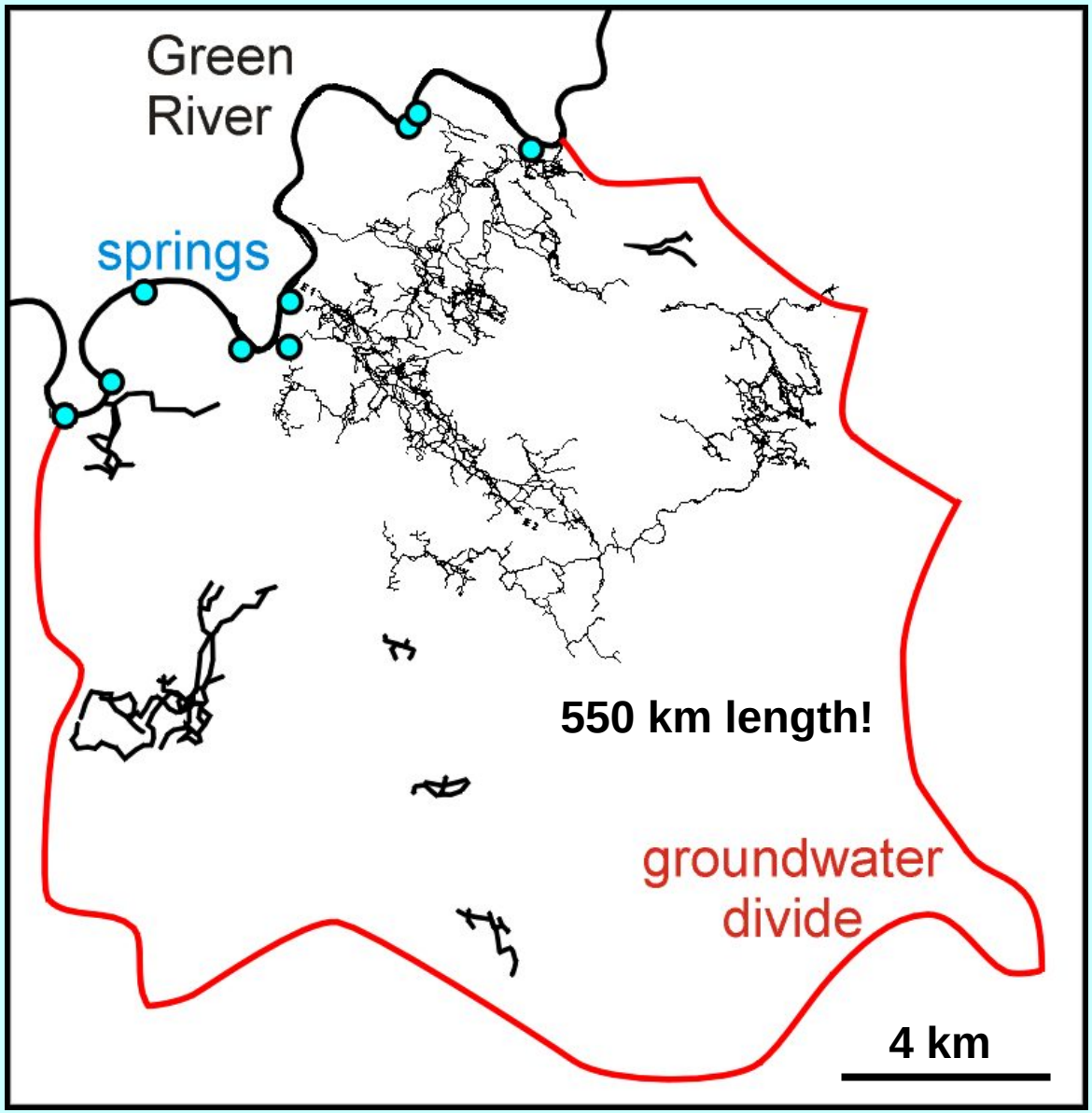
Extended example: Numerical simulation of the aquifer at Mammoth Cave (MODFLOW)

(Steven Worthington, unpublished data)



hydrogeological cross section through the aquifer

Map of the Mammoth Cave area



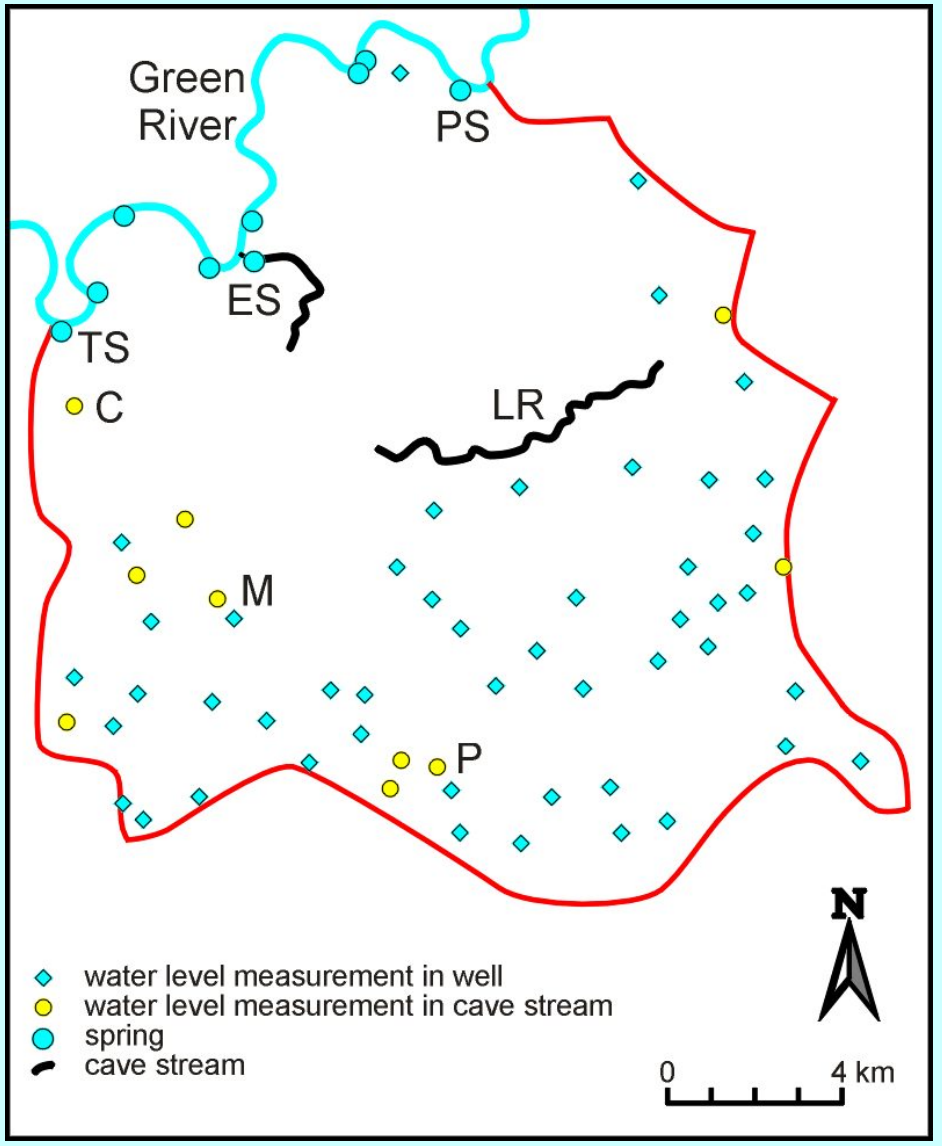
(Steven Worthington)

Model 1: homogeneous Equivalent Porous Medium (EPM)

Data for calibration

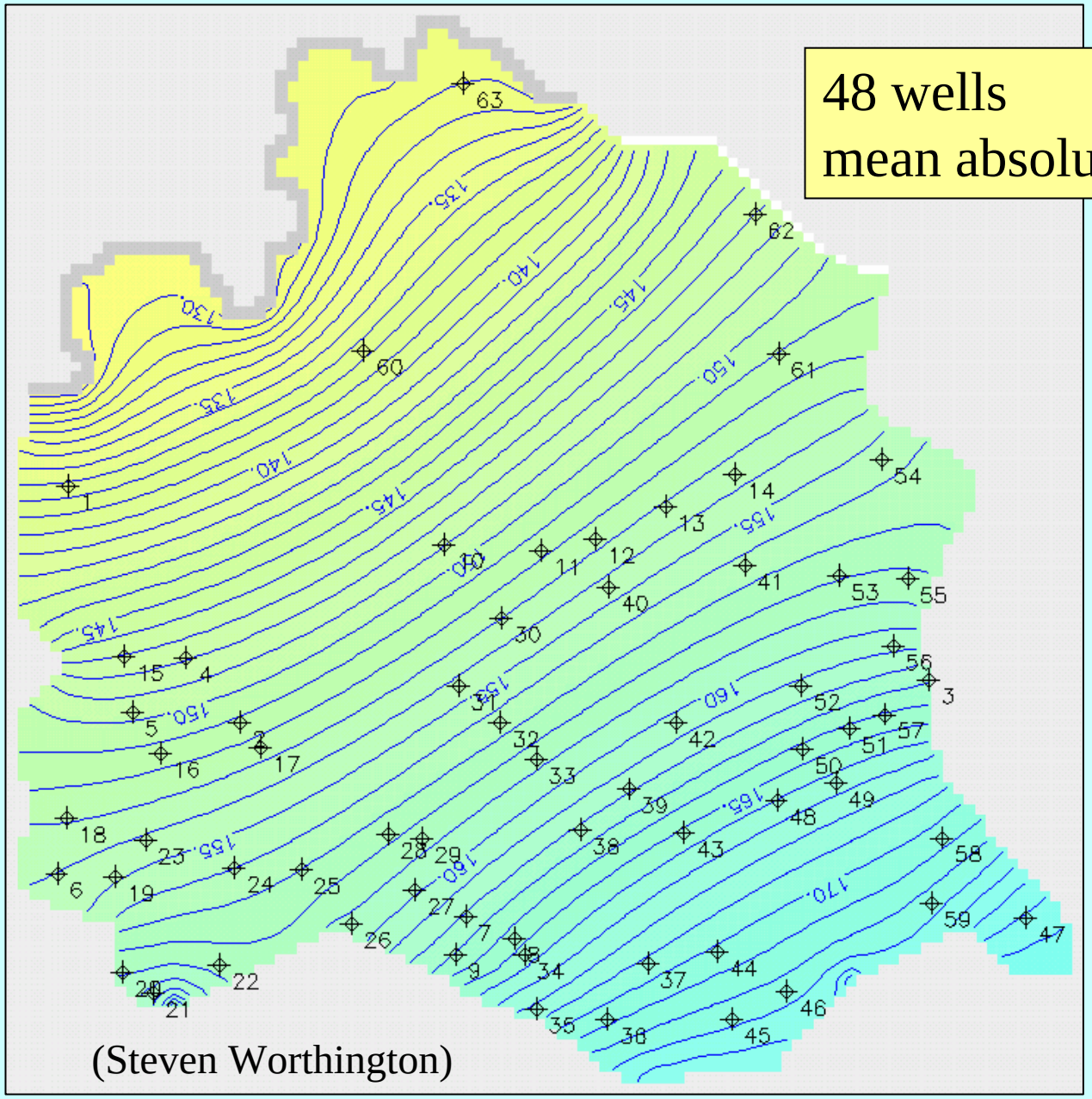
- Heads in wells
- Hydraulic conductivity from well tests

Matrix	2 x10^{-11} m/s
Slug tests (geo. mean)	6 x 10^{-6} m/s
Slug test (arith. mean)	3 x 10^{-5} m/s
Pumping tests	3 x 10^{-4} m/s
MODFLOW (EPM)	1 x 10^{-3} m/s



(Steven Worthington)

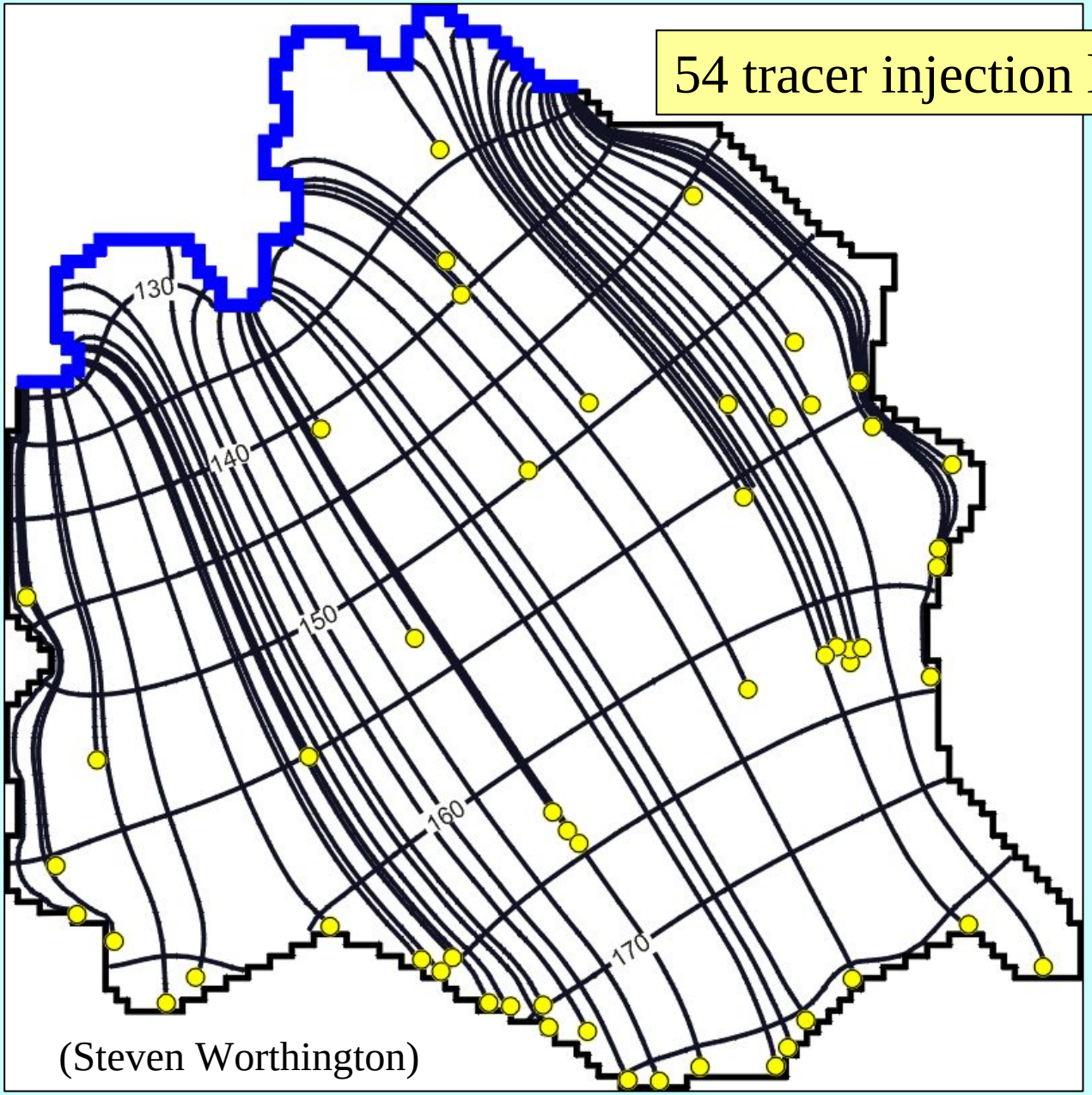
Results: groundwater contour lines



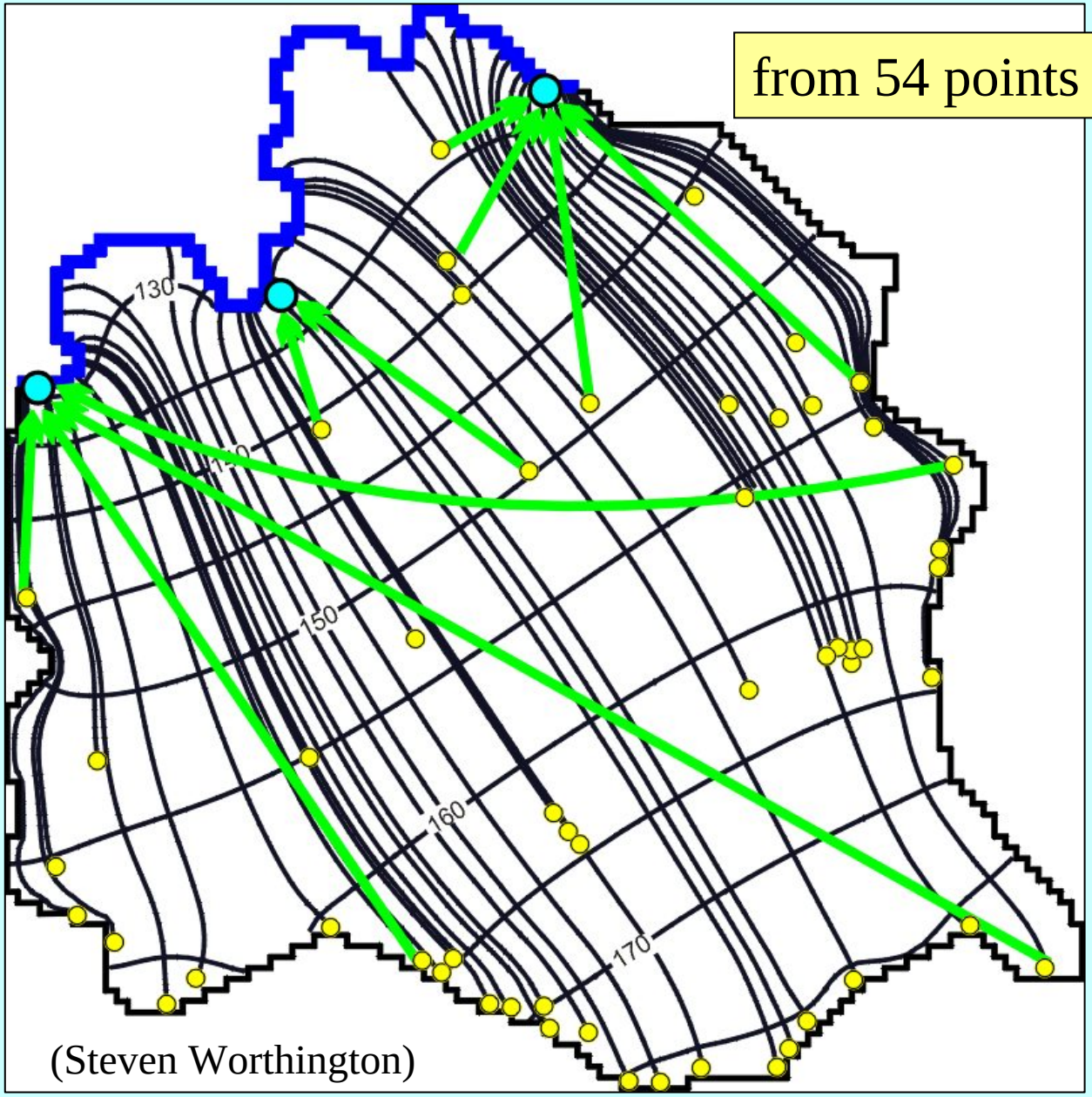
48 wells
mean absolute error = 12 m

(Steven Worthington)

Results: Simulated tracer paths

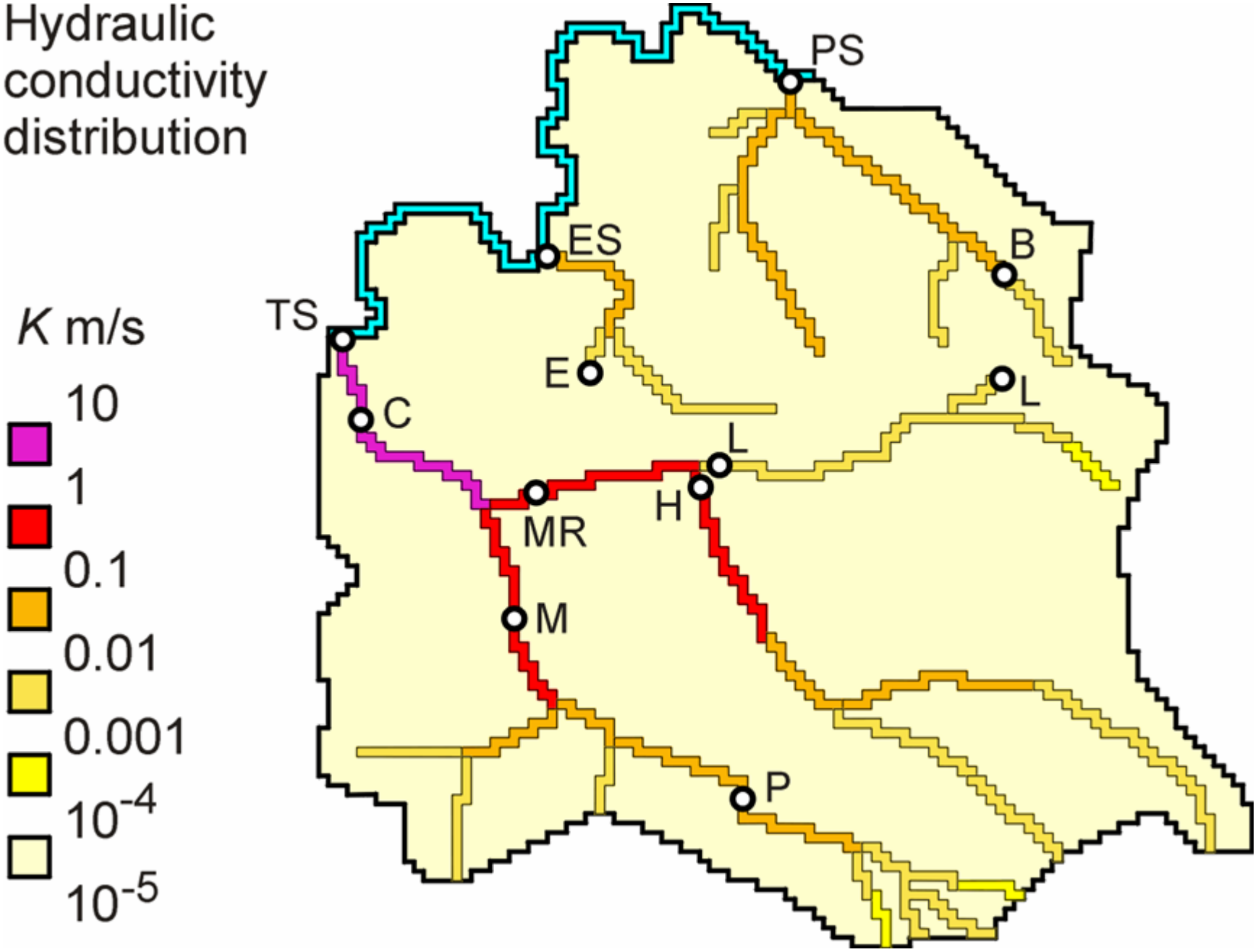


Actual tracer paths



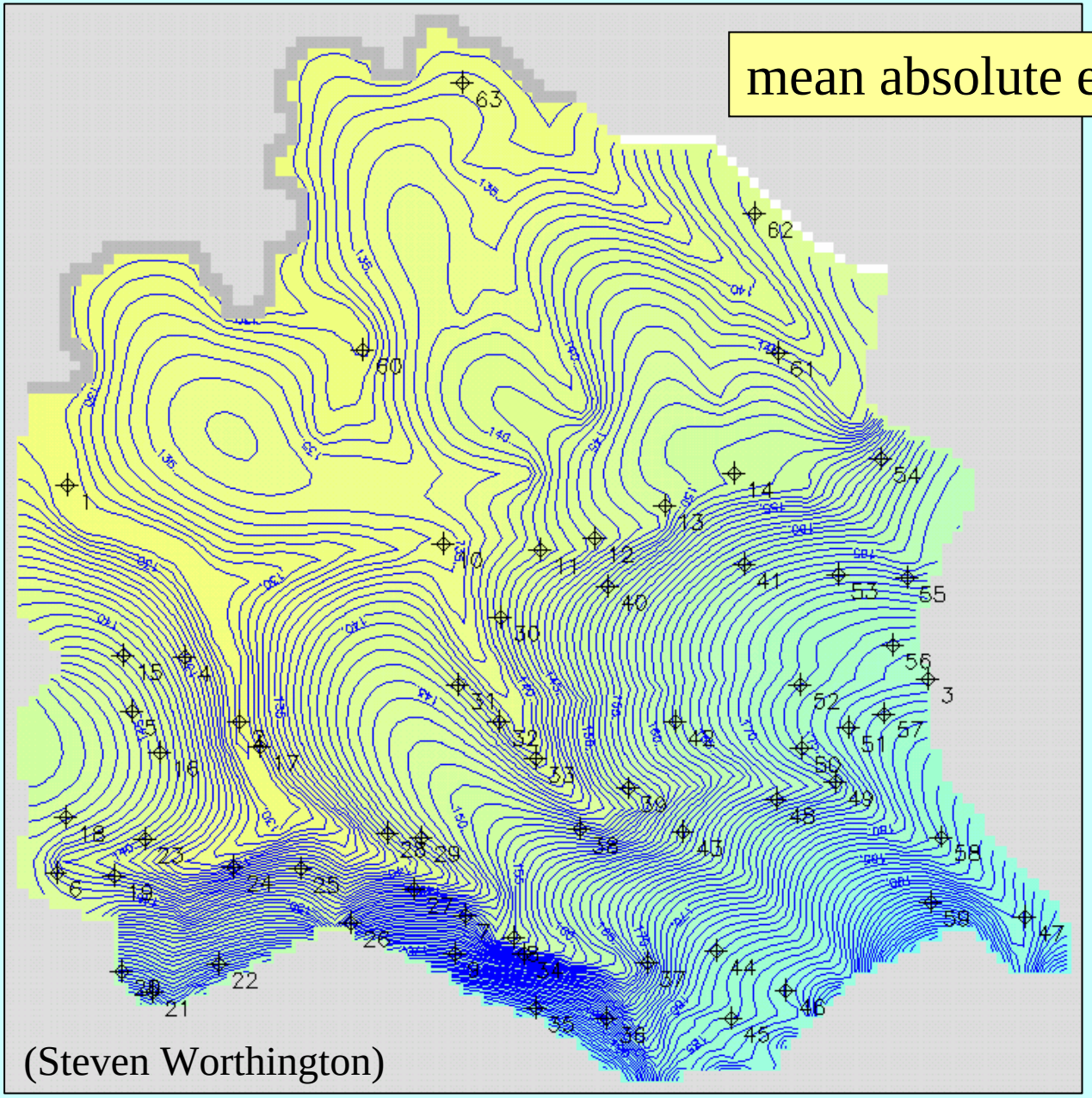
Model 2: EPM with ‘conduit cells’

- Aquifer has integrated conduit network
- Can be simulated with high conductivity cells
- Useful data for calibration
  - 1) Heads in wells
  - 2) Hydraulic conductivity from well tests
  - 3) Heads and discharge in conduits
  - 4) Tracer tests

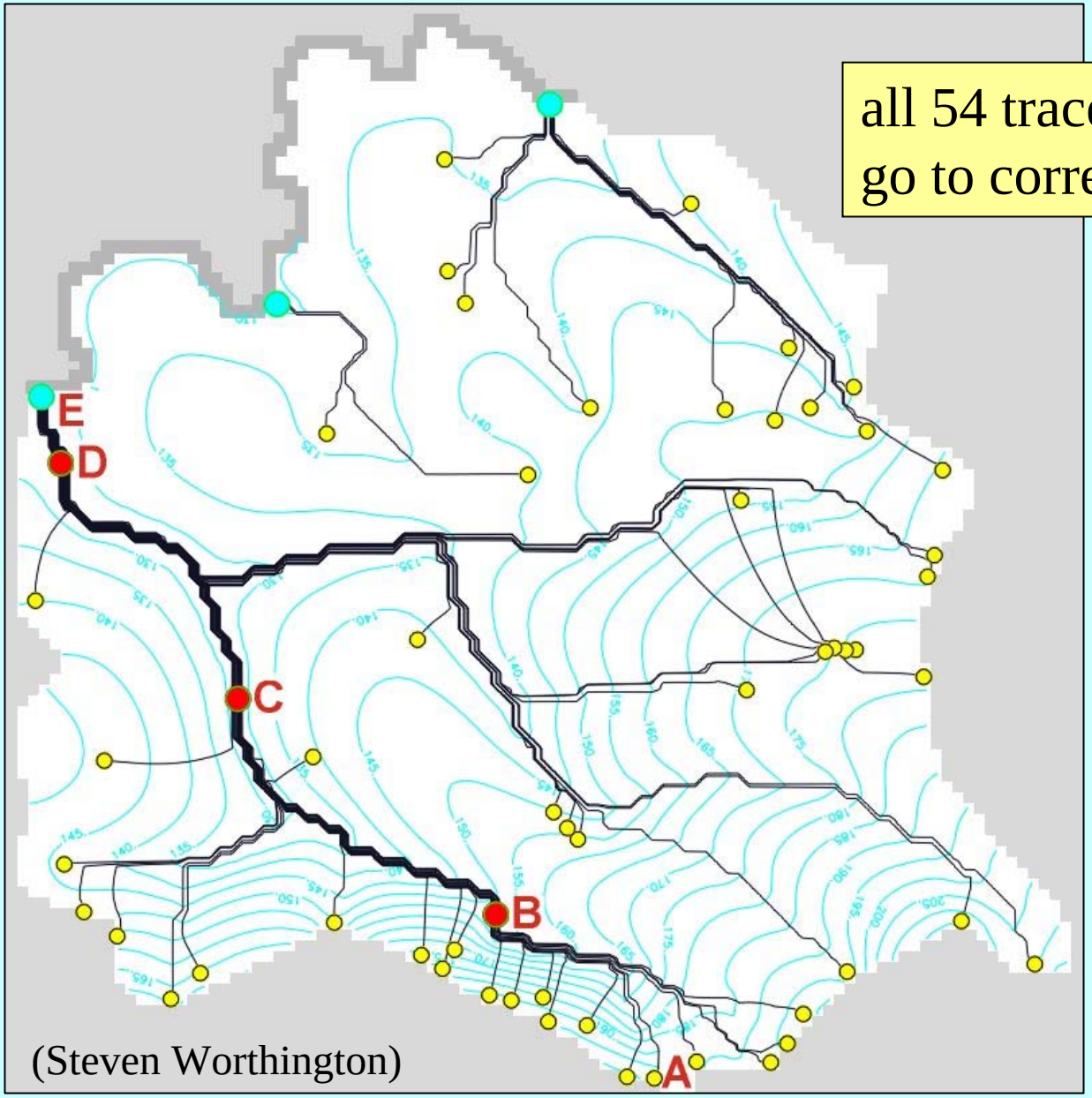


(Steven Worthington)

Results: groundwater contour lines

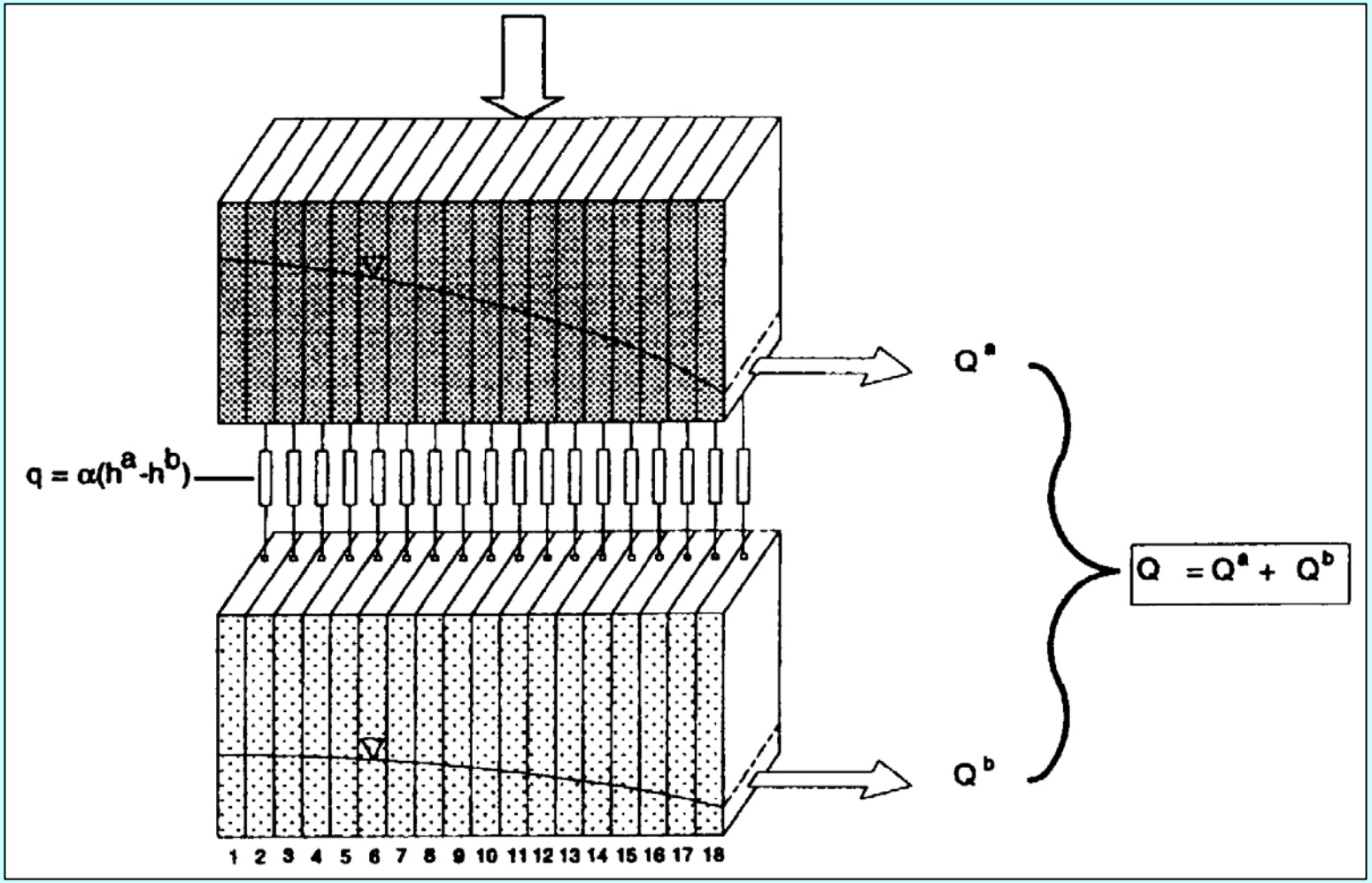


Results: Simulated tracer paths



all 54 tracer paths
go to correct spring

Double Continuum Approach (DC)

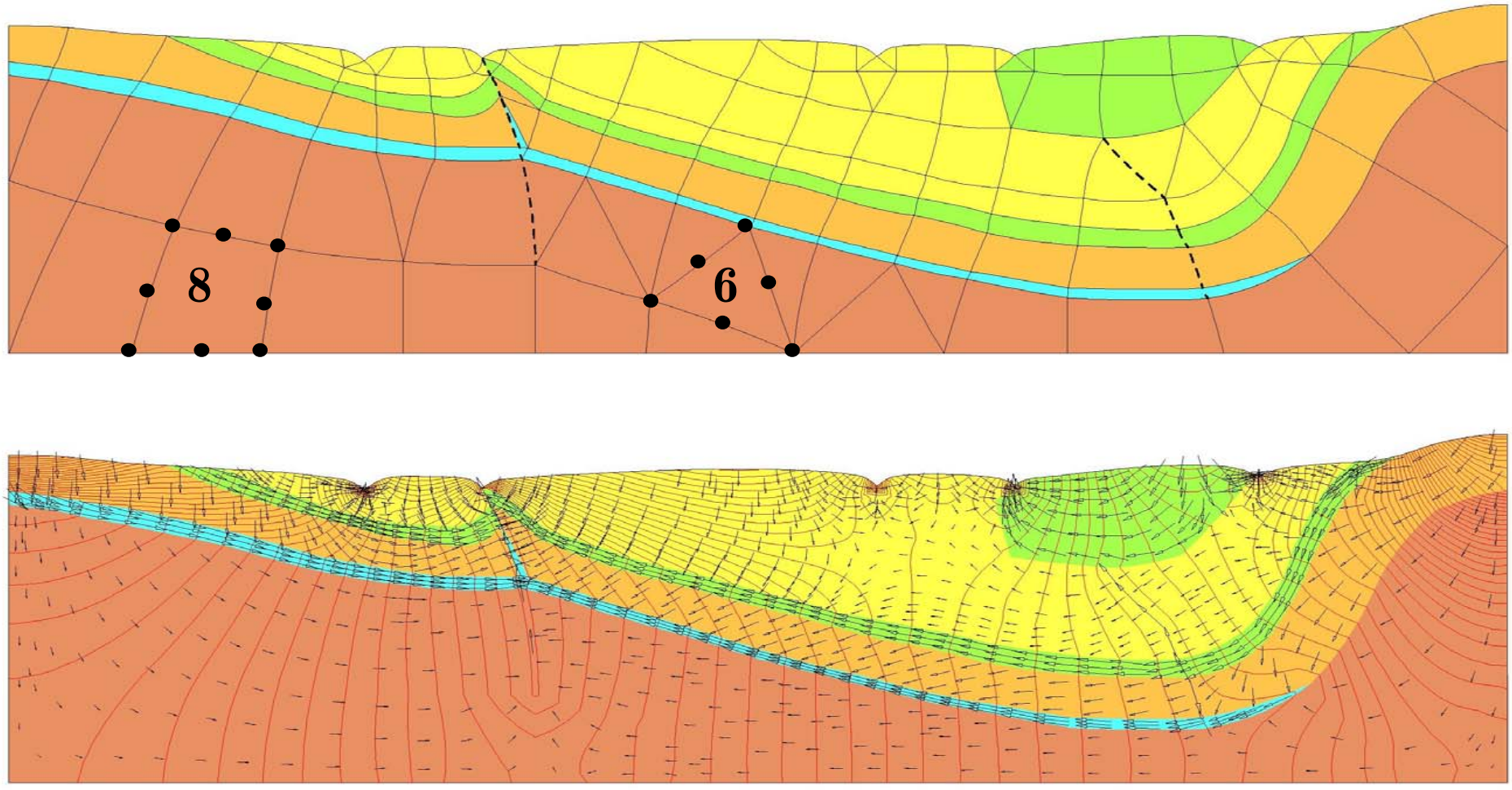


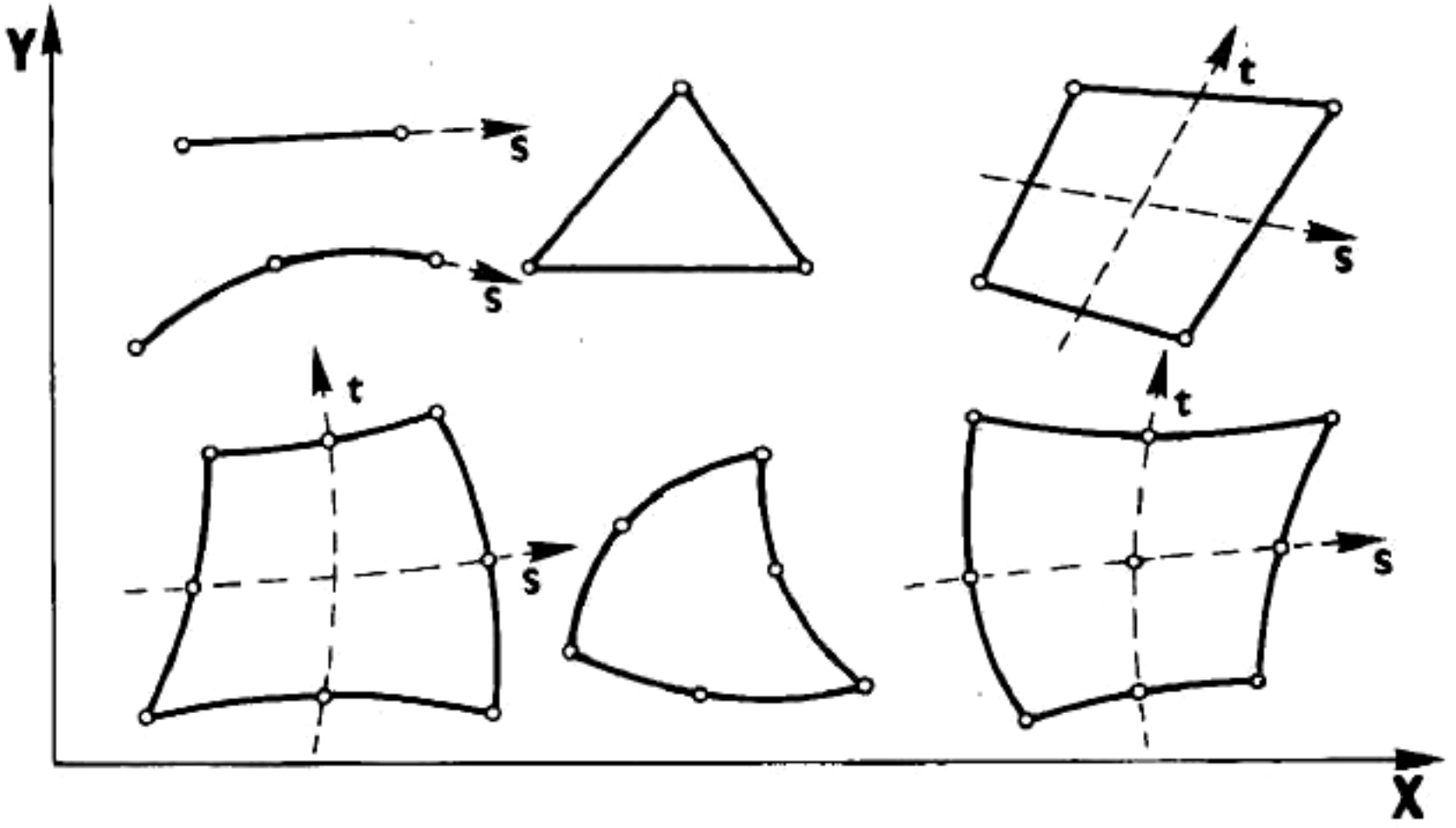
Teutsch 1988

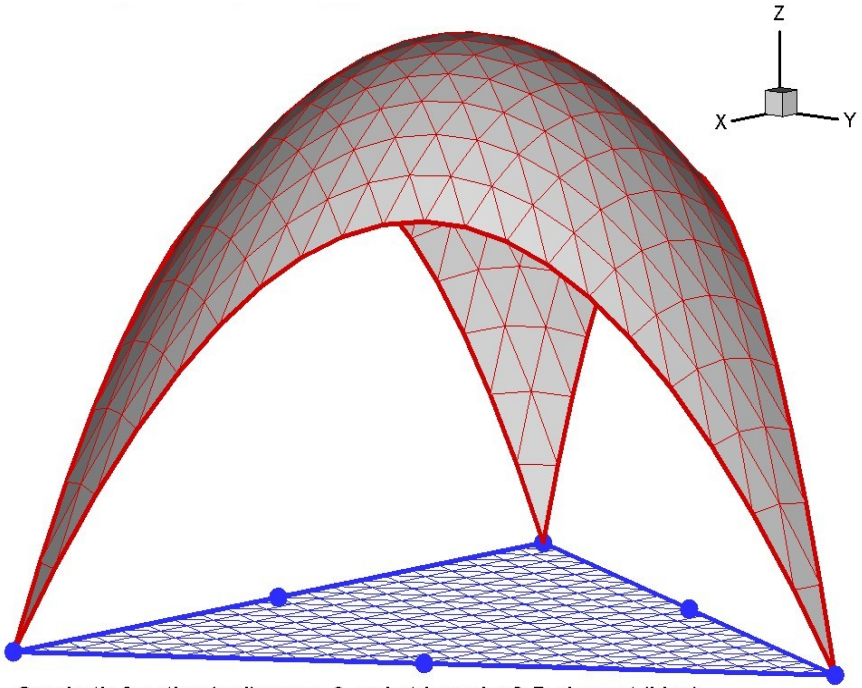
EXAMPLE OF FINITE ELEMENT MODEL

6: six-node quadratic triangle 8: eight-node quadratic rectangle

– – – – – – · : three-node 1-D quadratic elements simulating faults

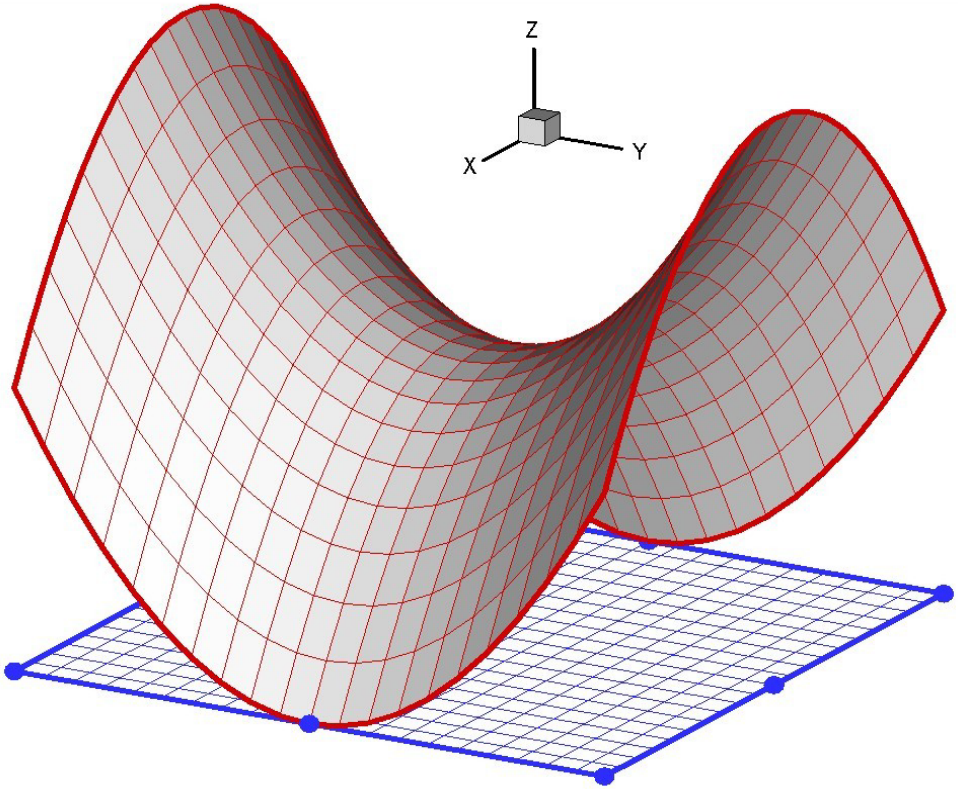



Y
X
s
s
t
s
t
s
t
s

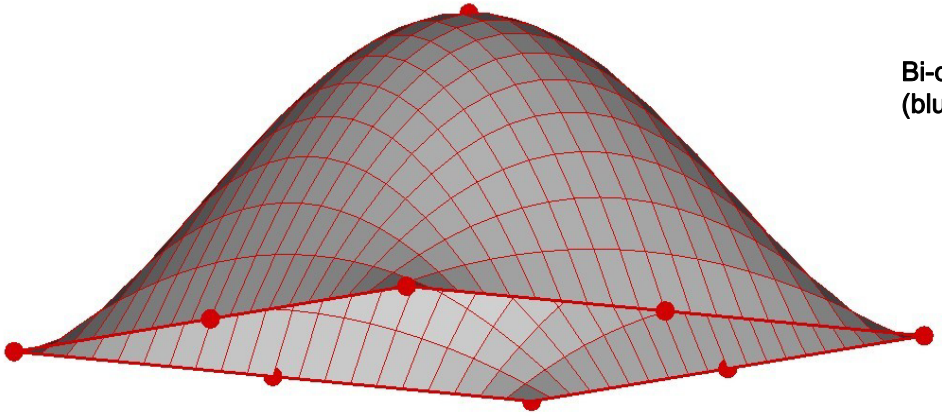


Quadratic function (red) over a 6-node triangular 2-D element (blue)

circles: nodal points on the 2-D element
thin lines: local coordinate lines on the 2-D element



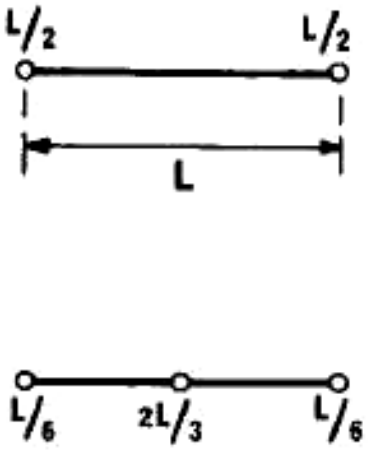
Bi-quadratic function over an 8-node 2-D element
(blue) circles: nodal points on the 2-D element

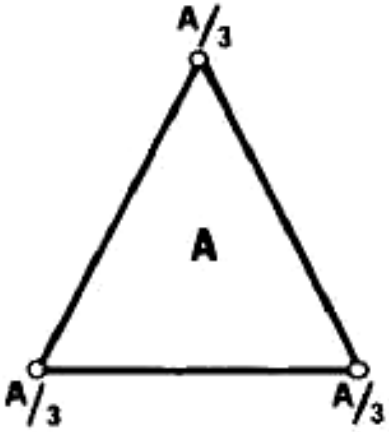


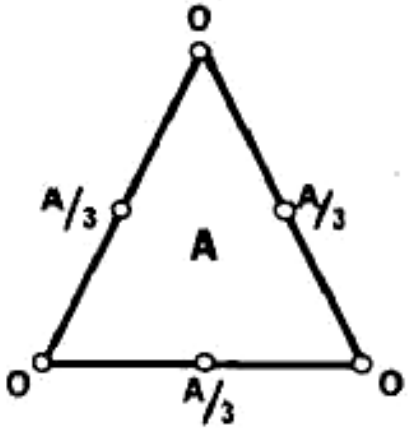
Bi-quadratic function over a 9-node 2-D element

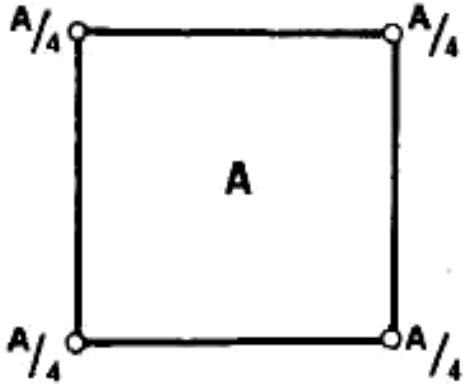
circles: nodal points of the 2-D element
thin lines: local coordinate lines on the 2-D element

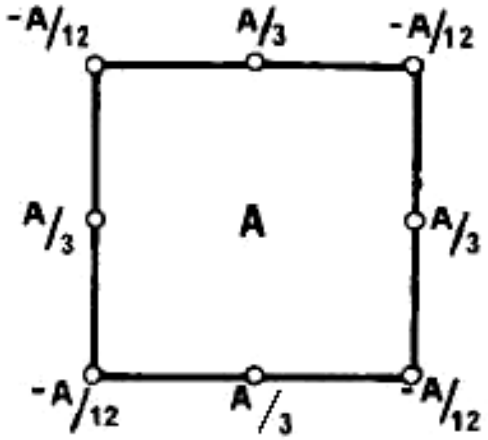
Examples of quadratic functions over 2-D quadratic finite elements.

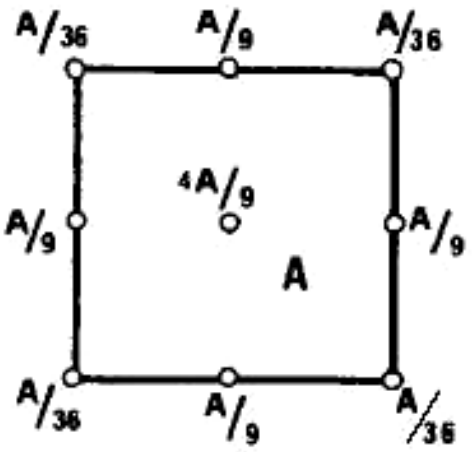

L/2
L/2
L
L/6
2L/3
L/6

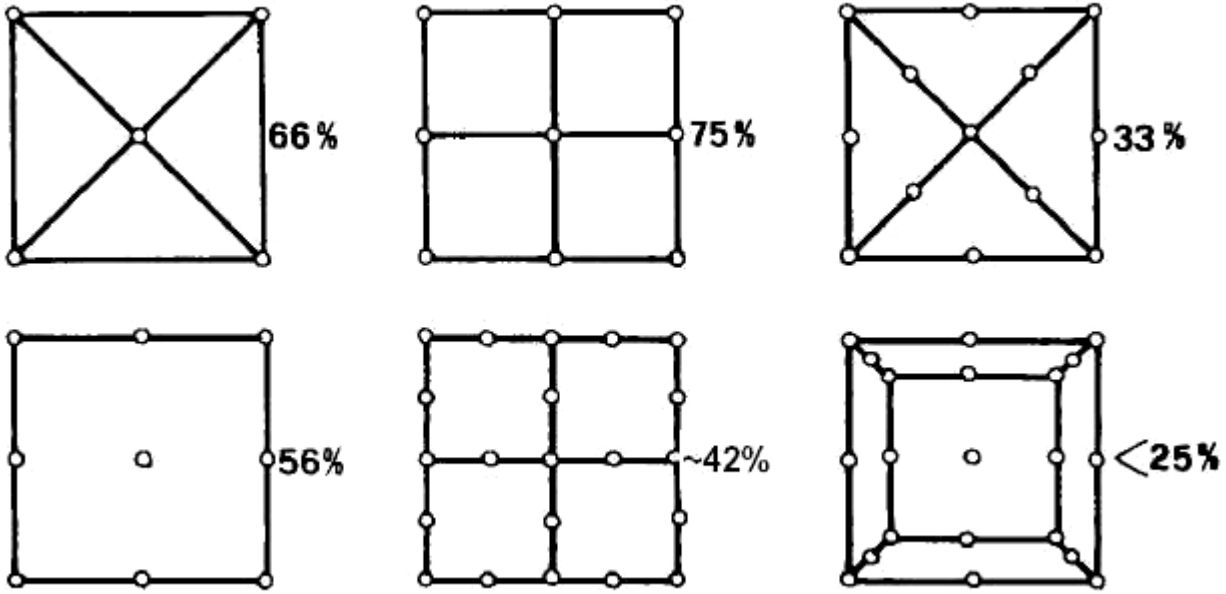

A/3
A
A/3
A/3


O
A/3
A
A/3
O
O
A/3


A/4
A/4
A
A/4
A/4

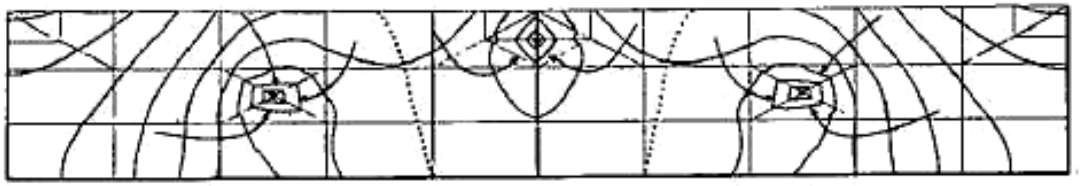

-A/12
A/3
-A/12
A/3
A
A/3
-A/12
A/3
-A/12


A/36
A/9
A/36
4A/9
A/9
A
A/9
A/36
A/9
A/36

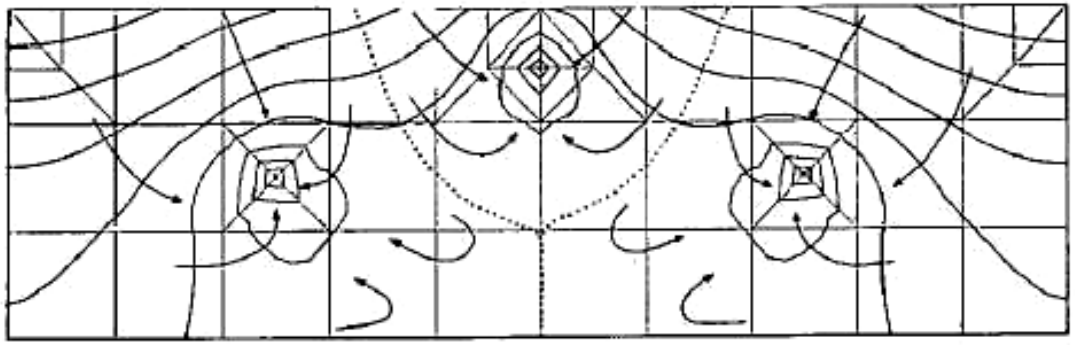

66%
75%
33%
56%
~42%
<25%

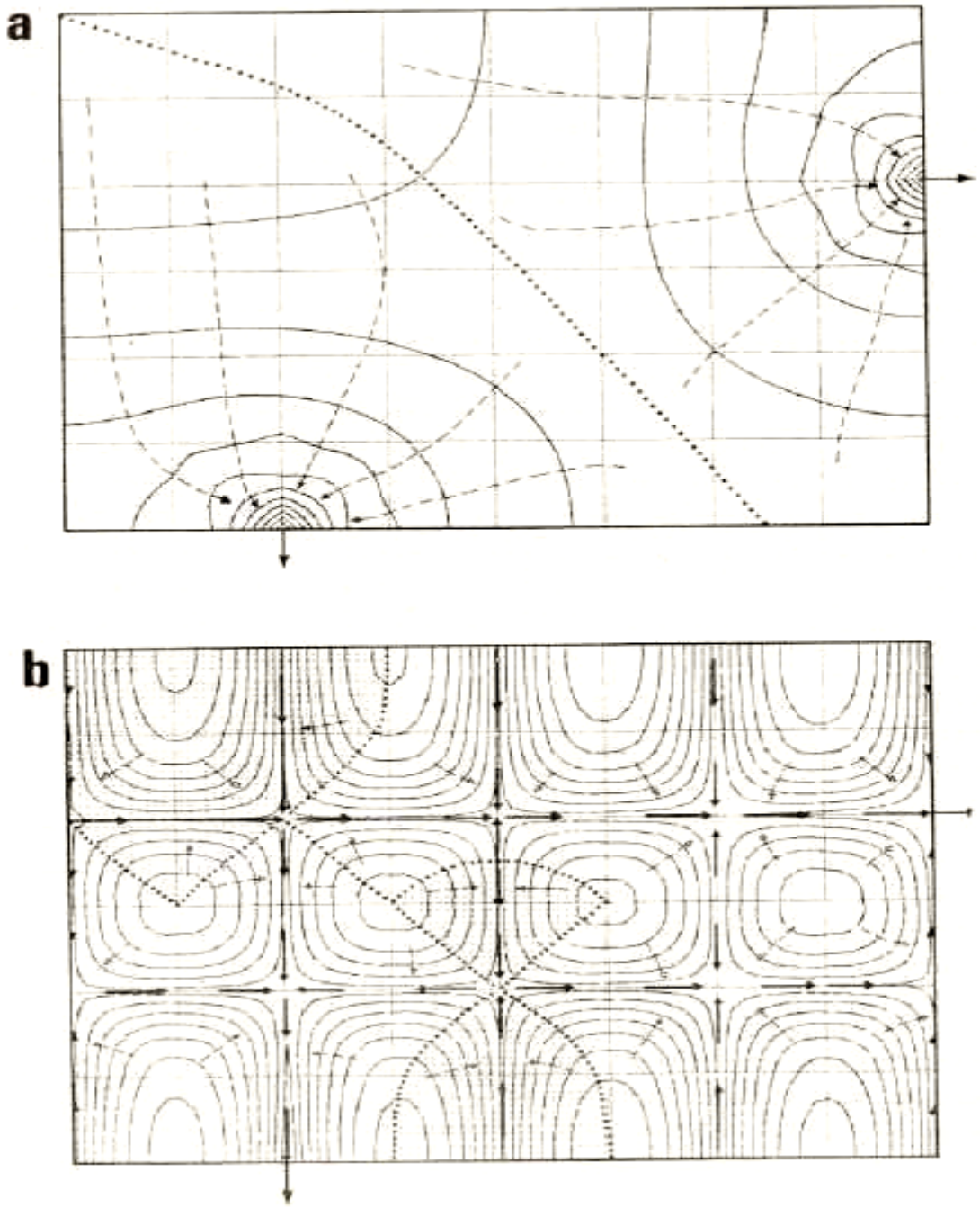
a

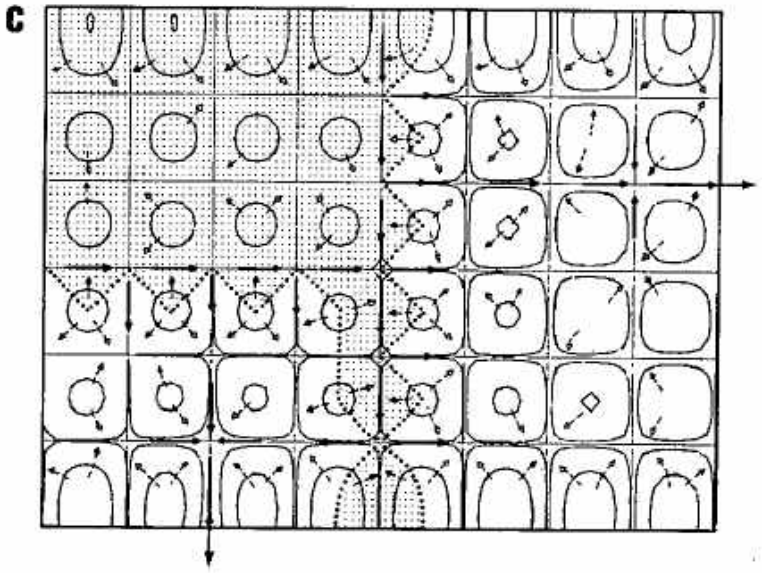
b

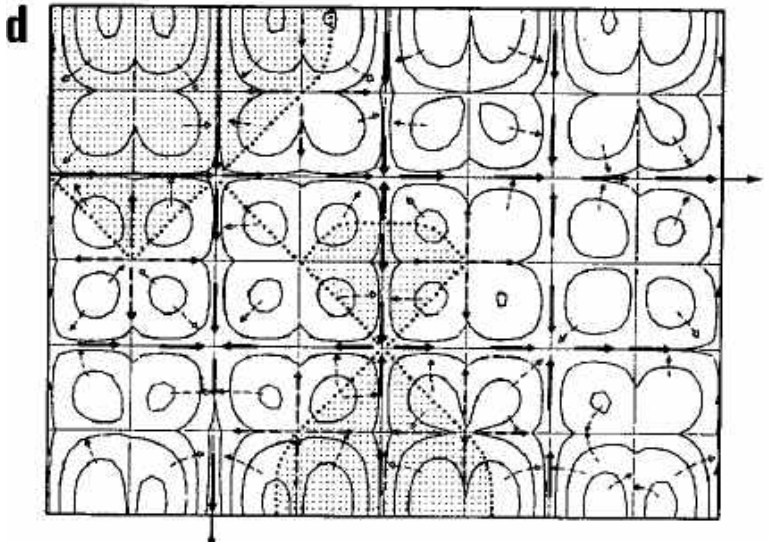


c




a
b


c


d

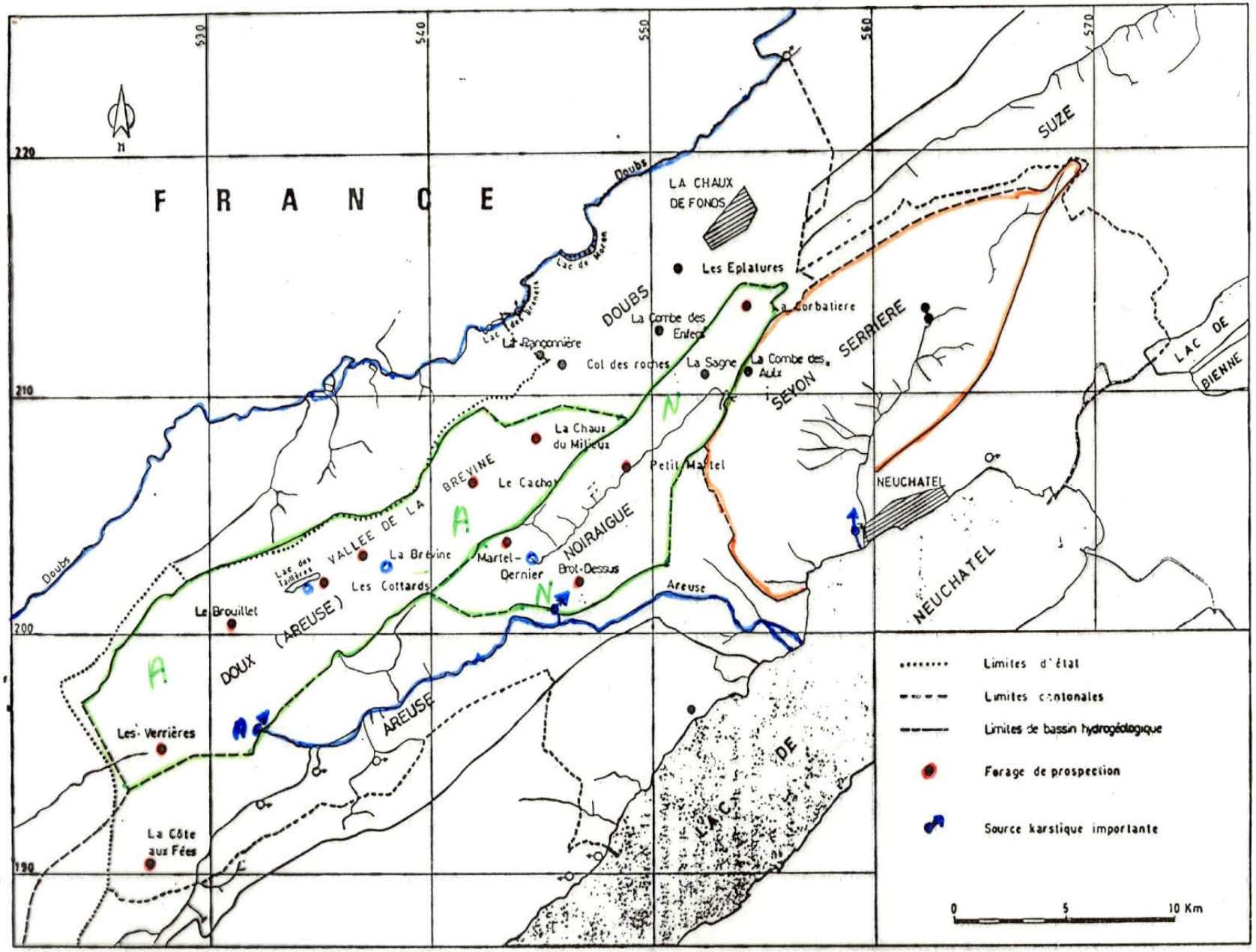
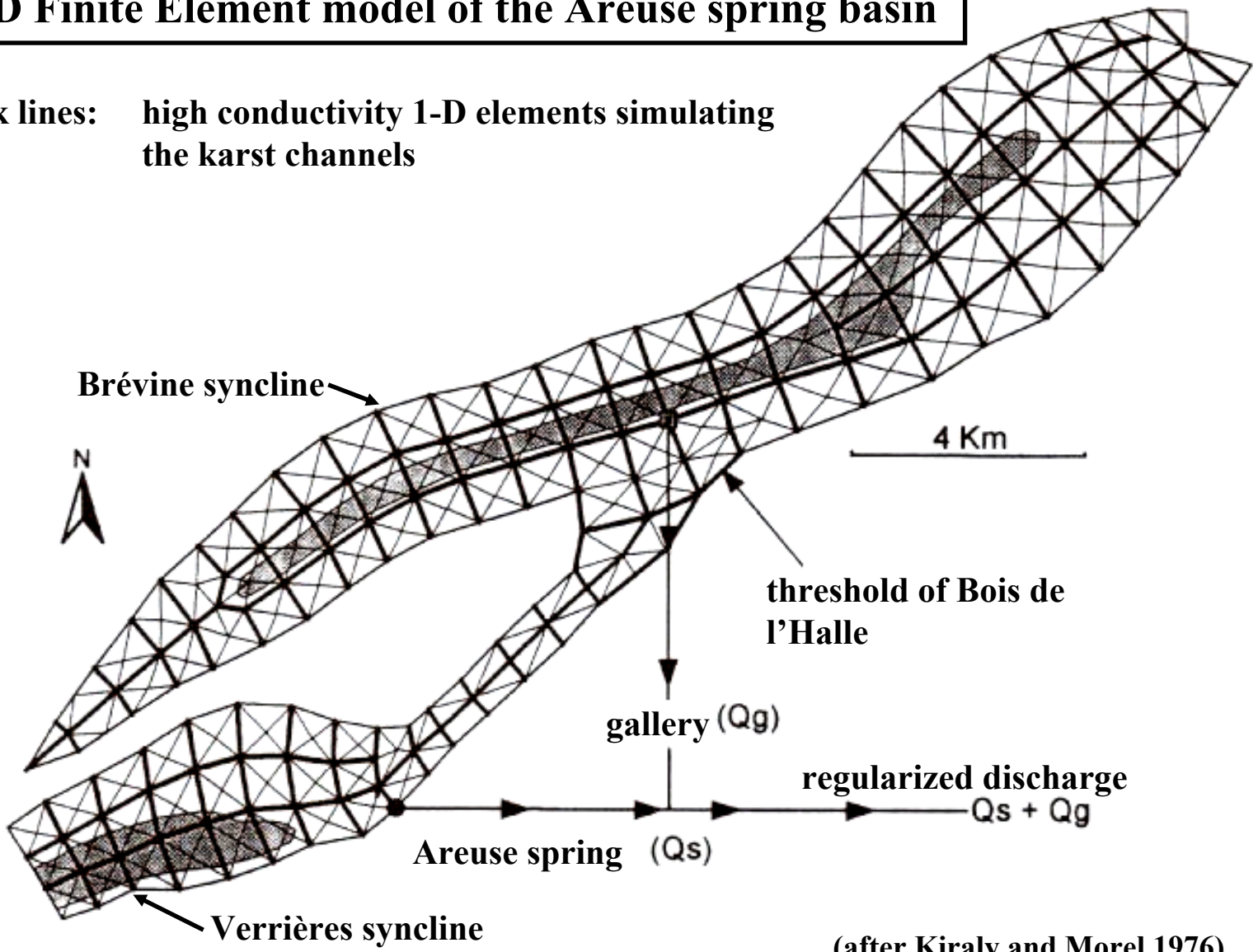


Fig. 1. Bassins hydrogéologiques importants, emplacement des forages profonds dans le canton de Neuchâtel et principales sources karstiques.

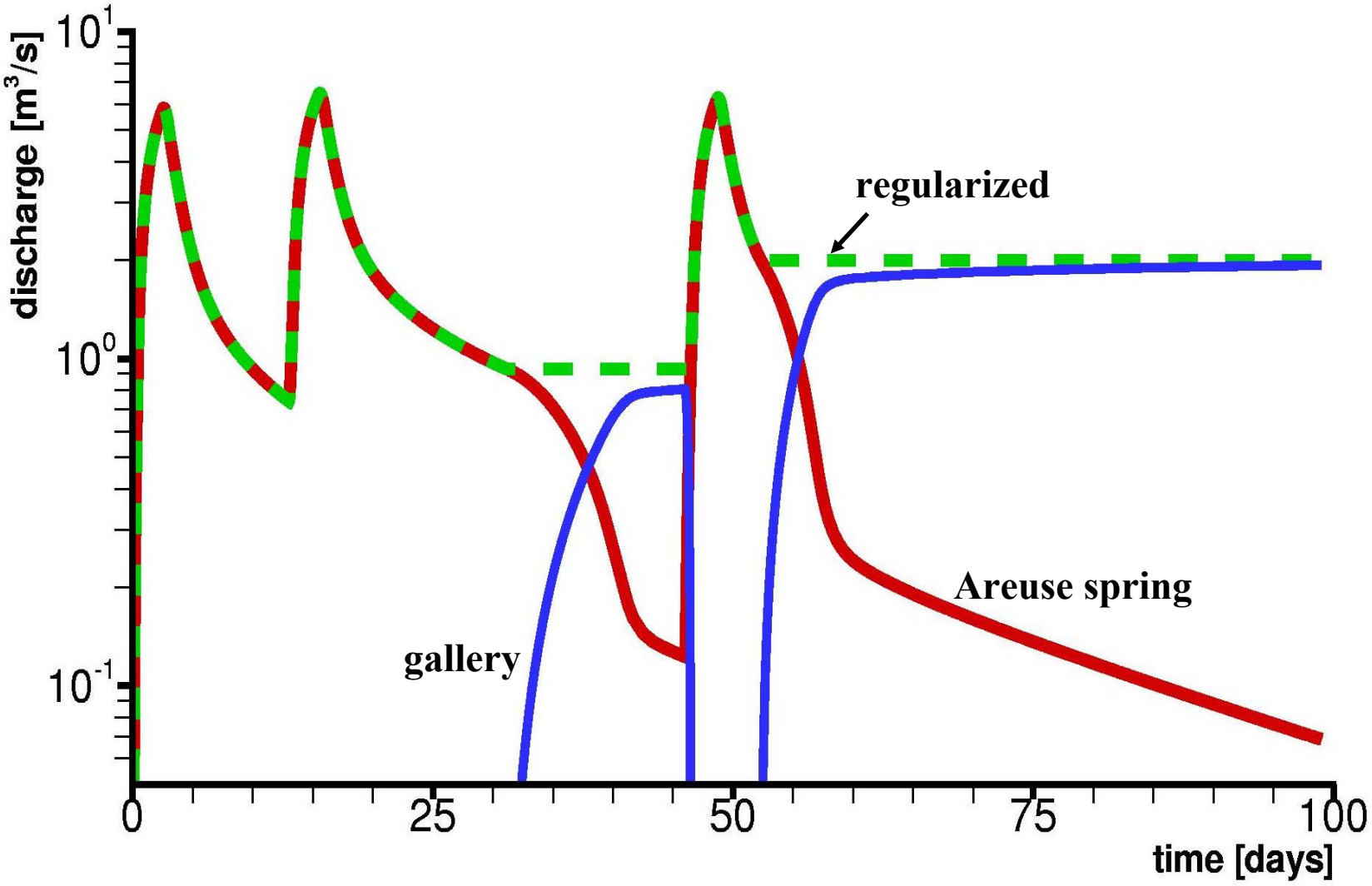
2-D Finite Element model of the Areuse spring basin

thick lines: high conductivity 1-D elements simulating the karst channels

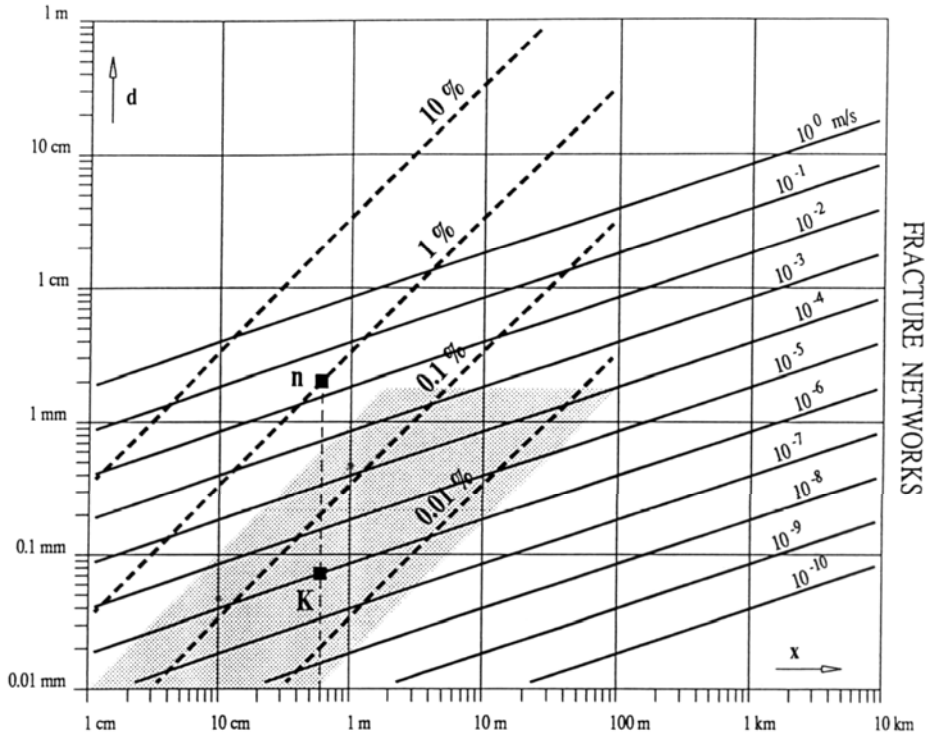


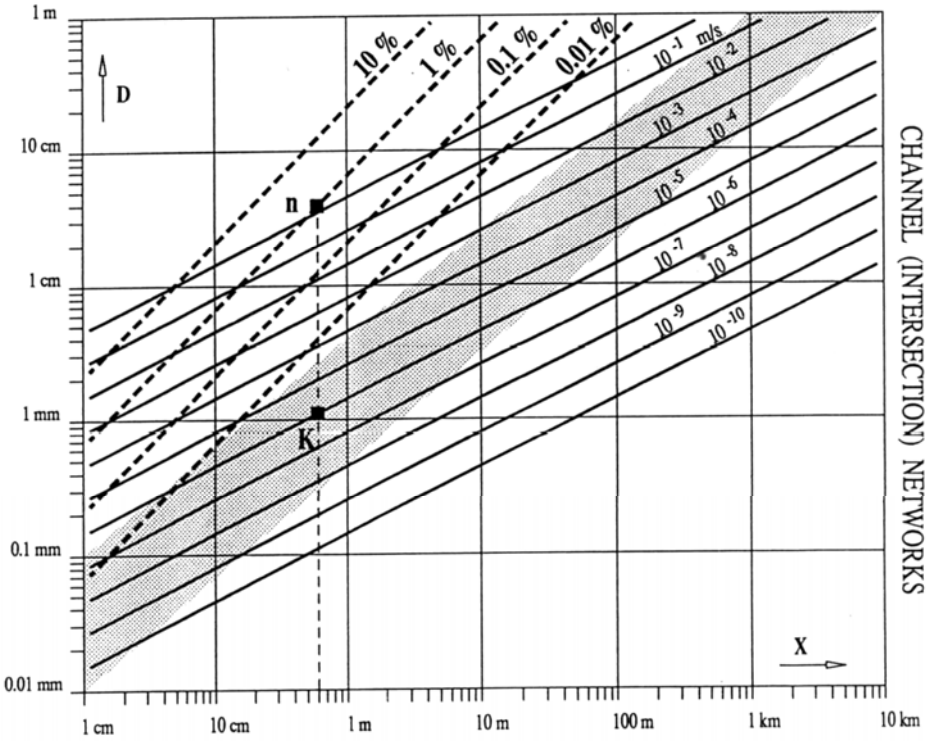
(after Kiraly and Morel 1976)

Example of regularization of the Areuse river

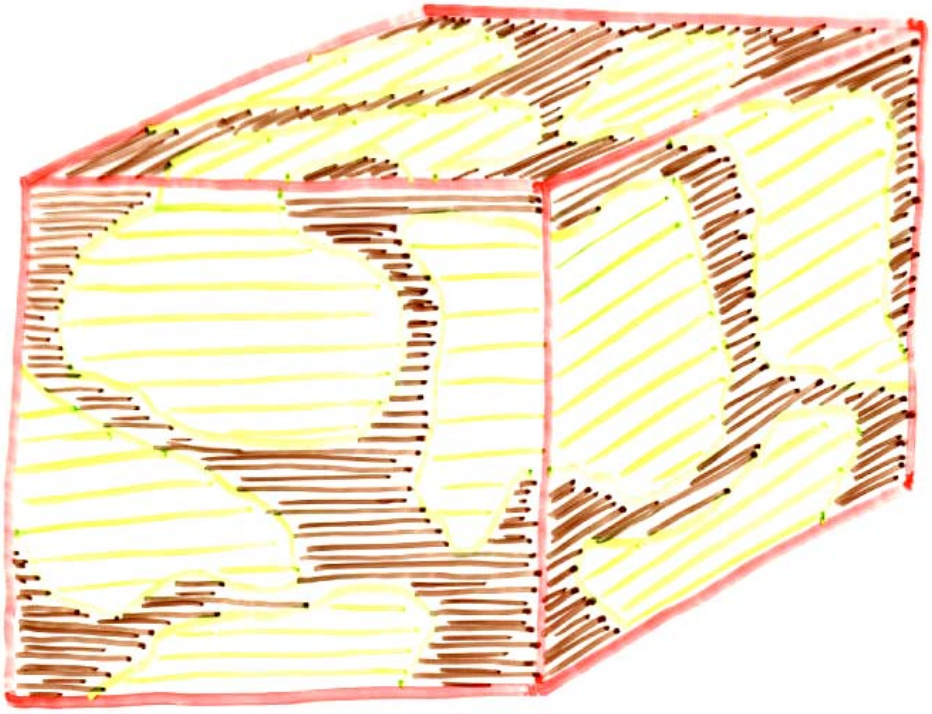


Hydraulic conductivity and efficient porosity values for various networks of fractures (left) and intersections of fractures or karst channels (right)



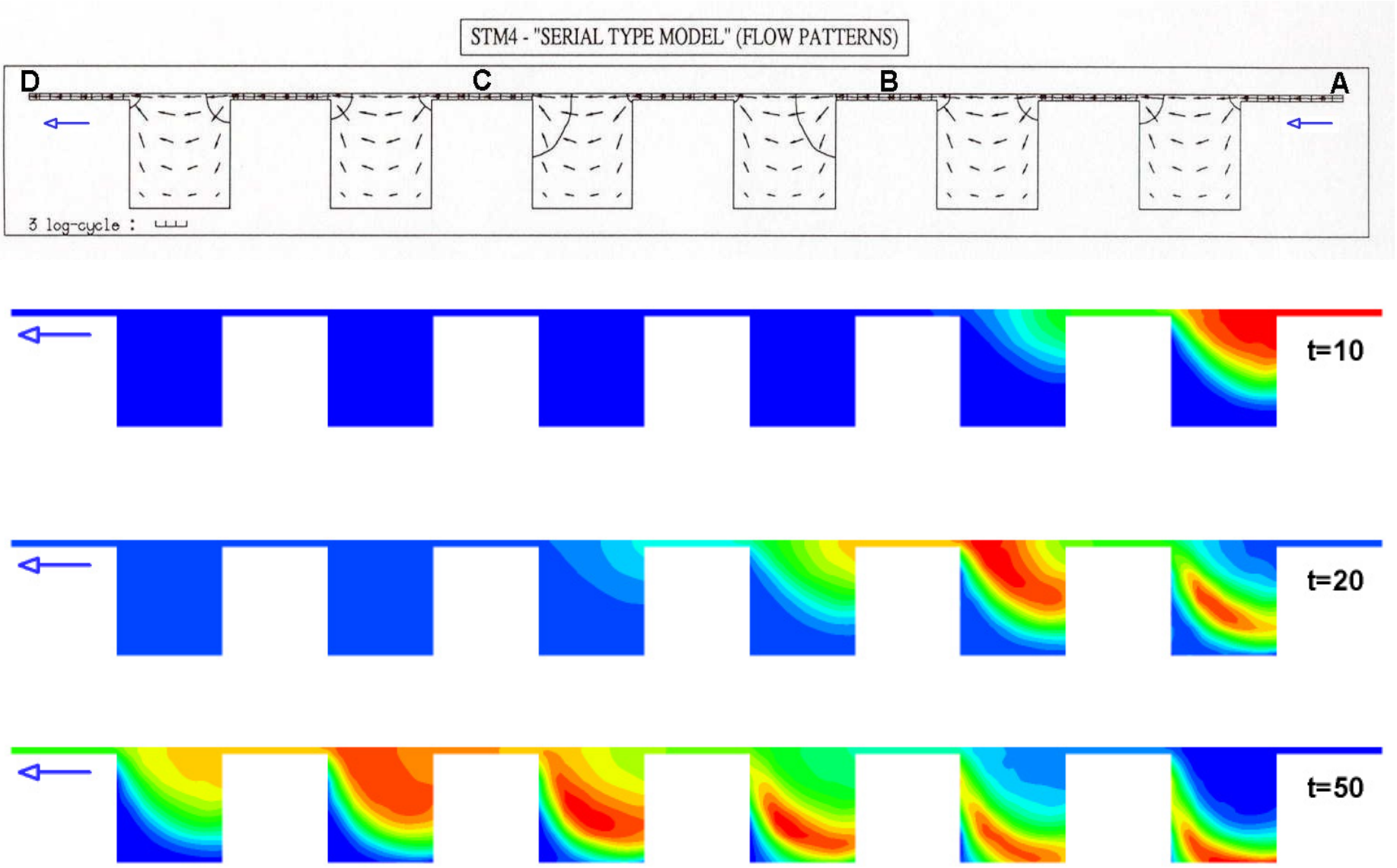


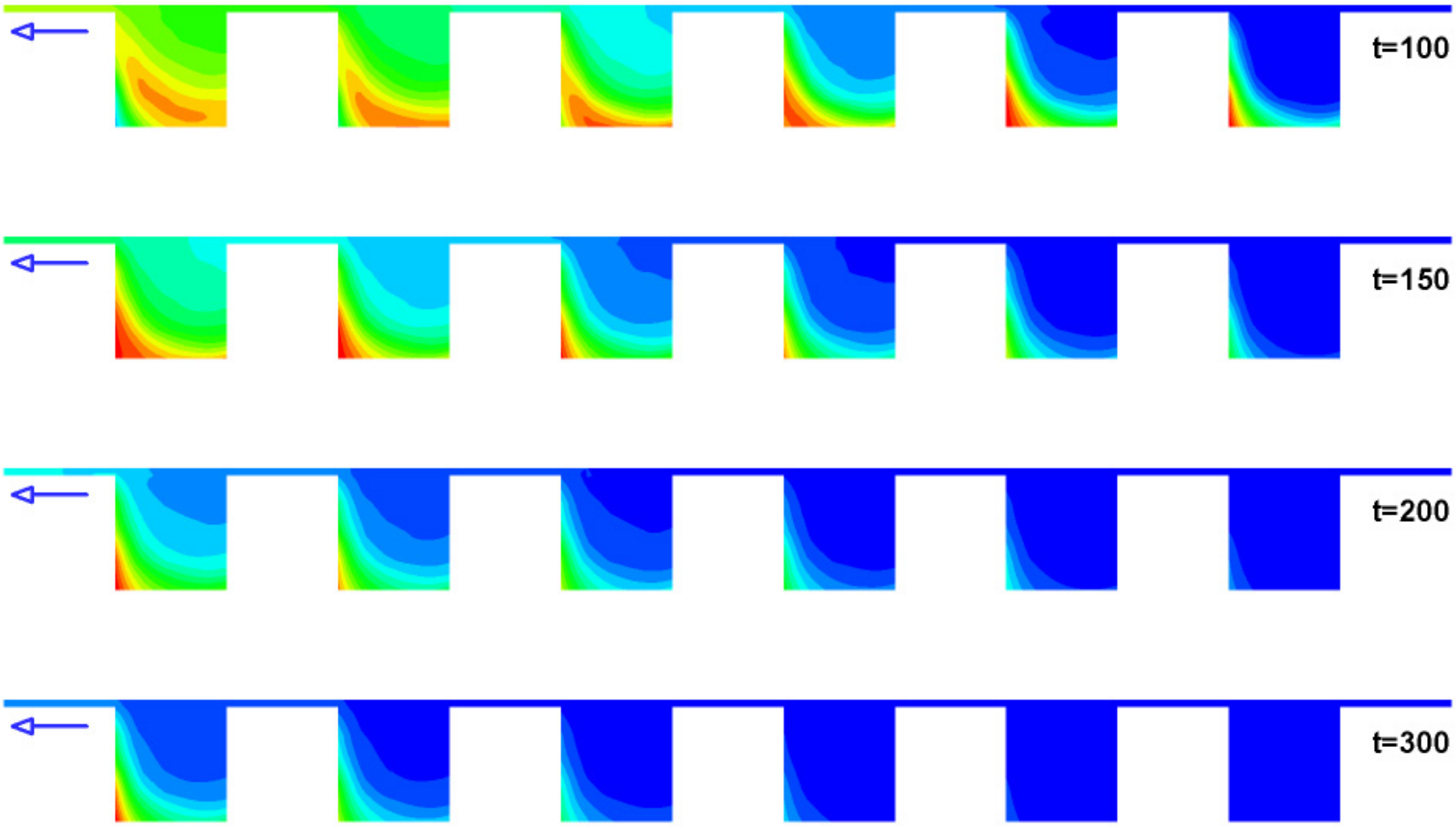
(after Kiraly 1975, modified)

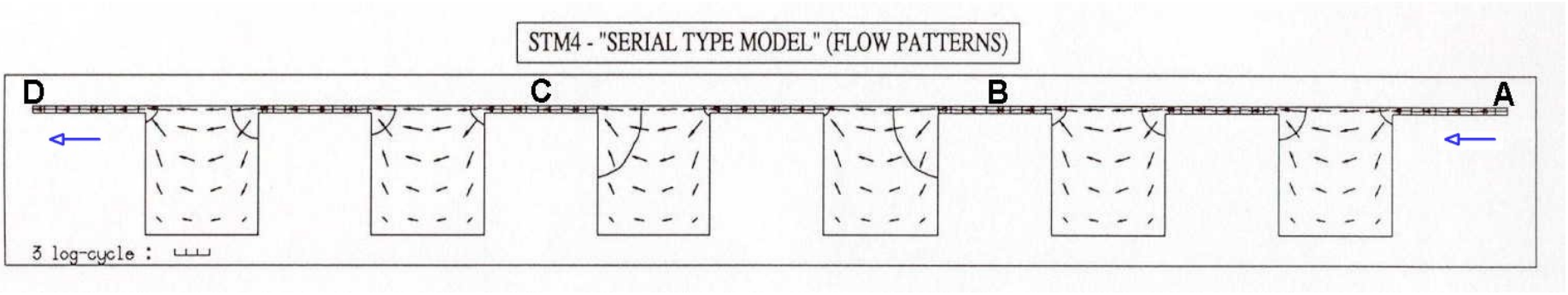


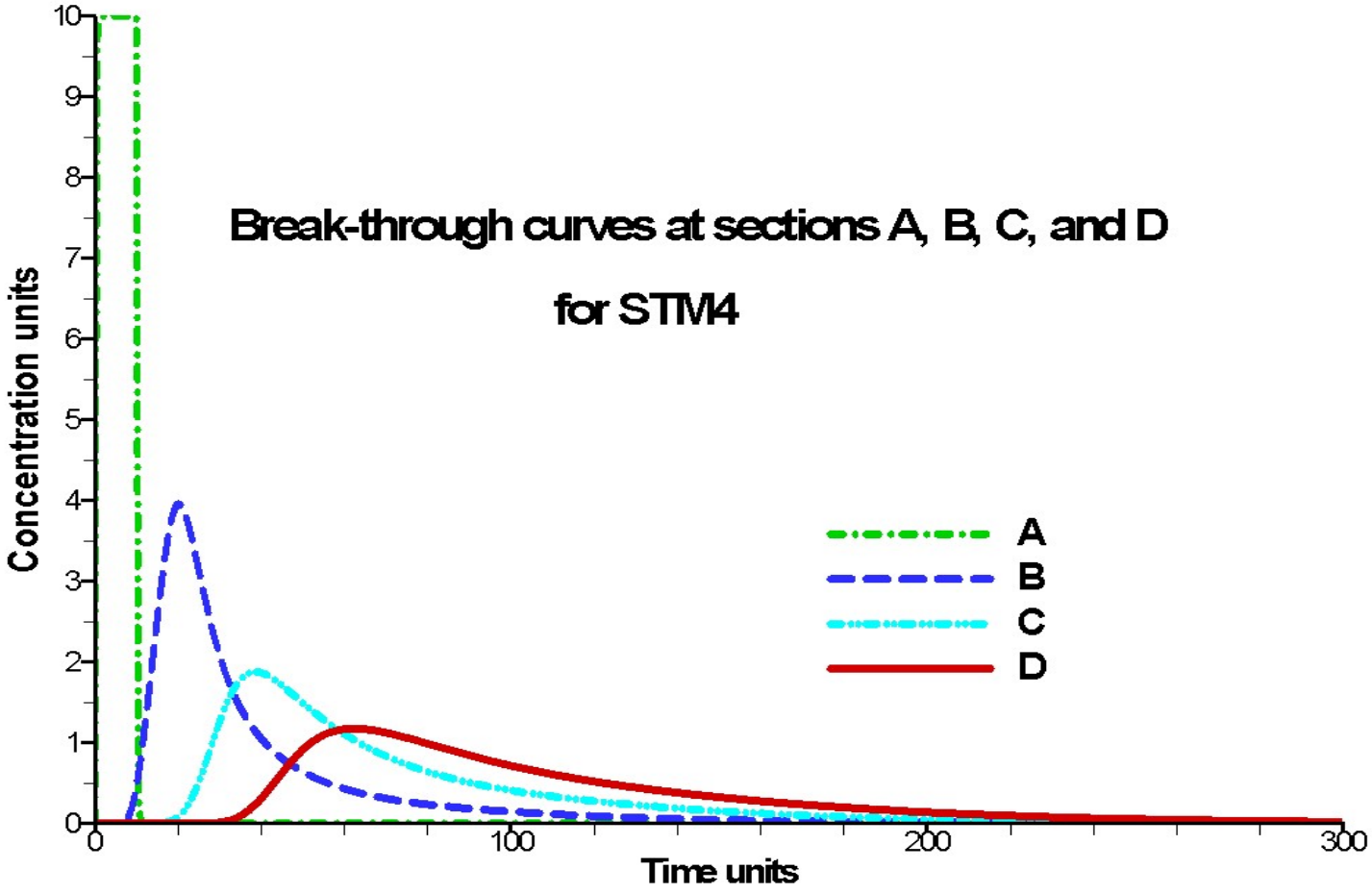
K is controlled by the intersections

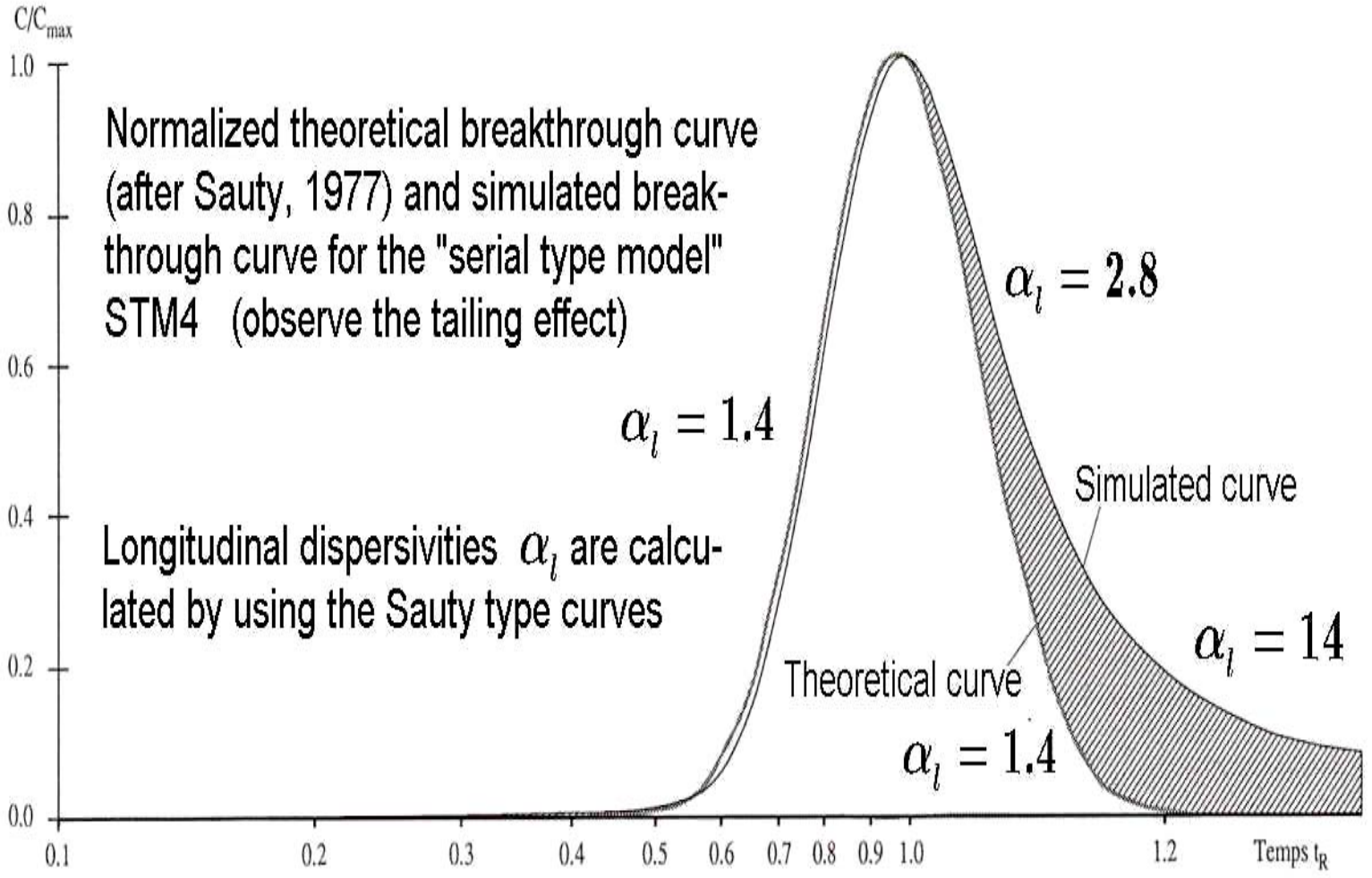
ε_e is controlled by the openings in the fracture planes


STM4 - "SERIAL TYPE MODEL" (FLOW PATTERNS)
D
C
B
A
3 log-cycle :
t=10
t=20
t=50

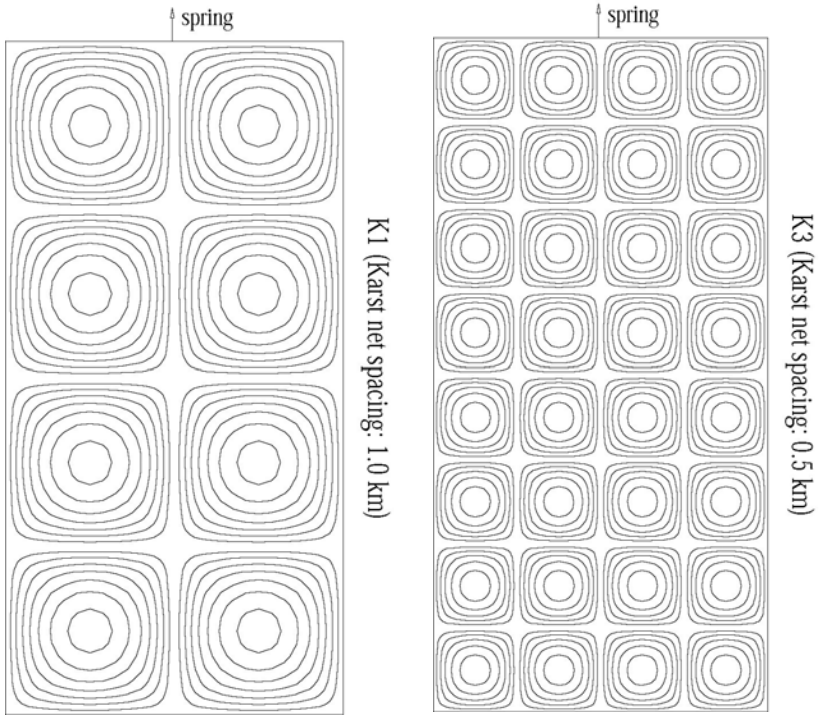

t=100
t=150
t=200
t=300

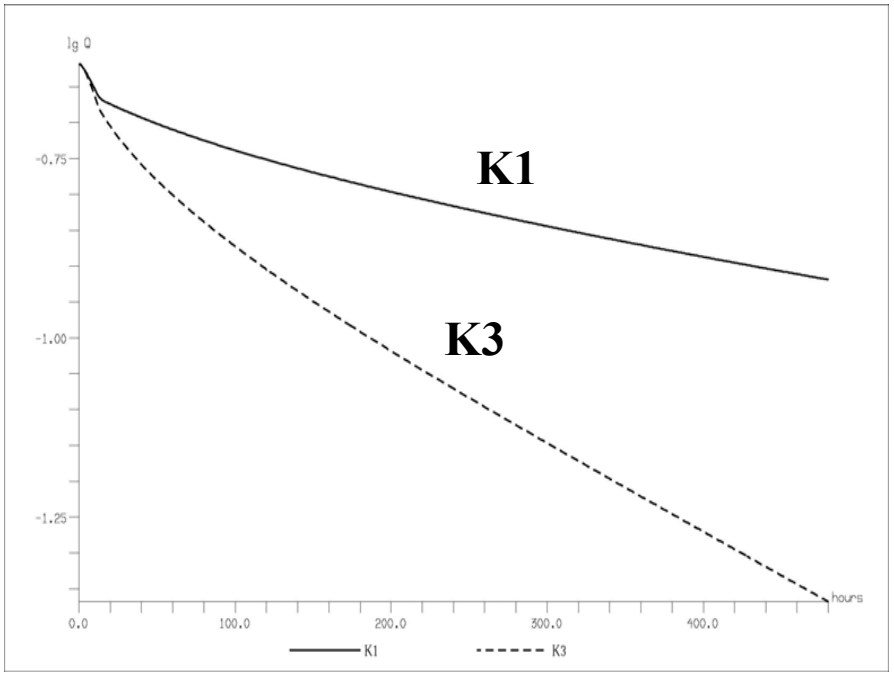

STM4 - "SERIAL TYPE MODEL" (FLOW PATTERNS)
D
C
B
A
3 log-cycle :

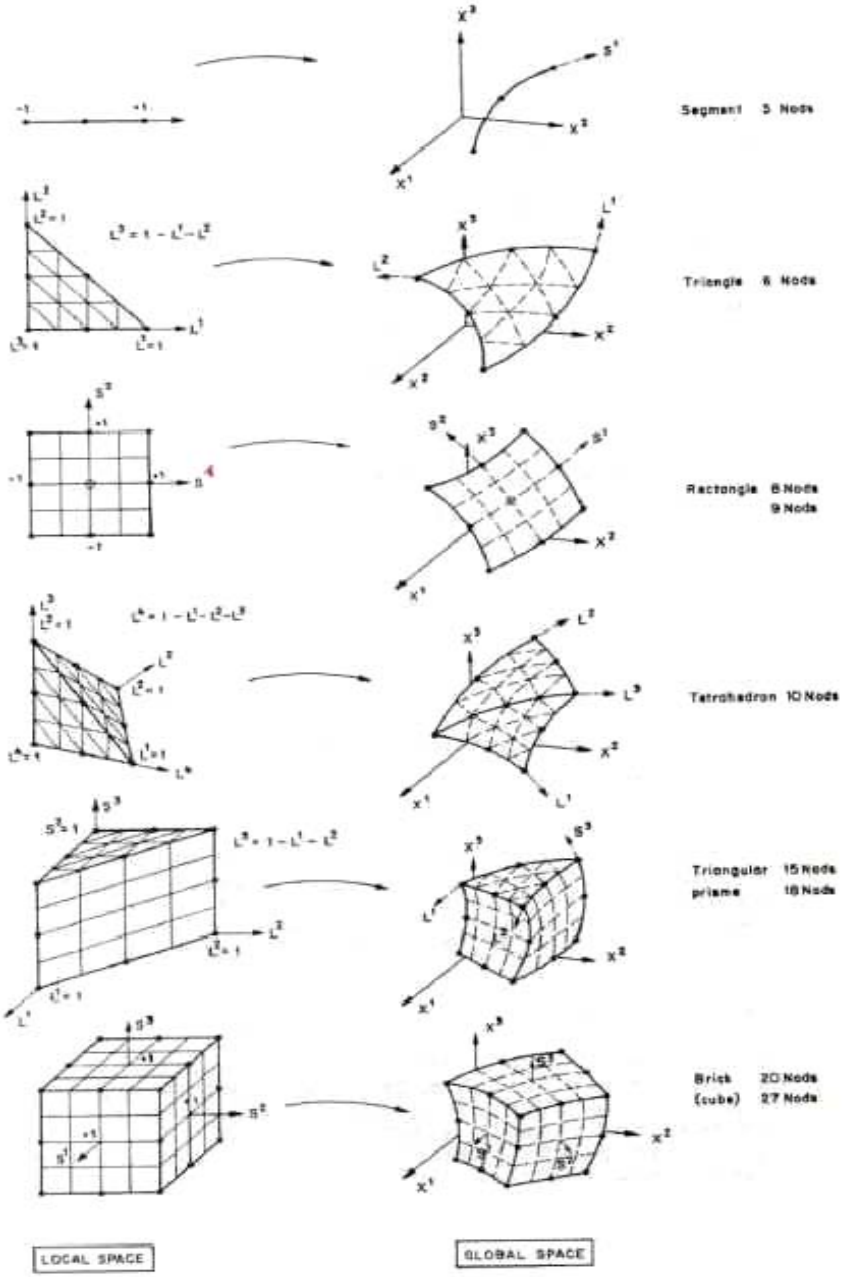

Break-through curves at sections A, B, C, and D
for STM4
Concentration units
Time units
0
1
2
3
4
5
6
7
8
9
10
0
100
200
300
A
B
C
D

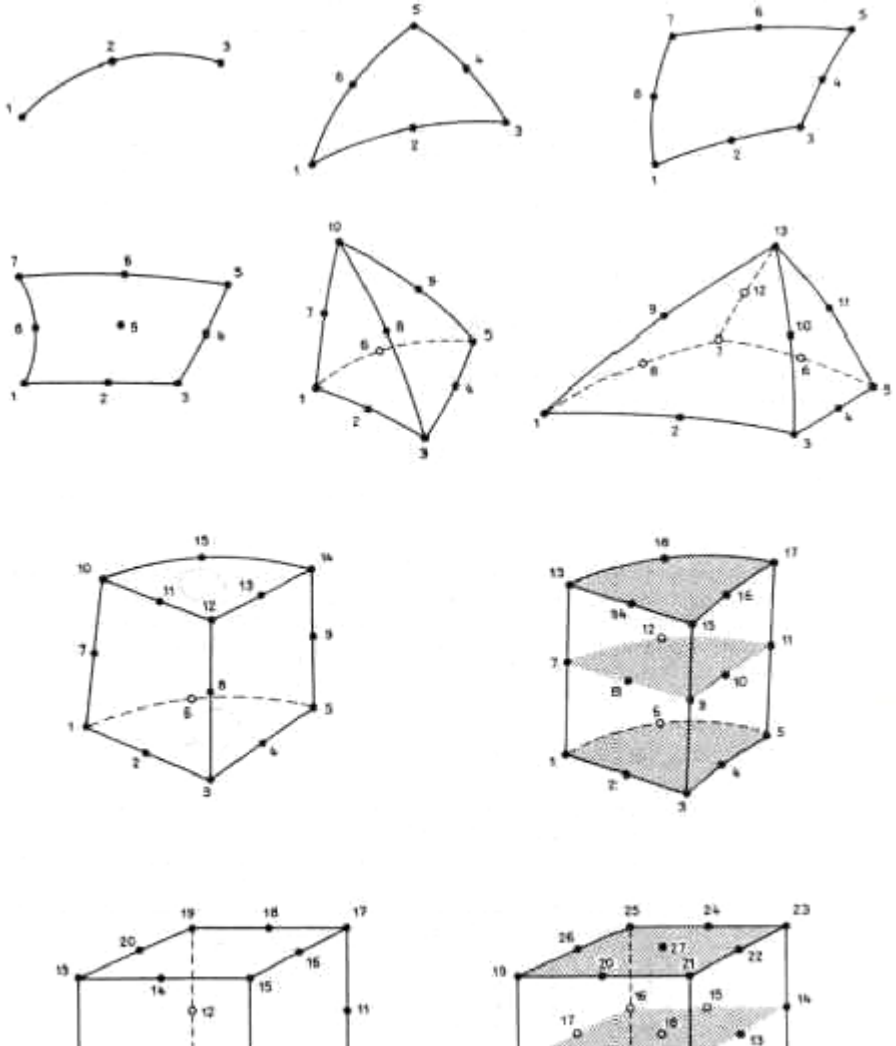

C/C_max
1.0
0.8
0.6
0.4
0.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.2
Temps t_R
Normalized theoretical breakthrough curve (after Sauty, 1977) and simulated break-through curve for the "serial type model" STM4 (observe the tailing effect)
Longitudinal dispersivities α_l are calcu-lated by using the Sauty type curves
α_l = 2.8
α_l = 1.4
Simulated curve
α_l = 14
Theoretical curve
α_l = 1.4

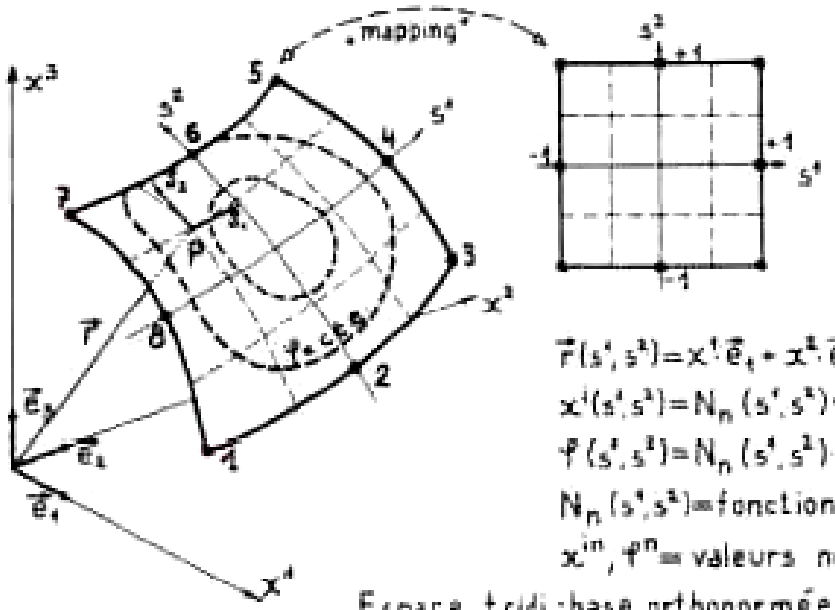
Effect of the density of the high conductivity drainage network on the recession curve of karst springs.






Segment 3 Nods
Triangle 6 Nods
Rectangle 8 Nods
9 Nods
Tetrahedron 10 Nods
Triangular prisme 15 Nods
18 Nods
Brick (cube) 20 Nods
27 Nods
LOCAL SPACE
GLOBAL SPACE





$\vec{r}(s^1,s^2) = x^1\cdot\vec{e}_1 + x^2\cdot\vec{e}_2 + x^3\cdot\vec{e}_3$

$x^i(s^1,s^2) = N_n(s^1,s^2)\cdot x^{in}$ $\quad n=1,8\ ;\ i=1,3$

$\varphi(s^1,s^2) = N_n(s^1,s^2)\cdot \varphi^n$ $\quad n=1,8$

$N_n(s^1,s^2)$ = fonctions d'interpolation

x^{in}, φ^n = valeurs nodales

Espace tridi : base orthonormée $(\vec{e}_i)$

Espace bidi : base covariante $(\vec{a}_k)$ $\quad \vec{a}_k = \partial\vec{r}/\partial s^k$

Tenseur métrique contravariant $g^{ik} = g_{ik}^{-1} = \left[\vec{a}_i\cdot\vec{a}_k\right]^{-1}$

$$\overrightarrow{\text{grad}}\,\varphi = \frac{\partial\vec{r}}{\partial s^k}\cdot g^{ik}\cdot\frac{\partial\varphi}{\partial s^i}$$

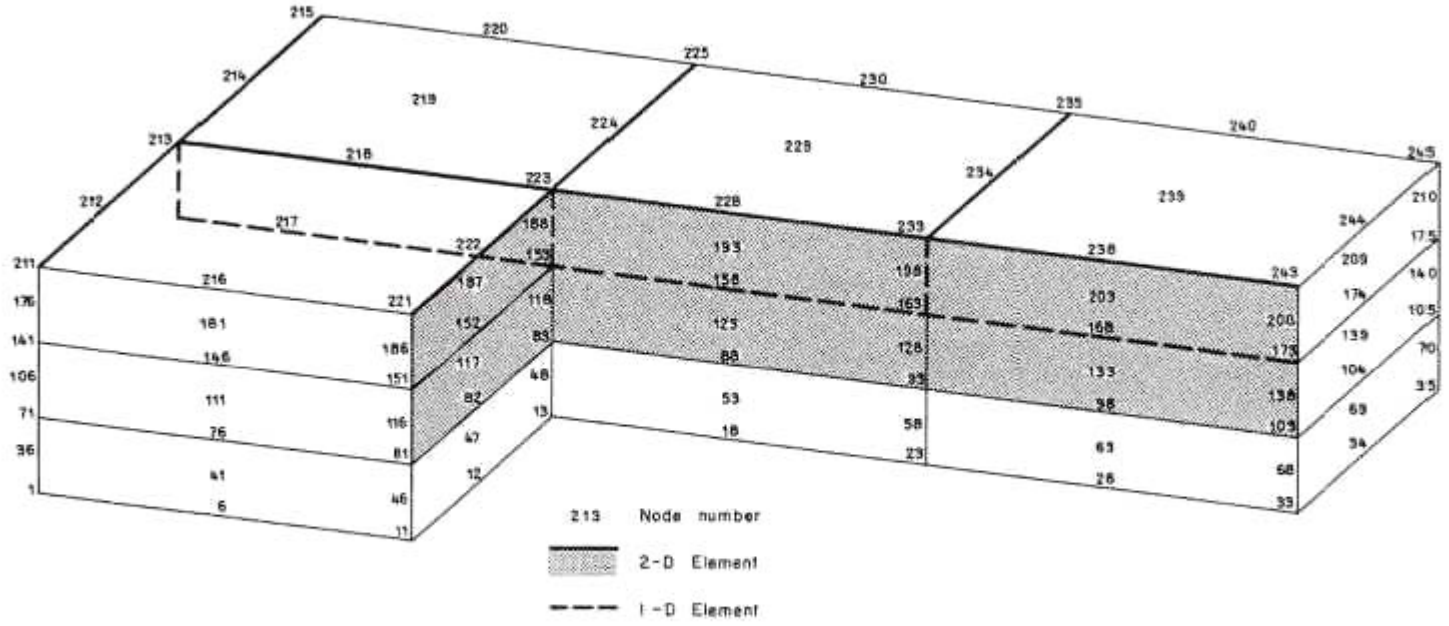
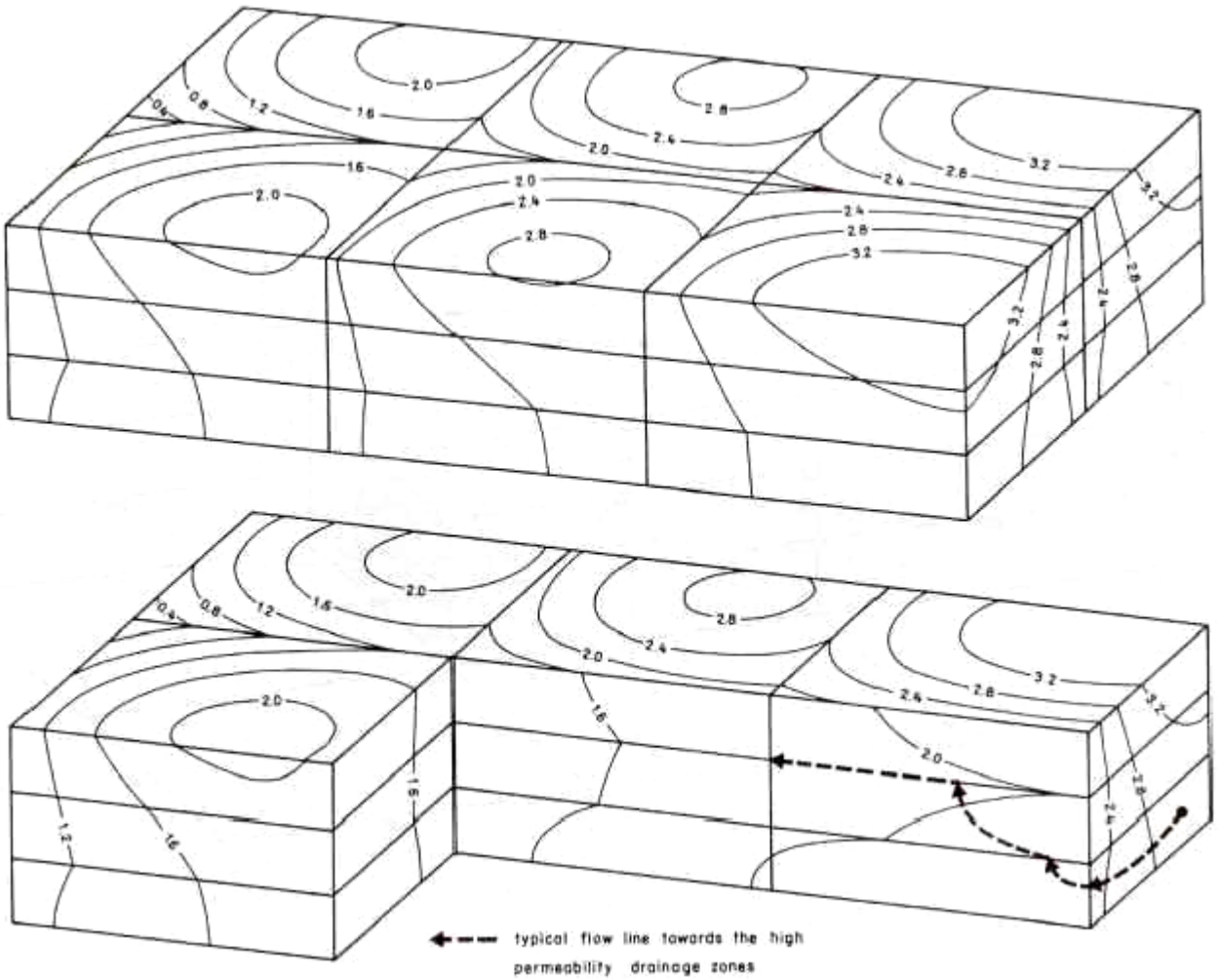
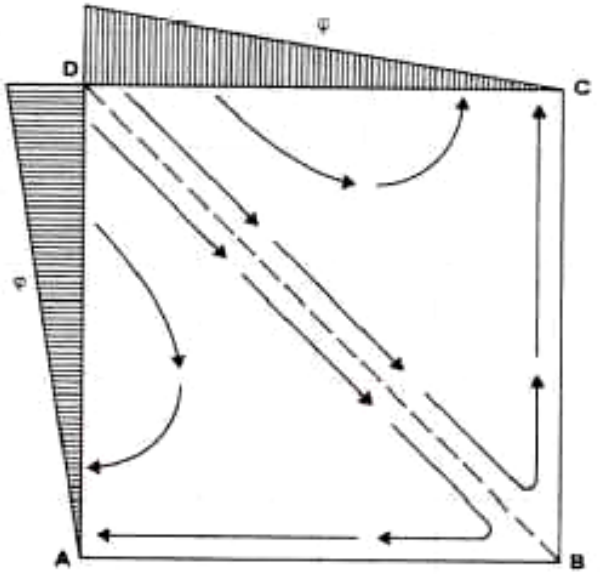


Figure 7-1: Three-Dimensional Fractured Block Model with 1-D, 2-D and 3-D Elements


0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
typical flow line towards the high permeability drainage zones



$\varphi_A = \varphi_C = 0$ [m]

$\varphi_D = 2$ [m]

$K = 1$ [m/s]

$q_n = 0$ on AB and BC.

Figure 7-10: Boundary conditions for large element example

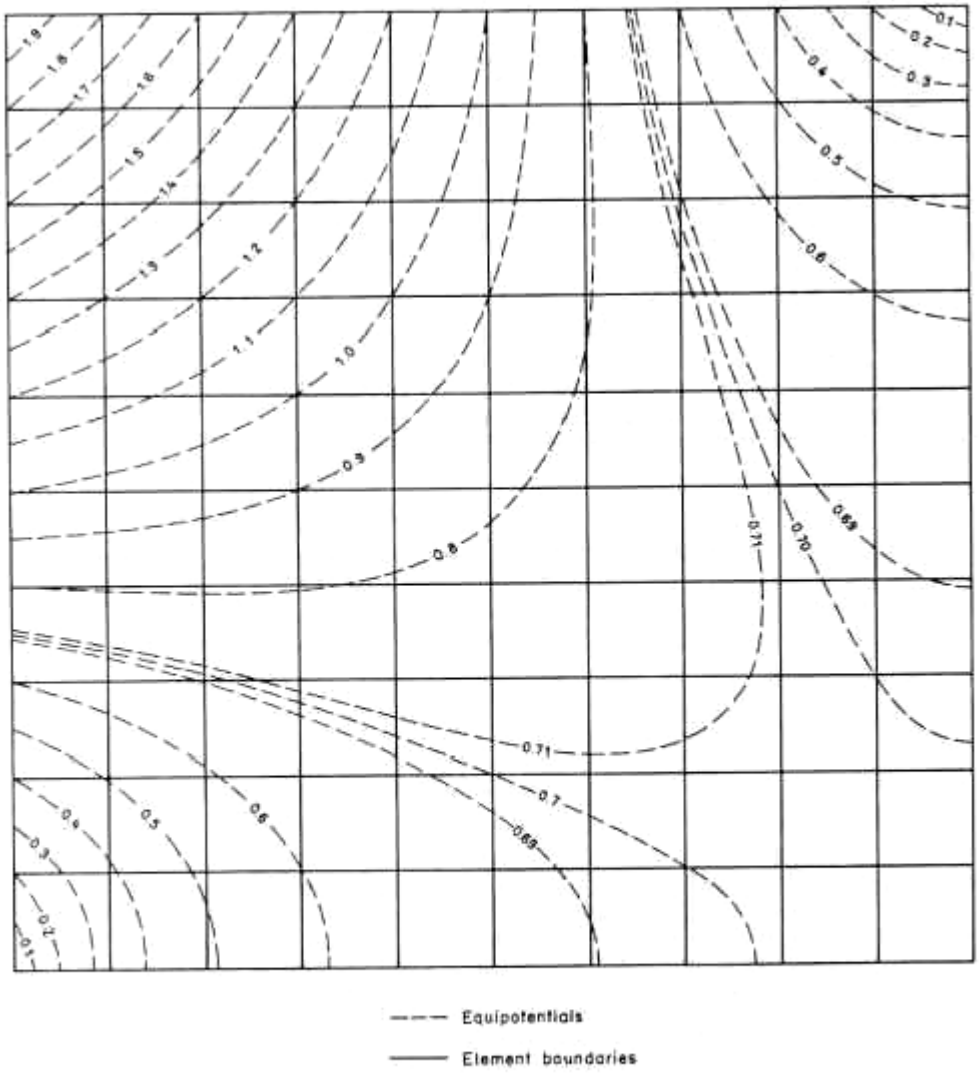


Figure 7-11: Results of large element example
a) "Exact" solution

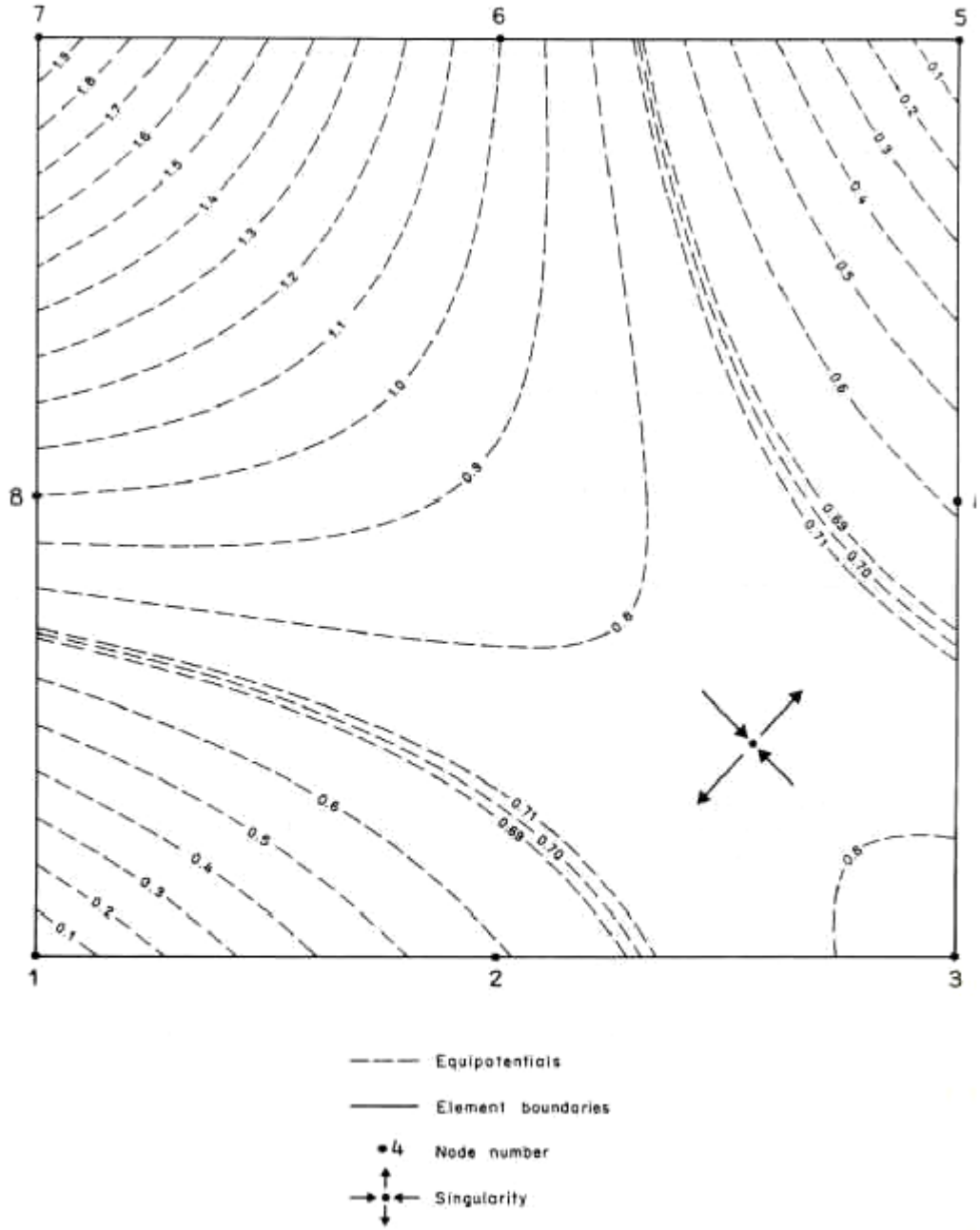
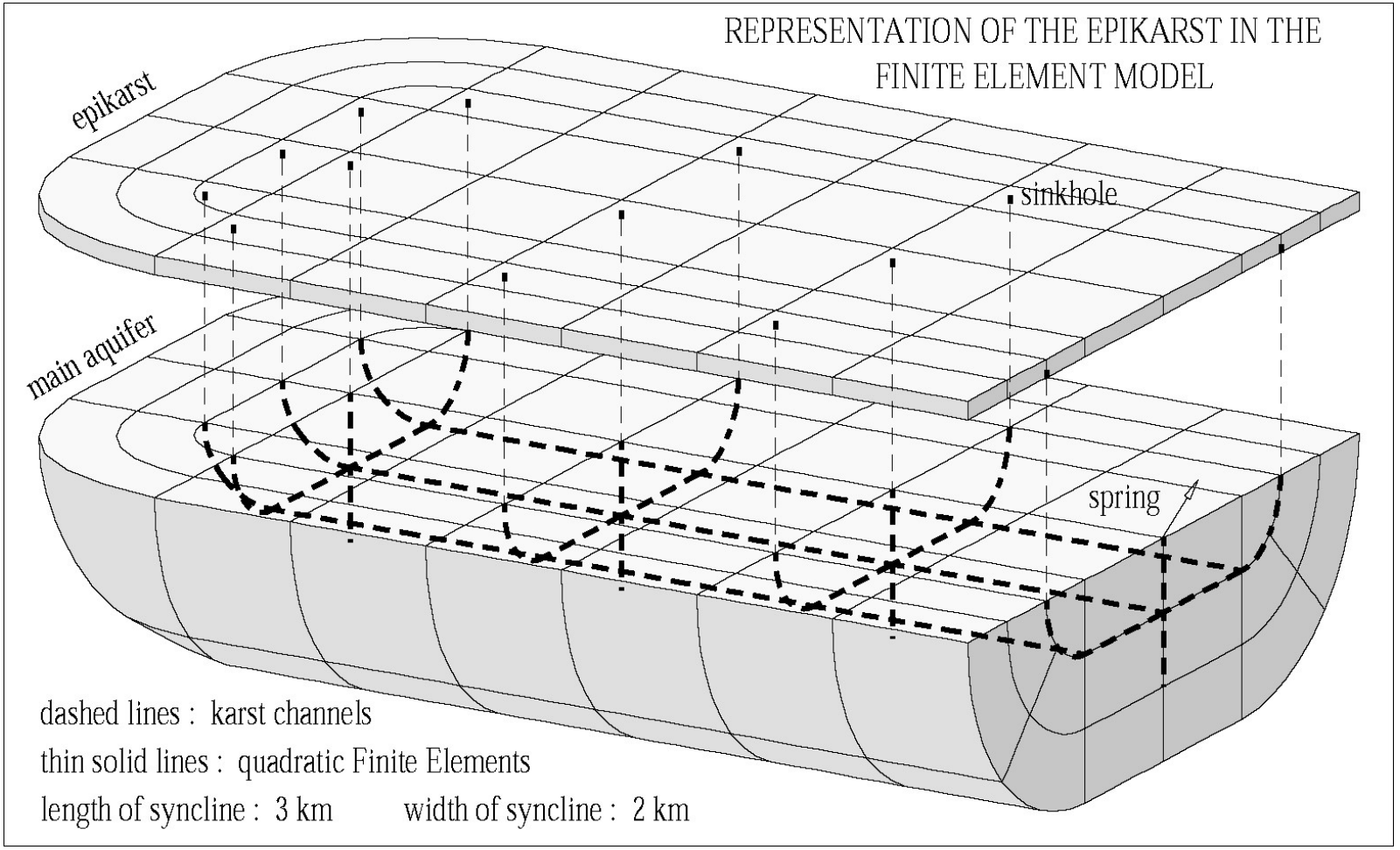
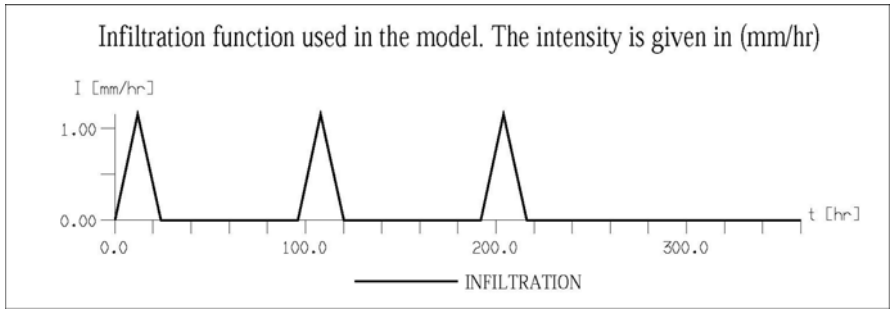
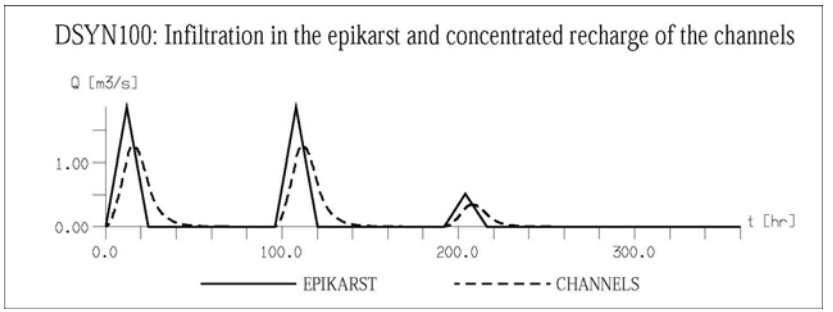


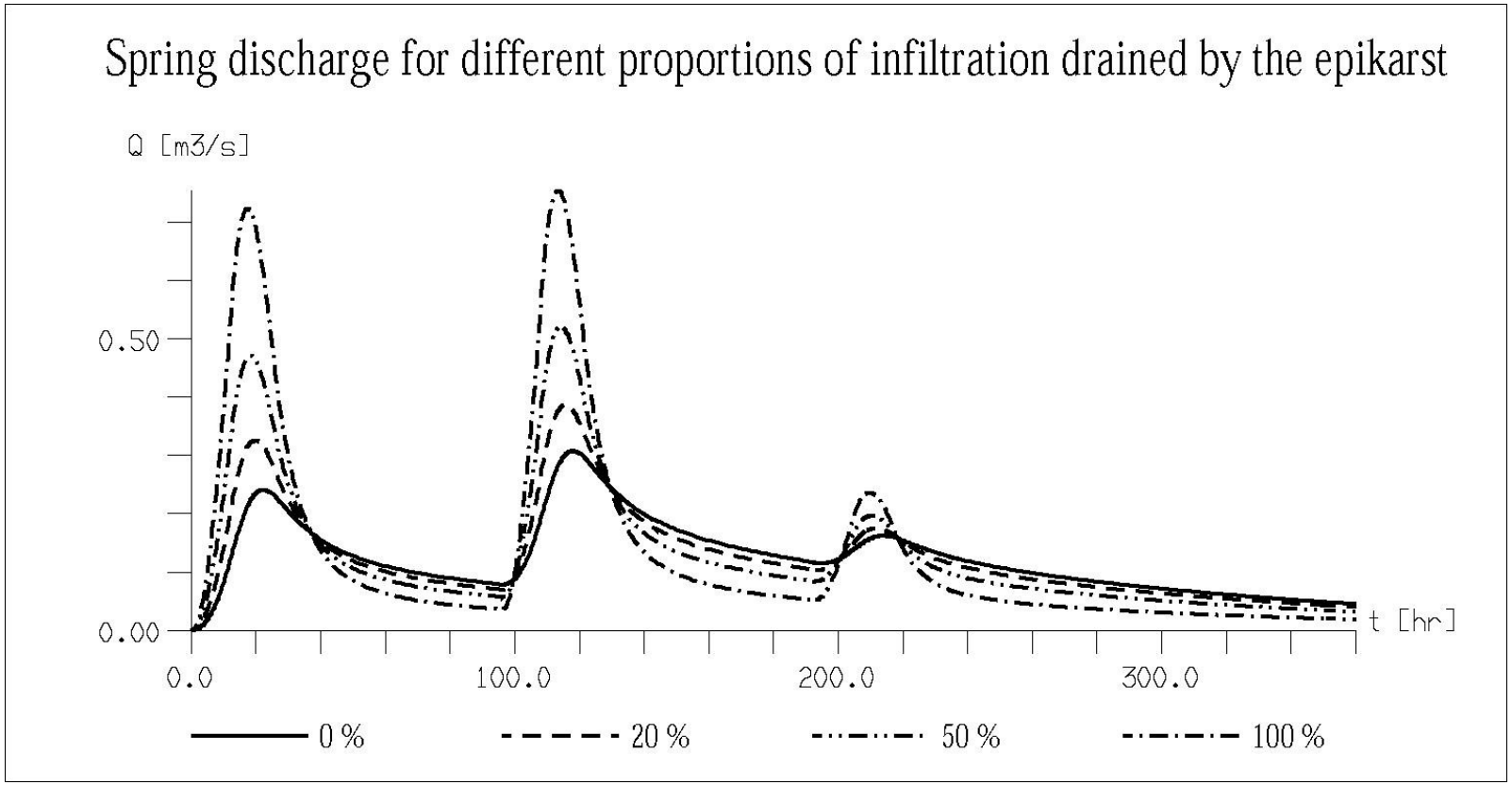
Figure 7-11: Results of large element example
b) Single element solution

Representation of the epikarst in the Finite Element model

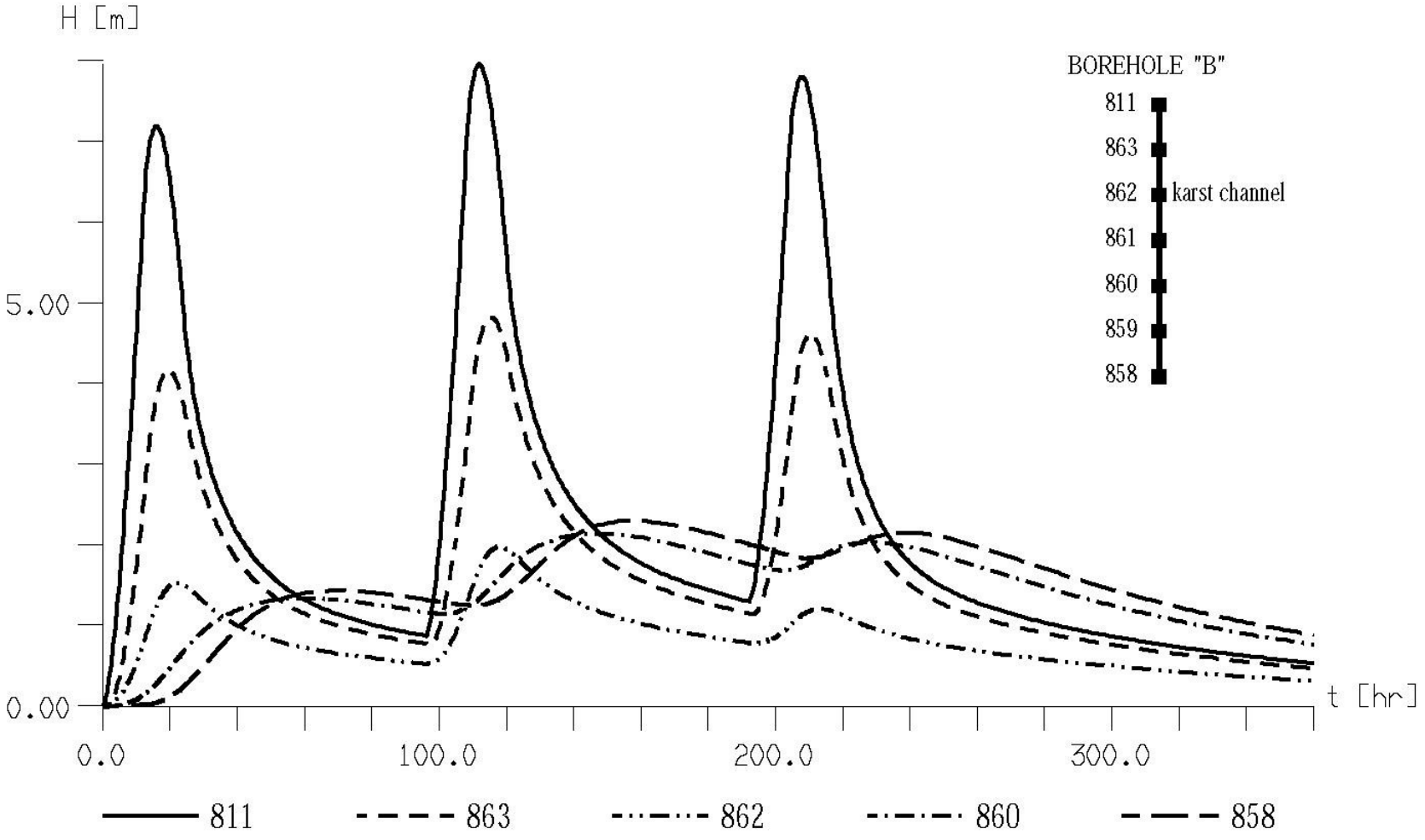



Infiltration function used in the model. The intensity is given in (mm/hr)
I [mm/hr]
1.00
0.00
0.0
100.0
200.0
300.0
t [hr]
INFILTRATION

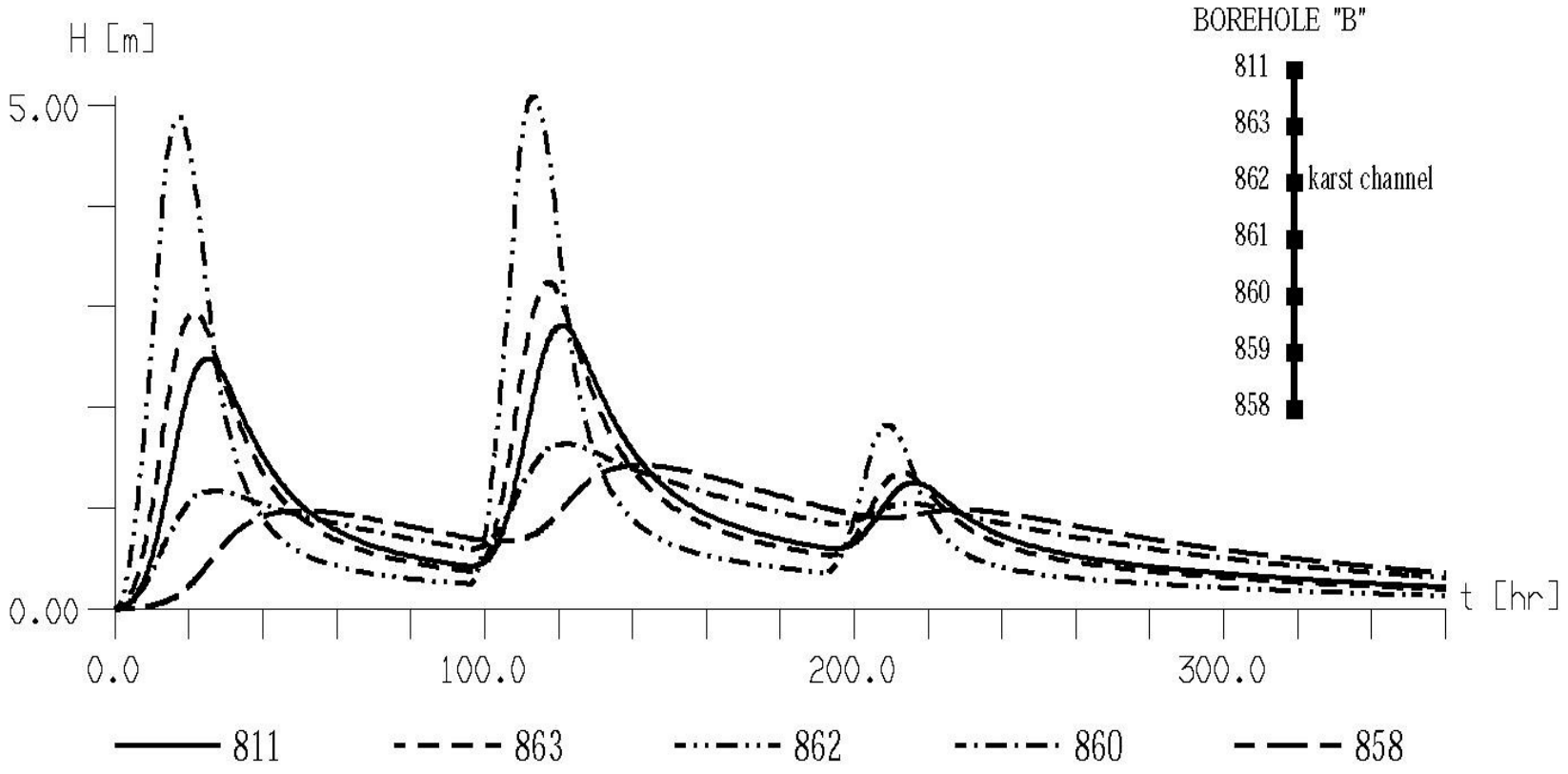

DSYN100: Infiltration in the epikarst and concentrated recharge of the channels
Q [m3/s]
1.00
0.00
0.0
100.0
200.0
300.0
t [hr]
EPIKARST
CHANNELS

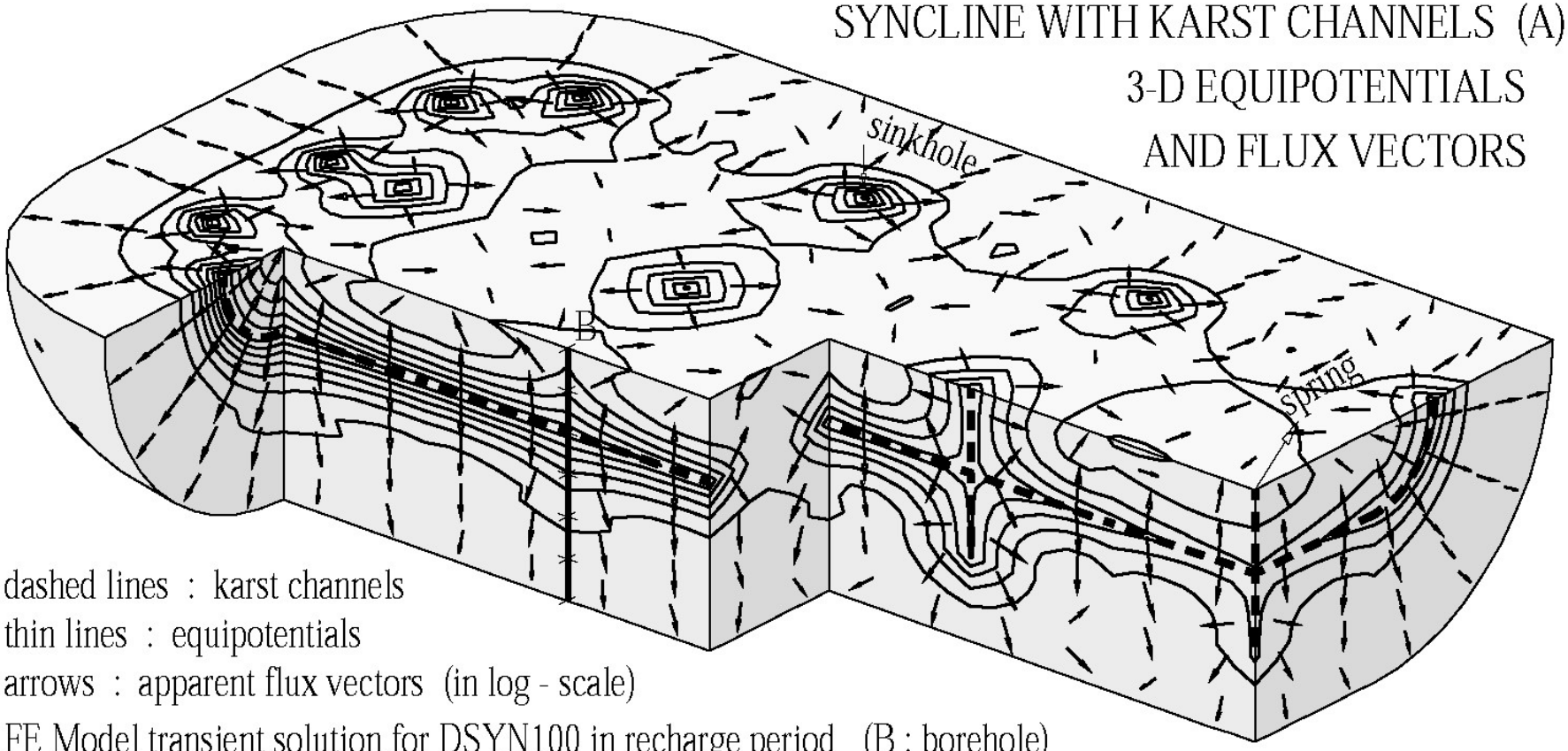

Spring discharge for different proportions of infiltration drained by the epikarst
Q [m3/s]
0.50
0.00
0.0
100.0
200.0
300.0
t [hr]
0 %
20 %
50 %
100 %

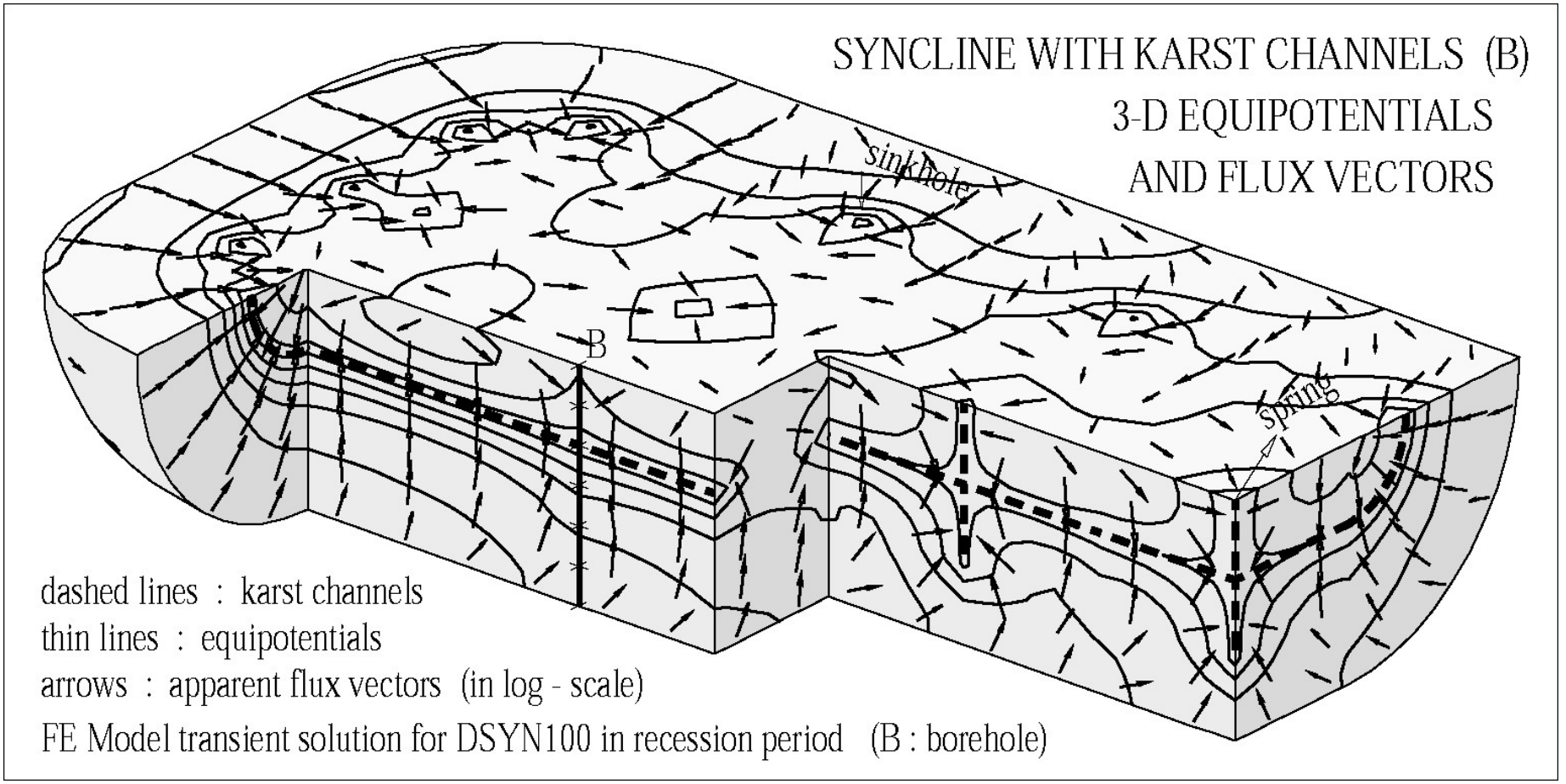
DSYN0 without epikarst. Hydraulic heads in borehole "B".

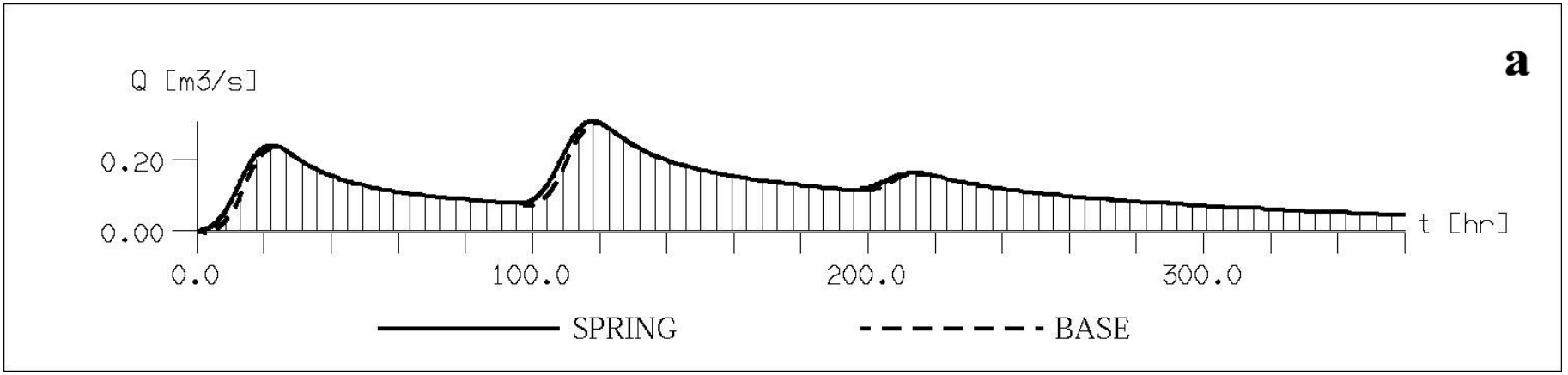


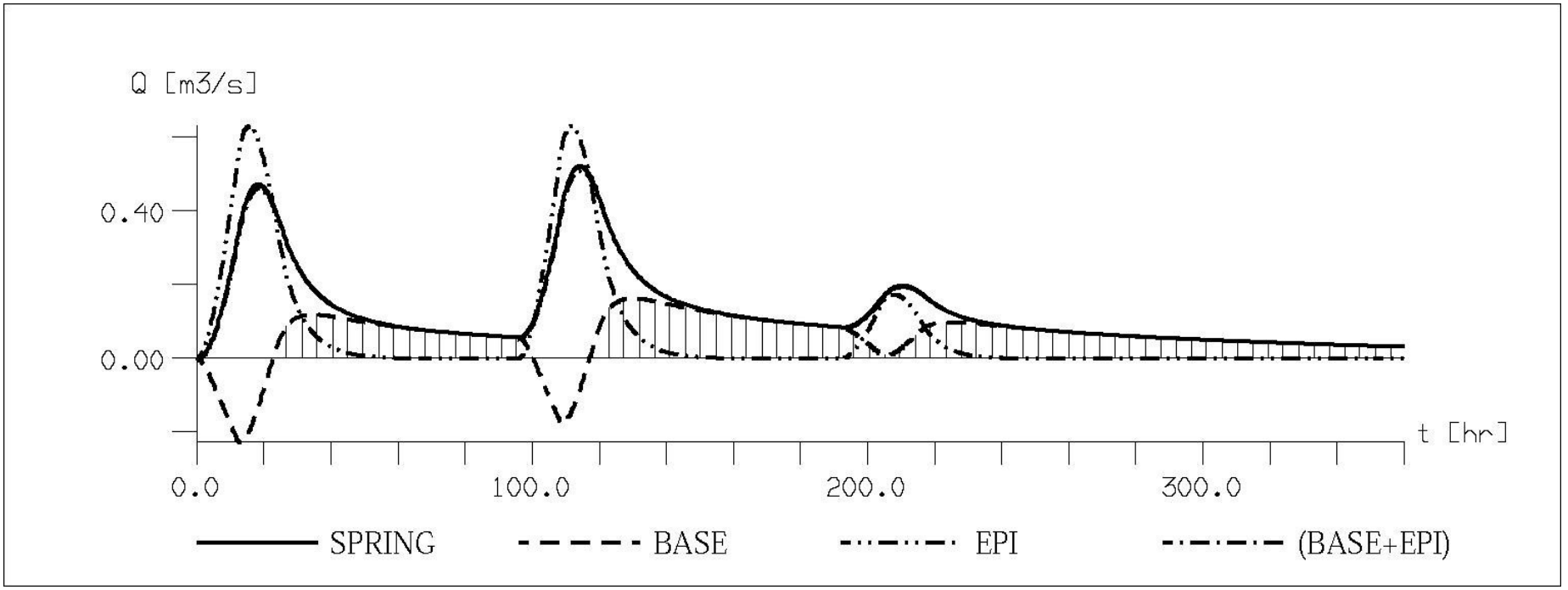
DSYN100 with epikarst. Hydraulic heads in borehole "B".

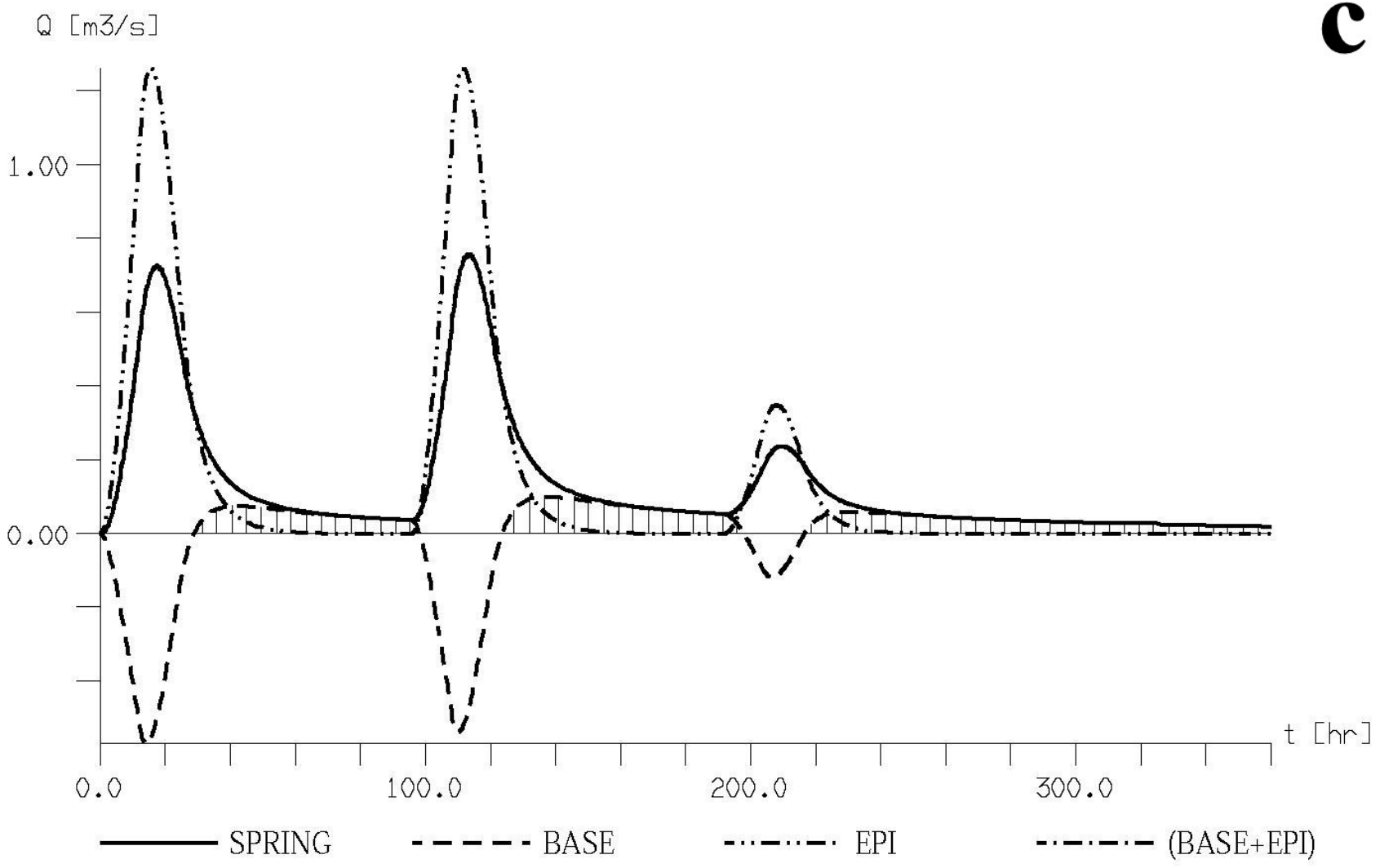


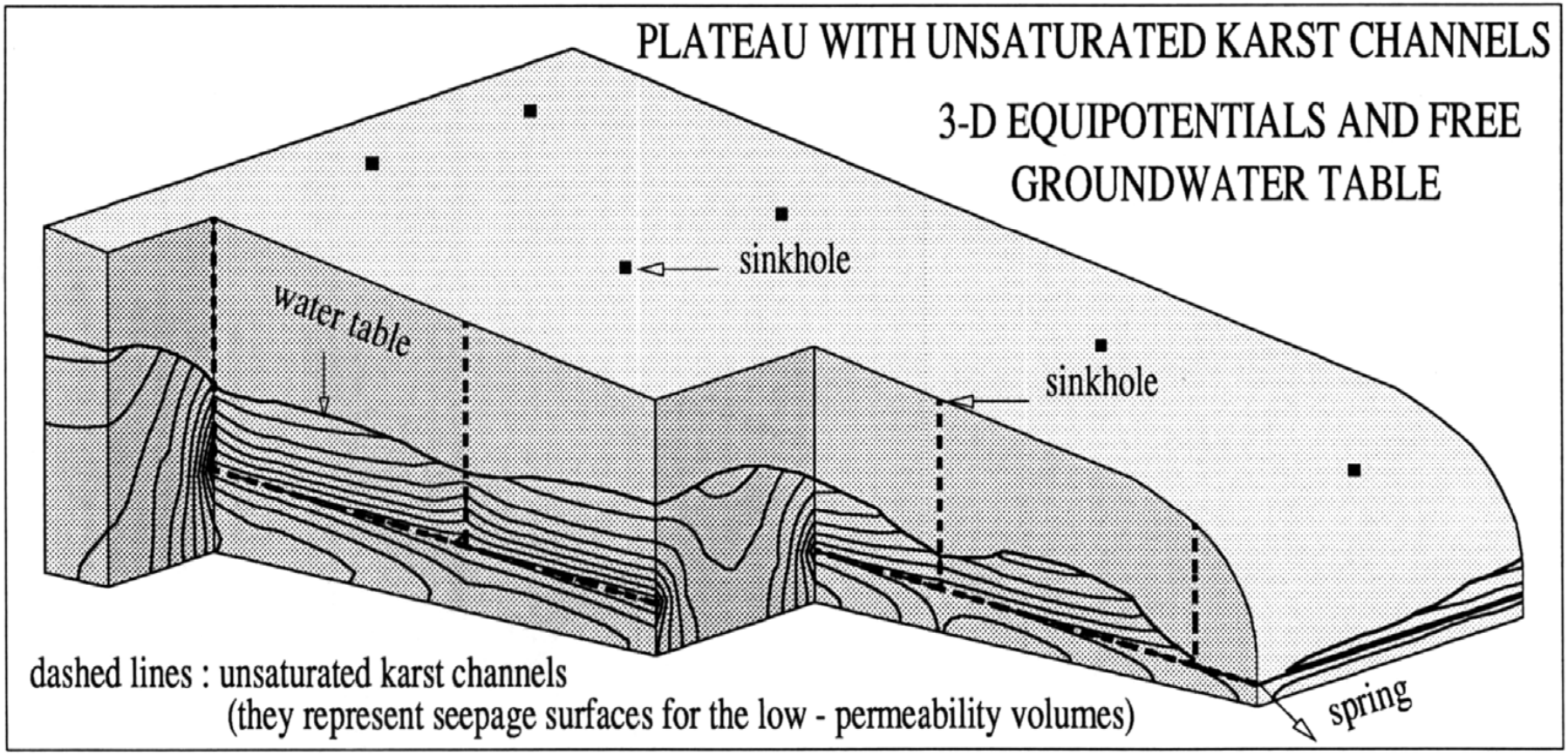

SYNCLINE WITH KARST CHANNELS (A)
3-D EQUIPOTENTIALS
AND FLUX VECTORS
sinkhole
B
spring
dashed lines : karst channels
thin lines : equipotentials
arrows : apparent flux vectors (in log - scale)
FE Model transient solution for DSYN100 in recharge period (B : borehole)


SYNCLINE WITH KARST CHANNELS (B)
3-D EQUIPOTENTIALS
AND FLUX VECTORS
sinkhole
B
spring
dashed lines : karst channels
thin lines : equipotentials
arrows : apparent flux vectors (in log - scale)
FE Model transient solution for DSYN100 in recession period (B : borehole)


a
Q [m3/s]
0.20
0.00
0.0
100.0
200.0
300.0
t [hr]
SPRING
BASE


Q [m3/s]
0.40
0.00
0.0
100.0
200.0
300.0
t [hr]
SPRING
BASE
EPI
(BASE+EPI)

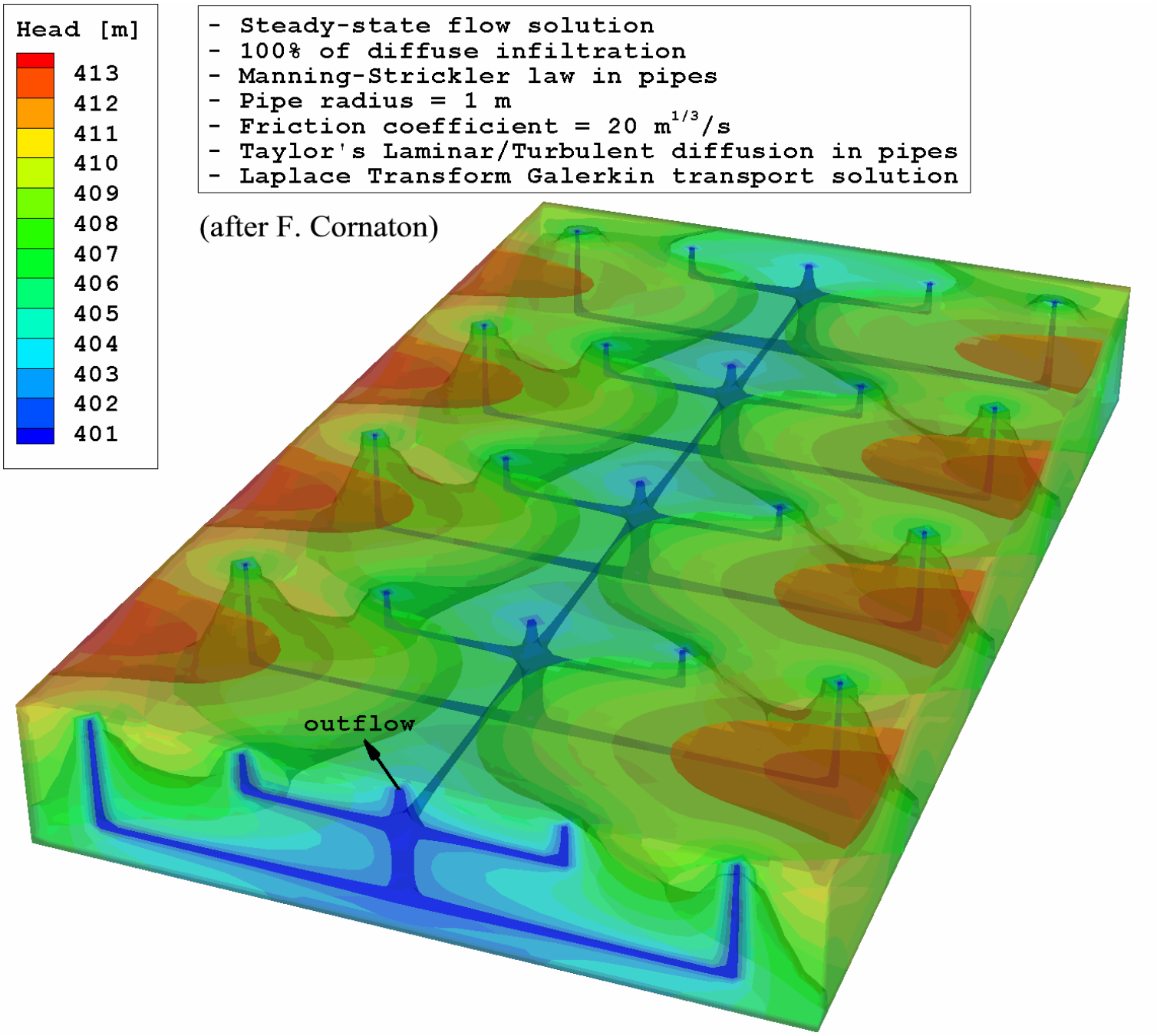

c
Q [m3/s]
1.00
0.00
t [hr]
0.0
100.0
200.0
300.0
SPRING
BASE
EPI
(BASE+EPI)

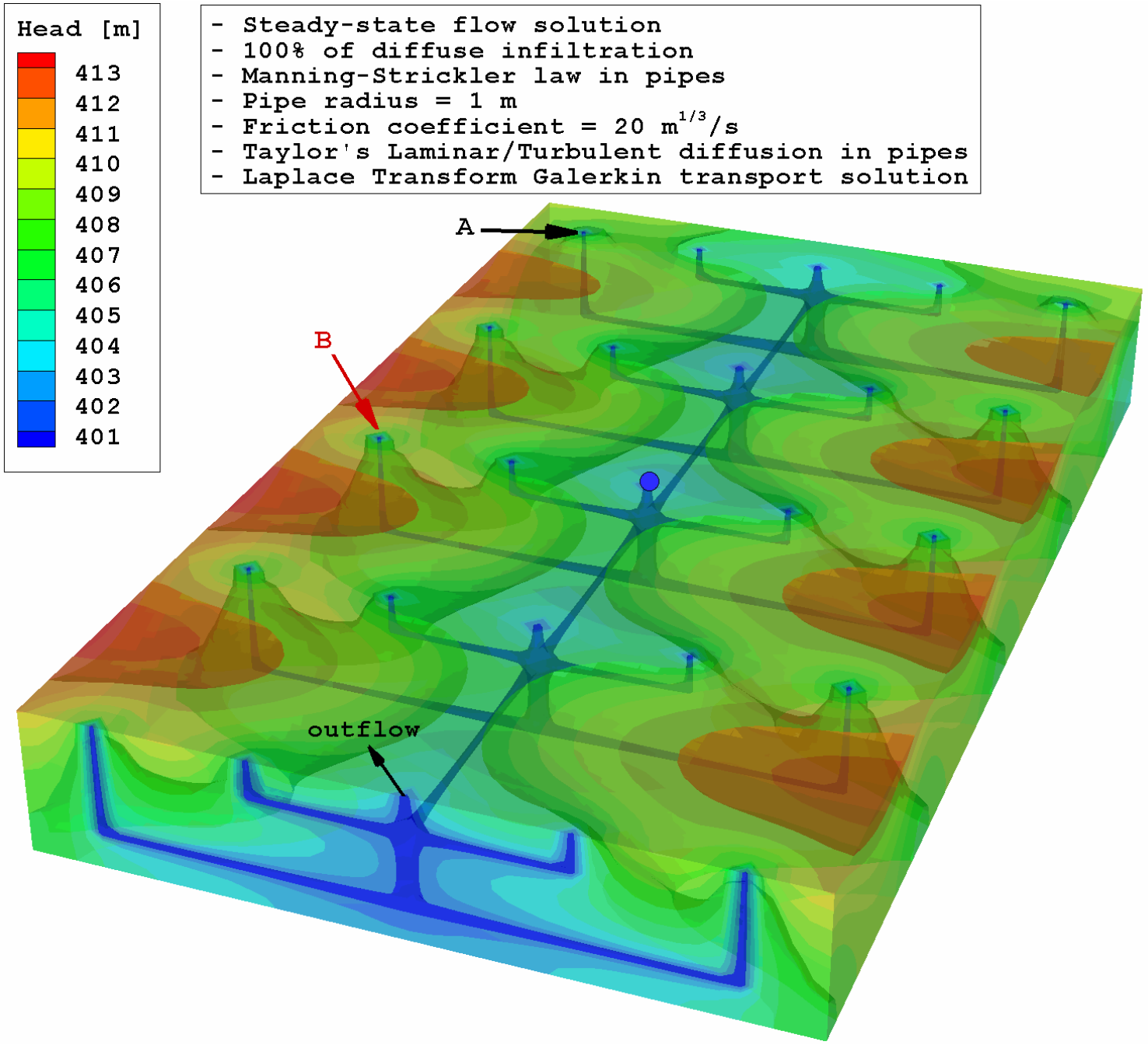

PLATEAU WITH UNSATURATED KARST CHANNELS
3-D EQUIPOTENTIALS AND FREE GROUNDWATER TABLE
sinkhole
water table
sinkhole
spring
dashed lines : unsaturated karst channels
(they represent seepage surfaces for the low - permeability volumes)

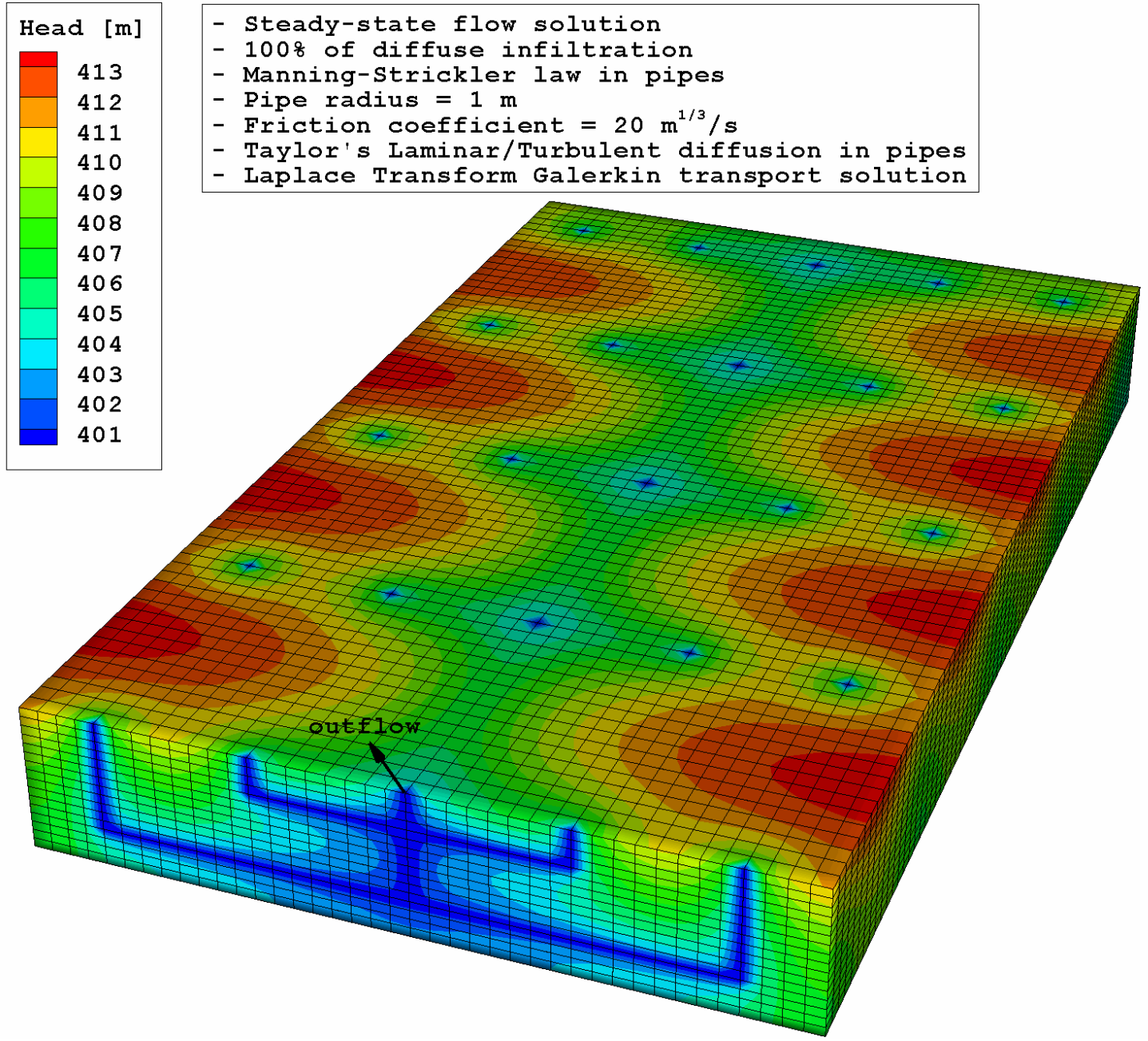
The "Faraday-cage" effect of epikarst

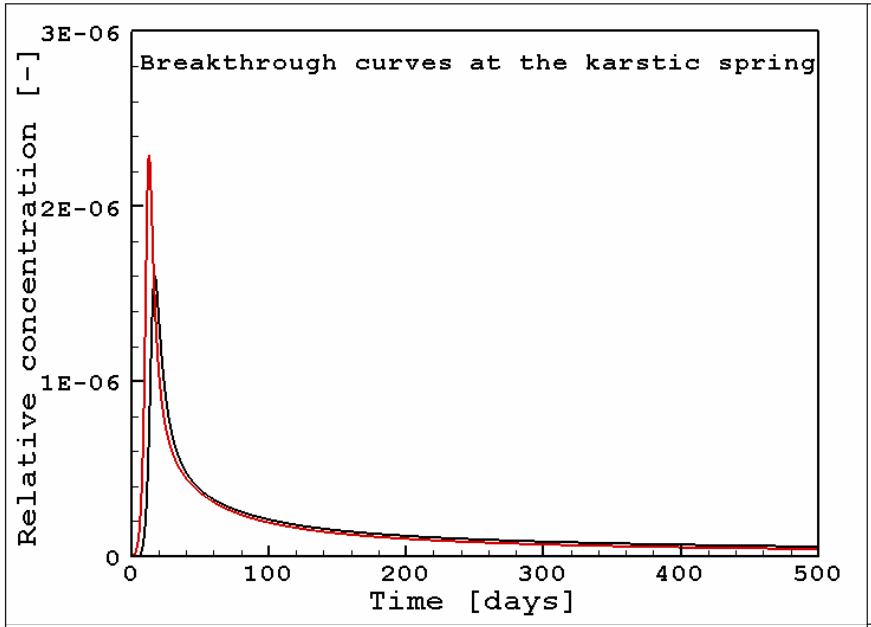
The recharge mechanisms of the huge low permeability volumes may have important practical consequences on the groundwater management problems. The theoretical model studies suggest, that a well developed epikarst layer enhancing the concentrated infiltration into the high conductivity karst channel network will short-circuit the low conductivity volumes and will play the role of a Faraday-cage with respect to the main aquifer.

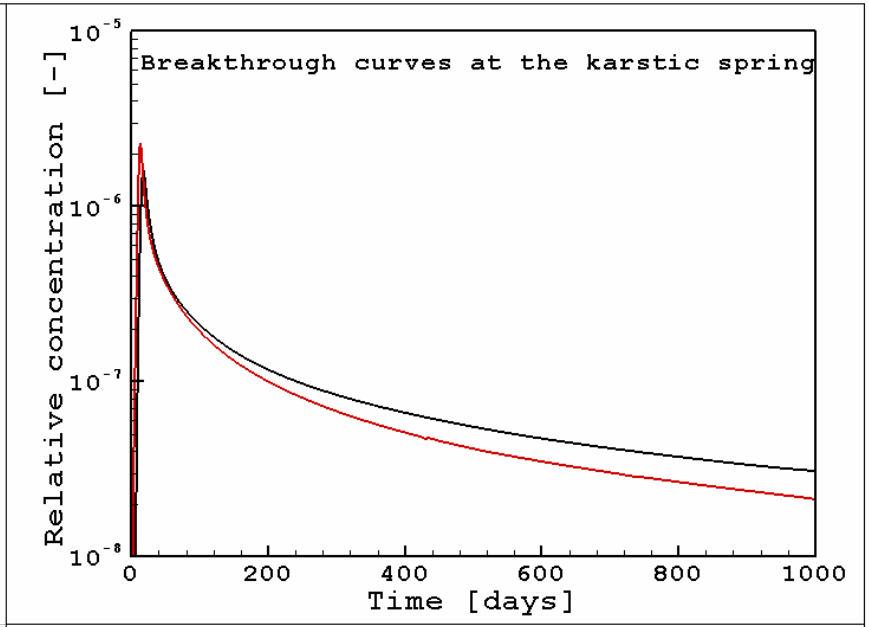
Depending on the importance of this Faraday-cage effect, the recharge of the low conductivity volumes could be much smaller than in case of pure diffuse infiltration, with important consequences on the groundwater management problems. In the deep syncline configuration the inversion of gradients will always contribute to recharging the low conductivity volumes "from the interior", but in the shallow karst configuration the short-circuit of the low permeability volumes might be almost total.

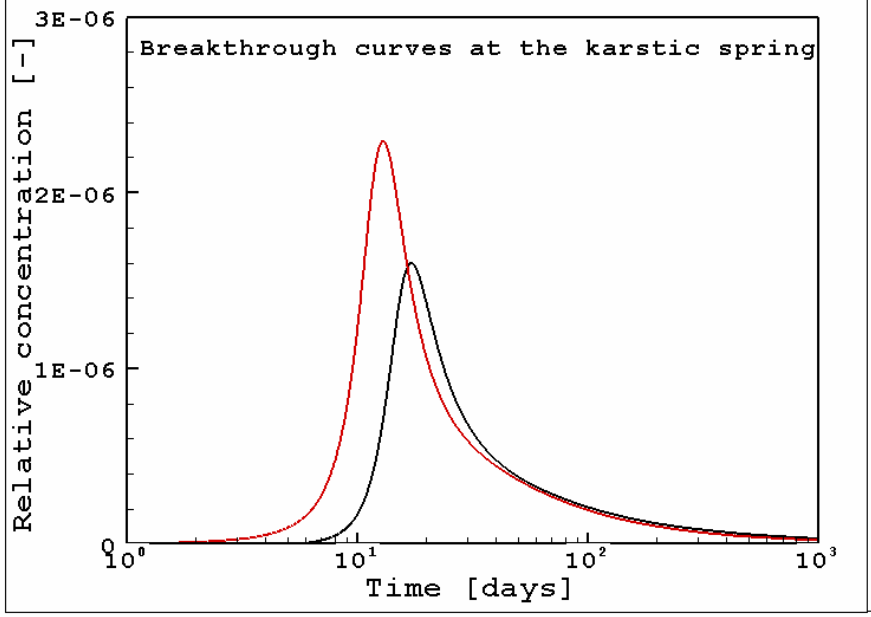

Head [m]
413
412
411
410
409
408
407
406
405
404
403
402
401
- Steady-state flow solution
- 100% of diffuse infiltration
- Manning-Strickler law in pipes
- Pipe radius = 1 m
- Friction coefficient = 20 m^1/3/s
- Taylor's Laminar/Turbulent diffusion in pipes
- Laplace Transform Galerkin transport solution
(after F. Cornaton)
outflow

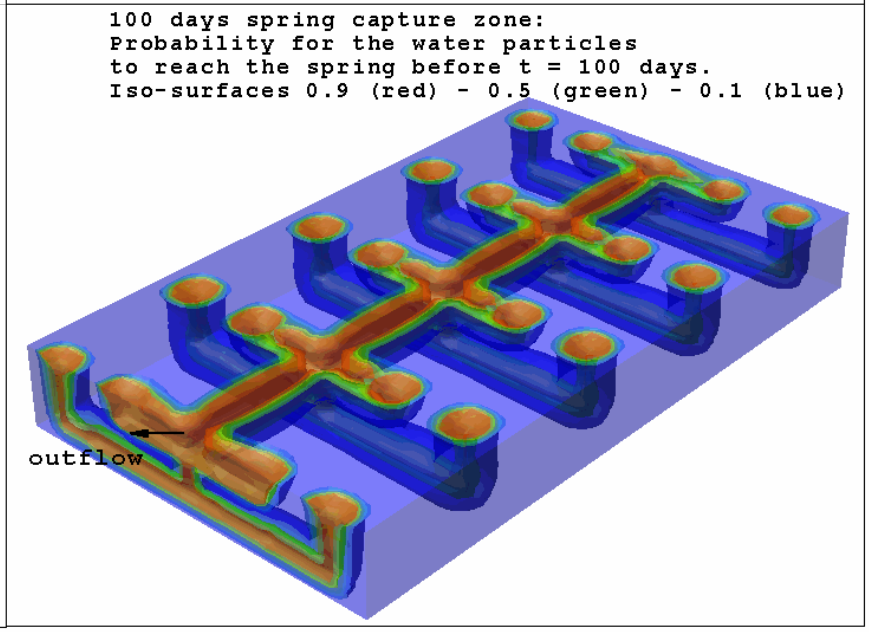

Head [m]
413
412
411
410
409
408
407
406
405
404
403
402
401
- Steady-state flow solution
- 100% of diffuse infiltration
- Manning-Strickler law in pipes
- Pipe radius = 1 m
- Friction coefficient = 20 m^1/3/s
- Taylor's Laminar/Turbulent diffusion in pipes
- Laplace Transform Galerkin transport solution
A
B
outflow


Head [m]
413
412
411
410
409
408
407
406
405
404
403
402
401
- Steady-state flow solution
- 100% of diffuse infiltration
- Manning-Strickler law in pipes
- Pipe radius = 1 m
- Friction coefficient = 20 m^1/3/s
- Taylor's Laminar/Turbulent diffusion in pipes
- Laplace Transform Galerkin transport solution
outflow


Breakthrough curves at the karstic spring
Relative concentration [-]
3E-06
2E-06
1E-06
0
0
100
200
300
400
500
Time [days]


Breakthrough curves at the karstic spring
Relative concentration [-]
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
200
400
600
800
1000
Time [days]


Breakthrough curves at the karstic spring
Relative concentration [-]
3E-06
2E-06
1E-06
0
10^0
10^1
10^2
10^3
Time [days]


100 days spring capture zone:
Probability for the water particles
to reach the spring before t = 100 days.
Iso-surfaces 0.9 (red) - 0.5 (green) - 0.1 (blue)
outflow