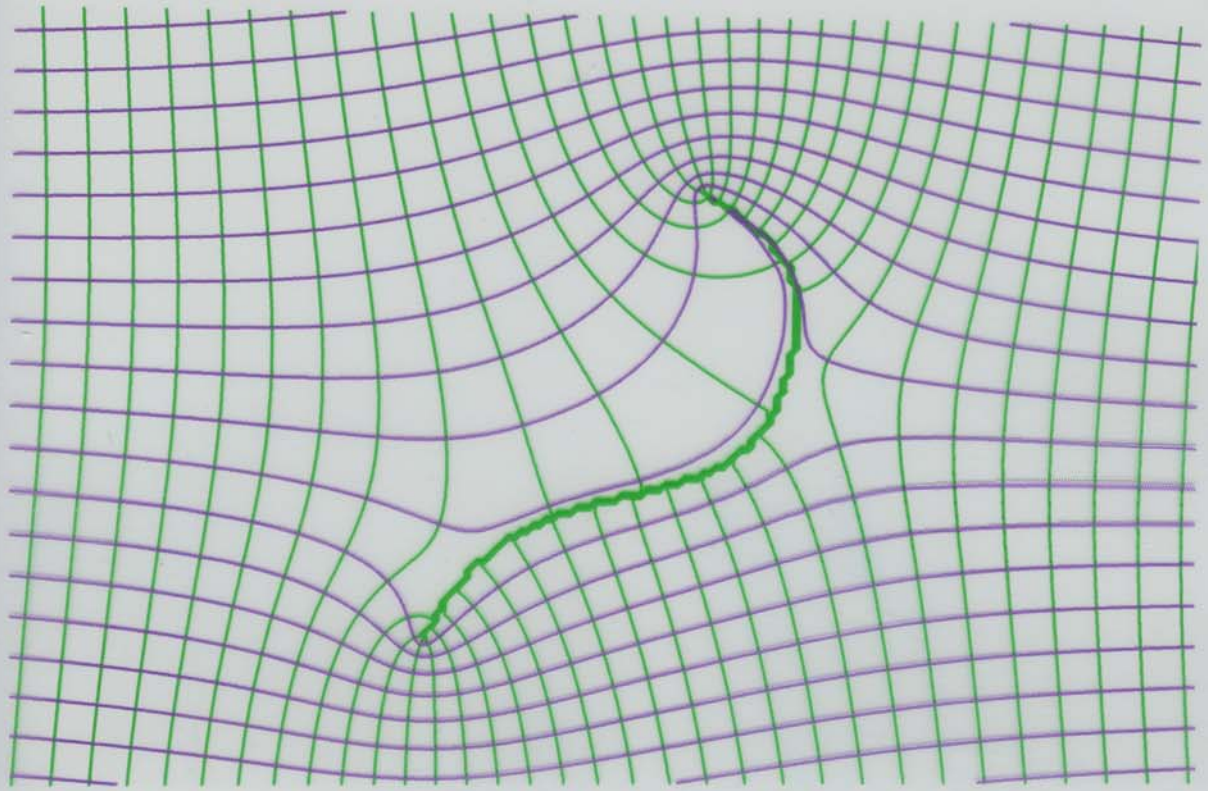
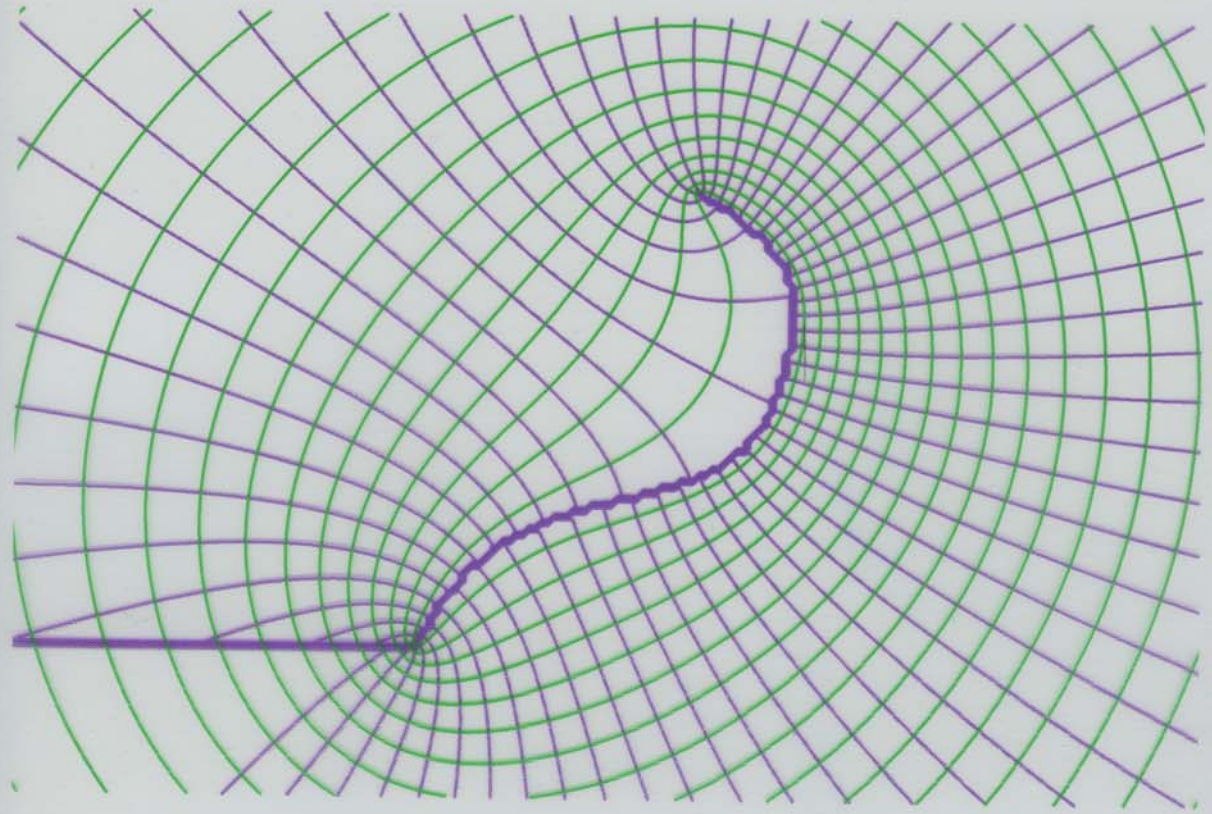
Groundwater Modeling using the Analytic Element Method

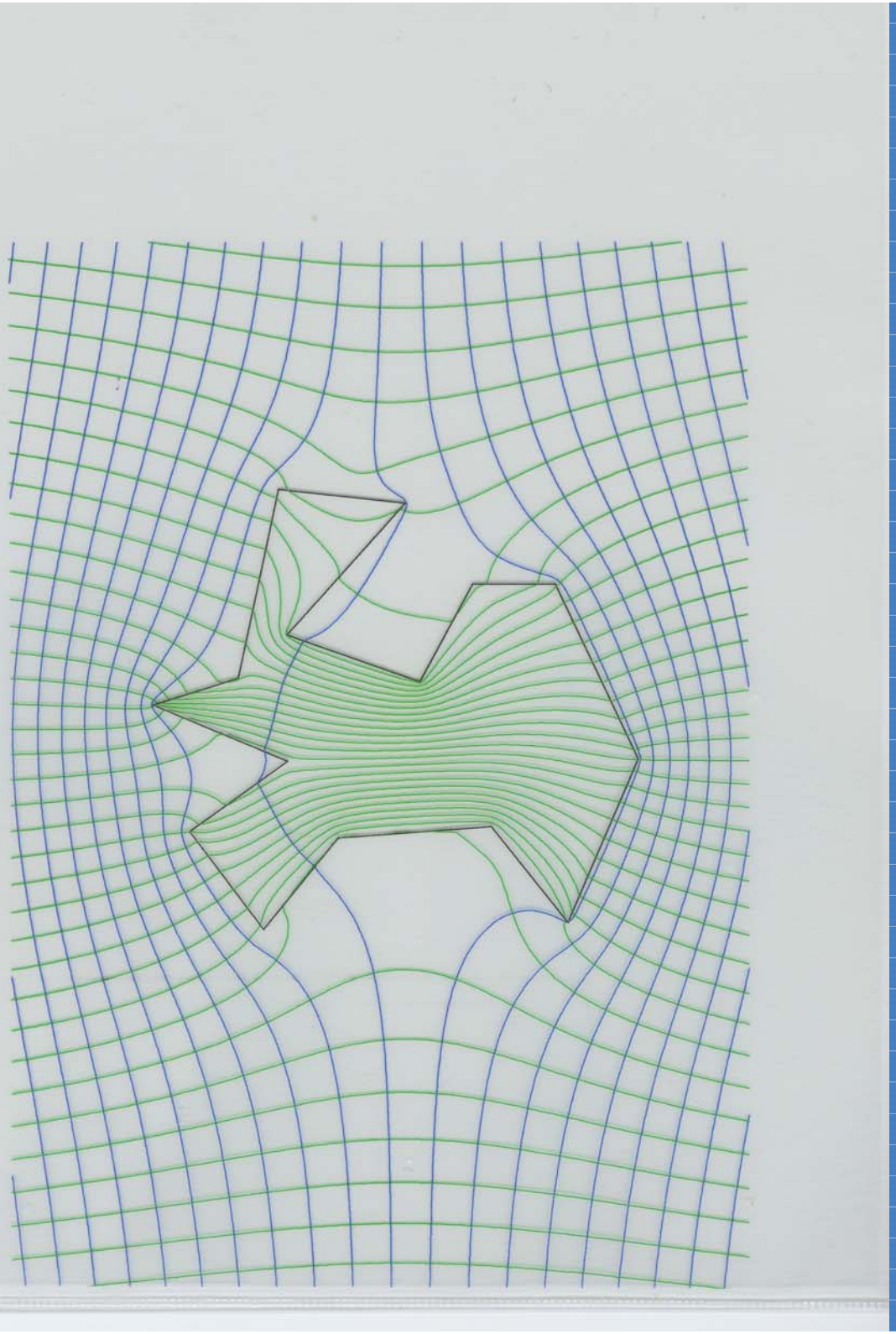
Otto D.L. Strack
Professor of Civil and Geological Engineering
Department of Civil Engineering
University of Minnesota
USA

Leaky Wall



Line Sink



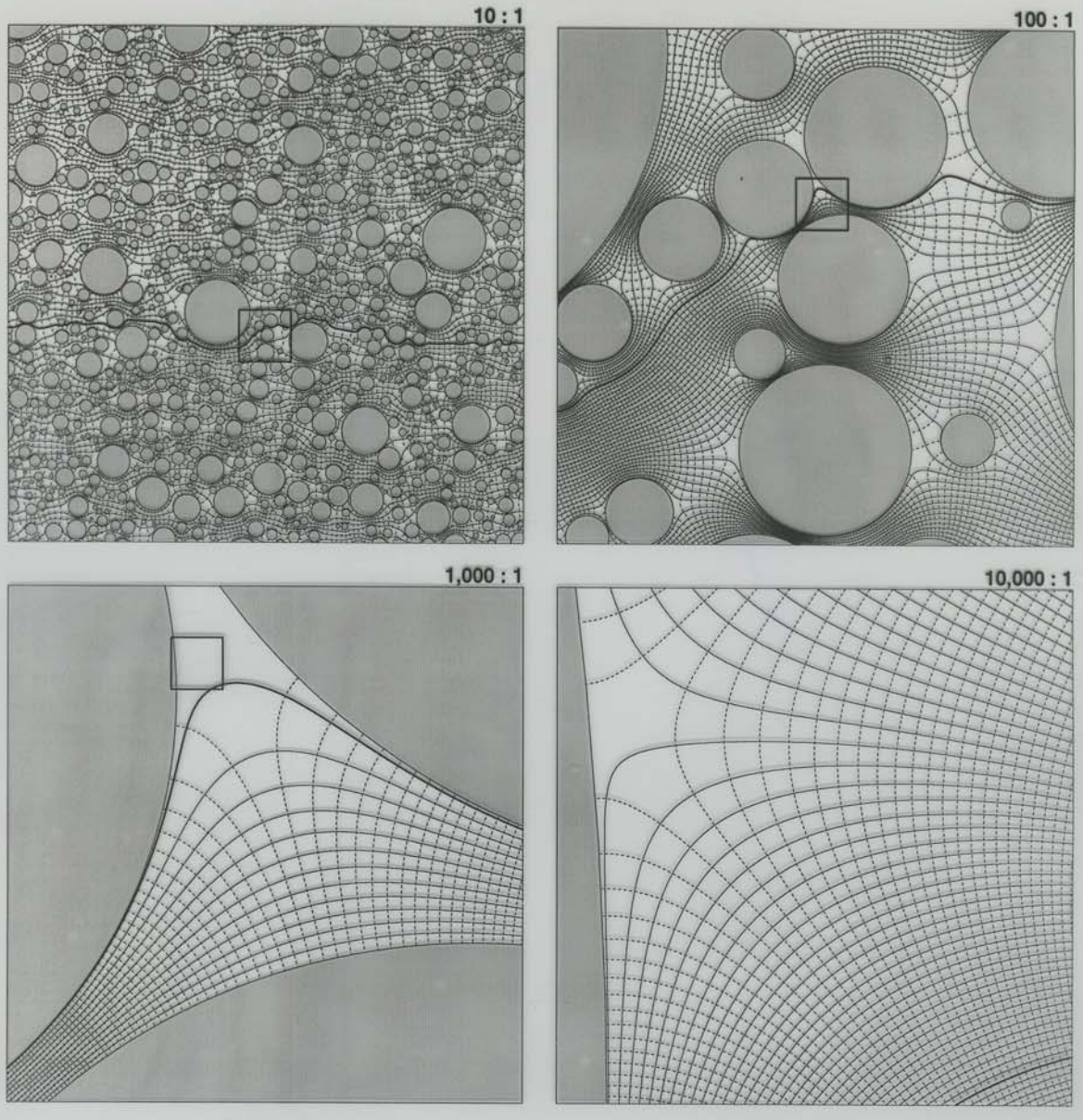


100,000 circles ; 6×10^6 degrees of freedom.
Solve: 19 cpu days (300 MHz) ; grid 10 min.

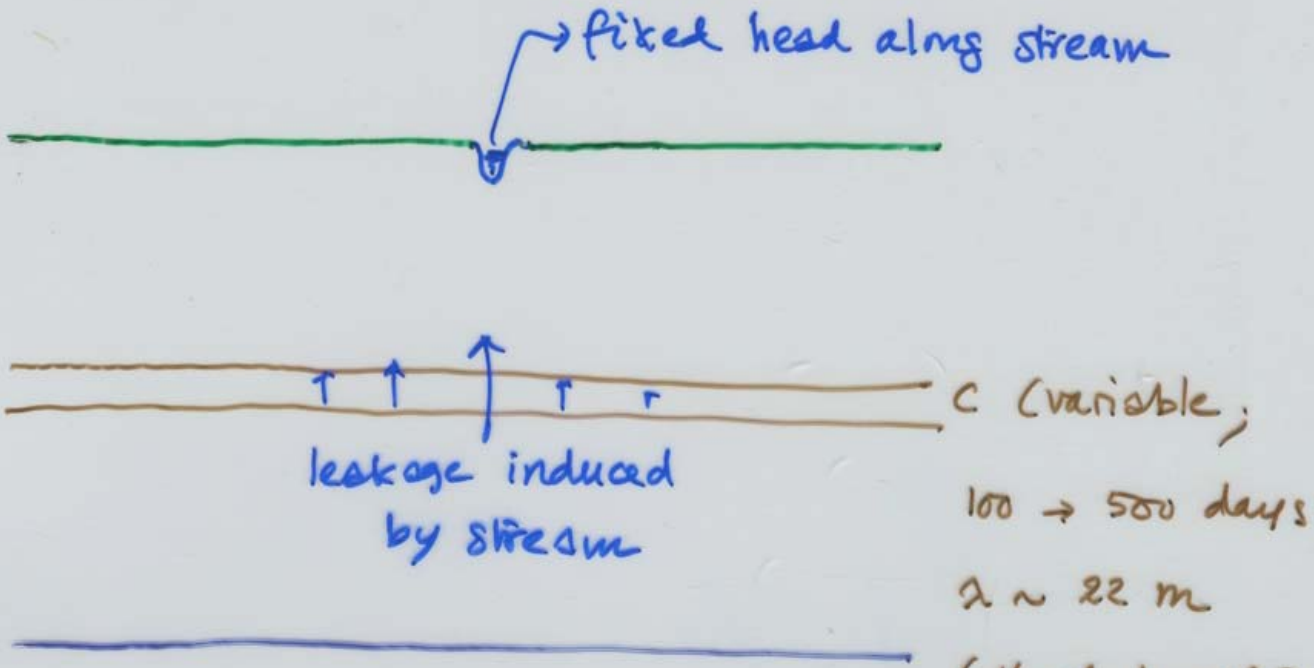
2D

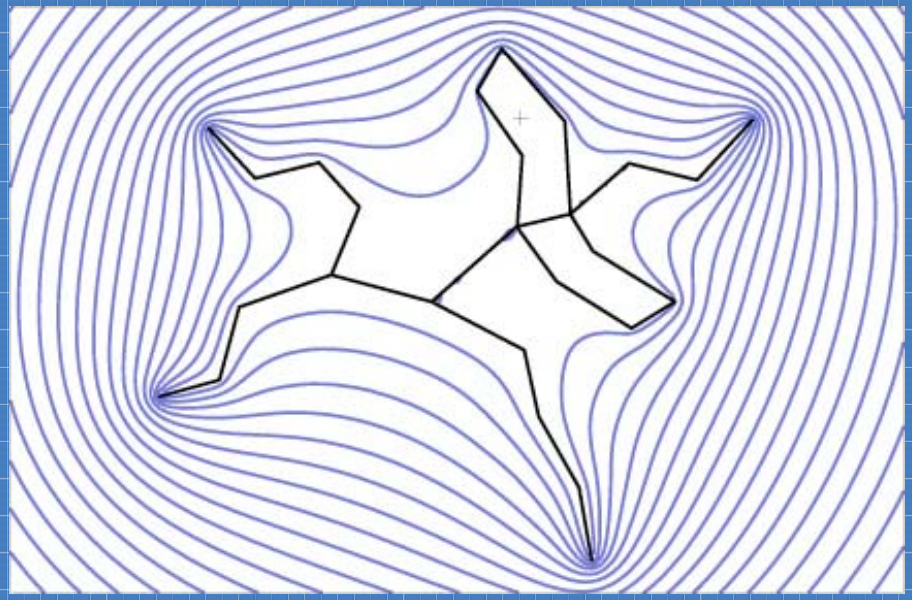
60 degrees of freedom per inhomogeneity

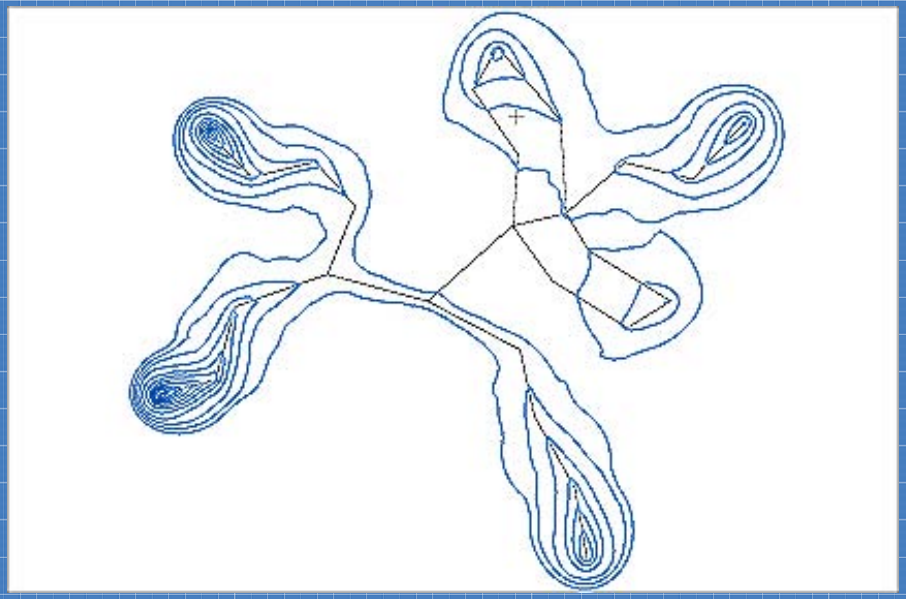
2D

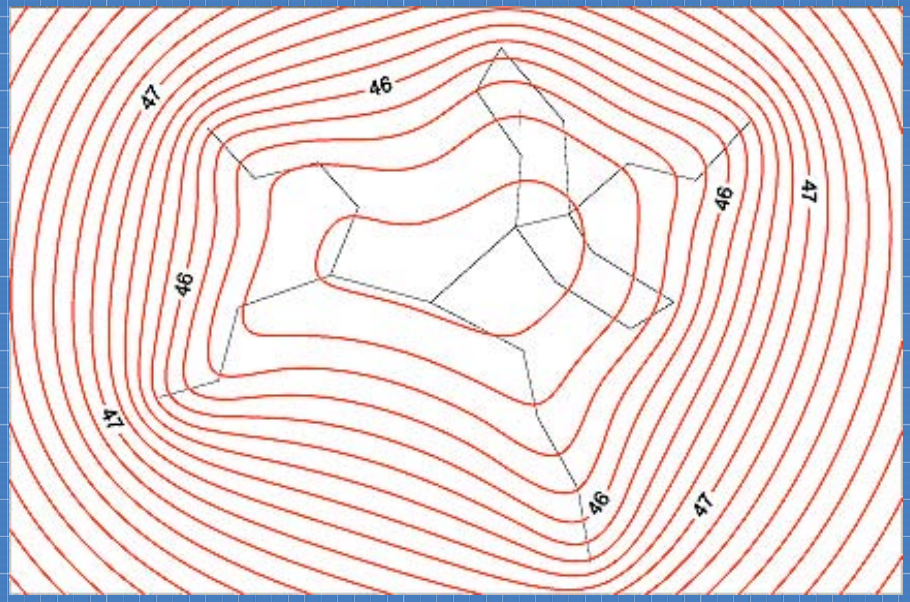


EXAMPLE : STREAM



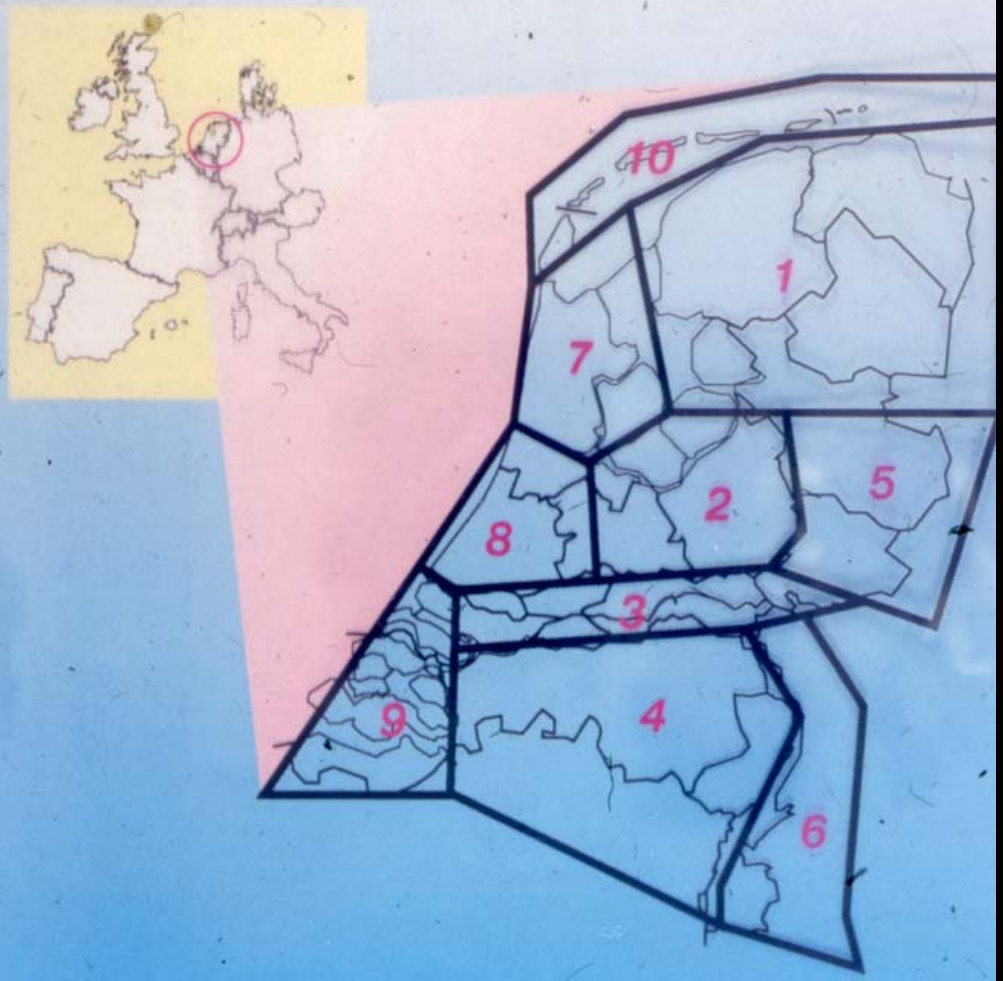





47
46
46
47
46
47
46
47


Netherlands
International boundary
Province boundary
National capital
Province capital
Railroad
Expressway
Road
0 10 20 30 Kilometers
0 10 20 30 Miles
WEST FRISIAN ISLANDS
Borkum
Schiermonnikoog
Nes
Ameland
Terschelling
Vlieland
Texel
Waddenzee
Den Burg
Den Helder
Harlingen
Leeuwarden
FRIESLAND
GRONINGEN
Emden
Delfzijl
Leer
Groningen
Sneek
Heerenveen
Assen
DRENTHE
Emmen
Hoogeveen
Meppel
Coevorden
IJsselmeer
NOORD-HOLLAND
Hoorn
Alkmaar
Emmeloord
Lelystad
Dronten
OVERIJSSEL
Zwolle
Lingen
Nordhorn
Beverwijk
Purmerend
Zaanstad
Haarlem
FLEVOLAND
Raalte
Almelo
Deventer
Rheine
Hengelo
Enschede
Amsterdam
Hilversum
Apeldoorn
Leiden
The Hague
Amersfoort
Utrecht
Zeist
Ede
GELDERLAND
Arnhem
Doetinchem
Hoek van Holland
Delft
ZUID-HOLLAND
UTRECHT
Gouda
Europoort (international seaport)
Rotterdam
Vlaardingen
Nijmegen
Kleve
Emmerich
Dordrecht
Oss
's-Hertogenbosch
Goch
Wesel
Waalwijk
Breda
NOORD-BRABANT
Tilburg
Roosendaal
Middelburg
Bergen op Zoom
Vlissingen
Helmond
Eindhoven
Dortmund
Essen
Duisburg
Knokke
Terneuzen
Turnhout
Venlo
Krefeld
LIMBURG
Brugge
Antwerp
Weert
Roermond
Düsseldorf
Wuppertal
Mönchengladbach
Gent
BELGIUM
Sittard
Heerlen
Eupen
Aalst
Hasselt
Kortrijk
Brussels
Leuven
Maastricht
Düren
Mouscron
Halle
Aachen
Bonn
Liège
North Sea
FEDERAL REPUBLIC OF GERMANY
Base 800383 (A01914) 3-87

NAGROM model domains



1	Drenthe	6	Limburg
2	Veluwe	7	Holland noord
3	Betuwe	8	Holland zuid
4	Brabant	9	Zeeland
5	Twente	10	Wadden

Figure 7.2.8: Sub-regional mesh of area elements between the North-East Polder and the nature domains Weerribben and Wieden.

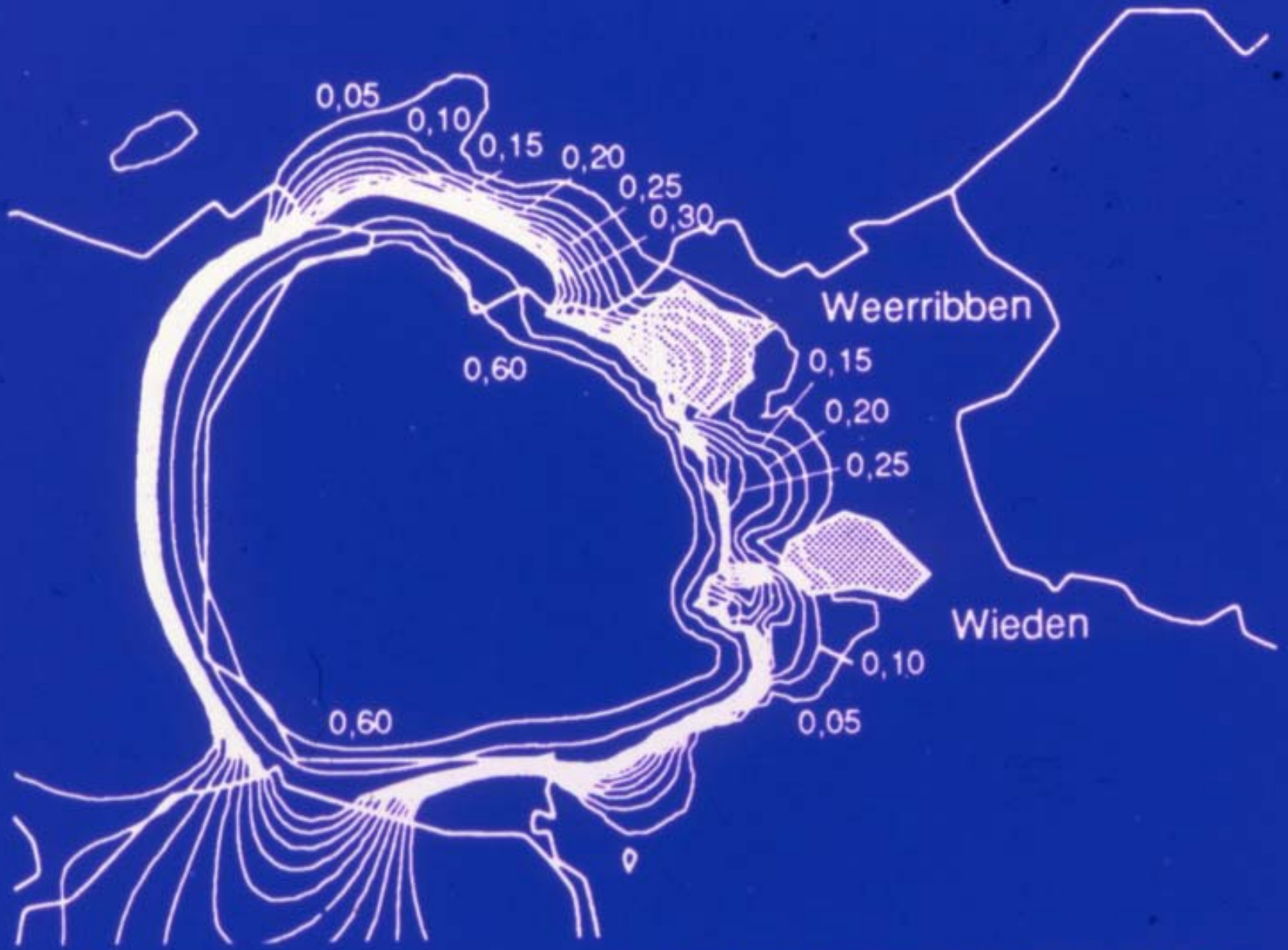


Figure 7.2.9: Computed lowering in the head in the upper aquifer caused by the reclaimed North-East Polder.

Figure 7.2.10: Effect of a narrow lake on the head in the upper aquifer.

Polders around the nature domains
Weerribben and Wieden

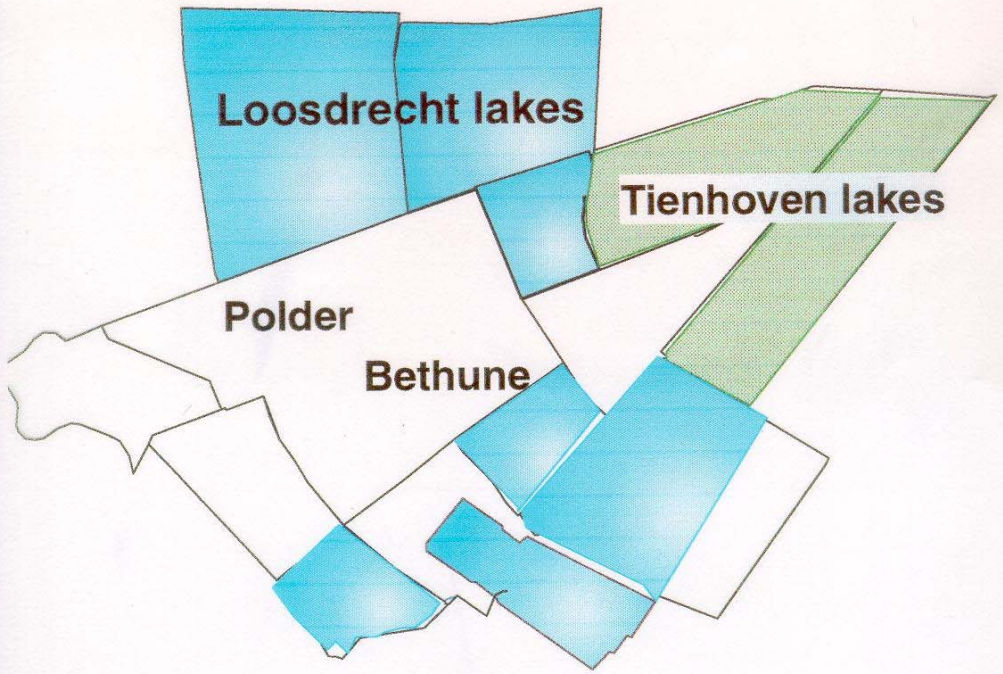
Figure 7.2.12: Effects of the polders around the Weerribben and Wieden on the head in the upper aquifer.

Amsterdam Water Supply

- Amsterdam Water Supply entered into a contract in 1930 with the ‘Waterschap’, the ‘plassencontract’. The contract was extended indefinitely in 1965.
- 30 million cubic meters per year.
- River water is pumped into surrounding nature areas.


Haarlem
Amsterdam
Hilversum
Leiden
Amersfoort
Utrecht
's-Gravenhage
Arnhem
Rotterdam
Nijmegen
Dordrecht
's-Hertogenbosch
Breda
Tilburg
Gelsenkirchen
Bochum
Dortmund

Plan view of southern part Vecht lakes area

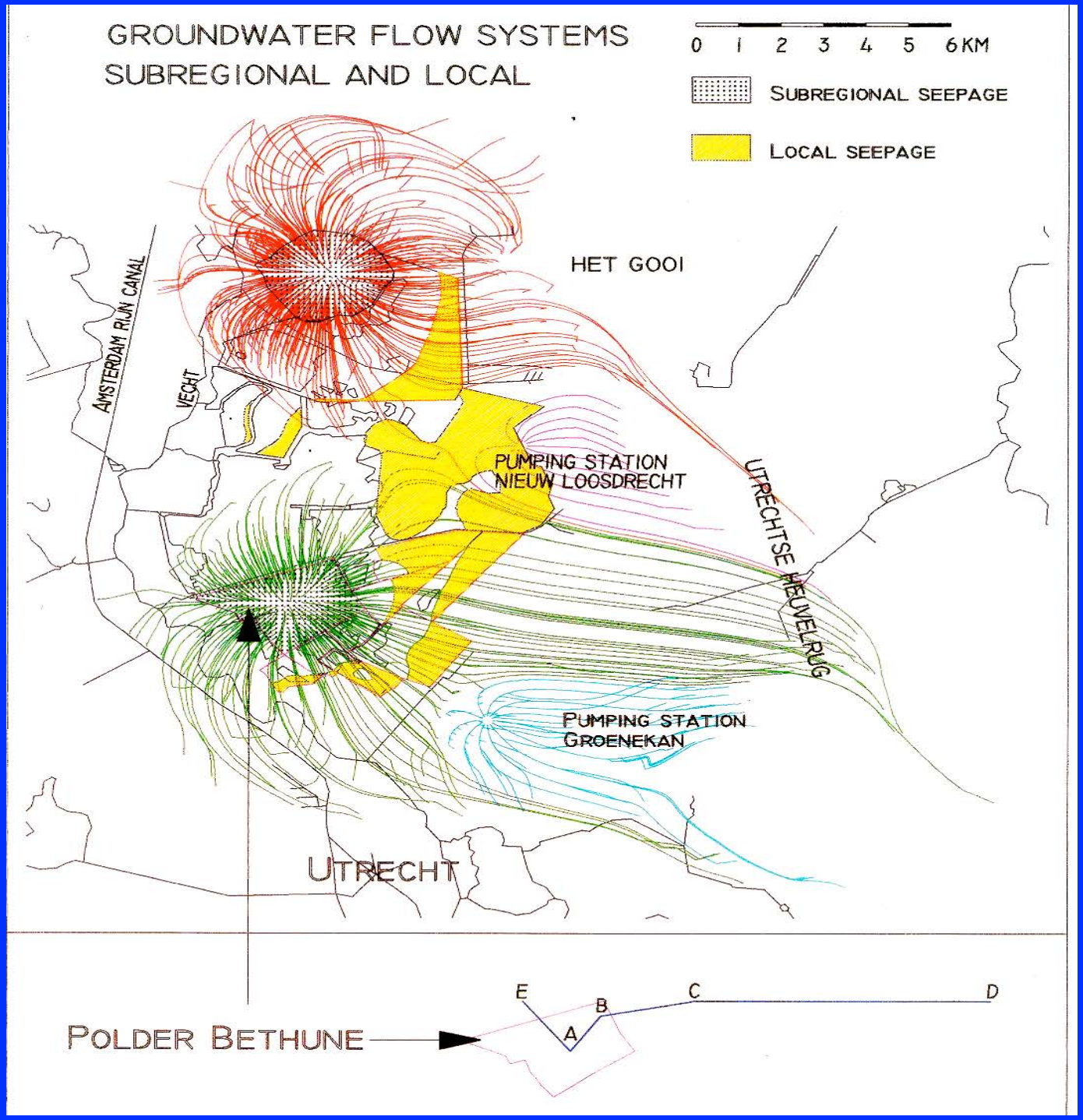


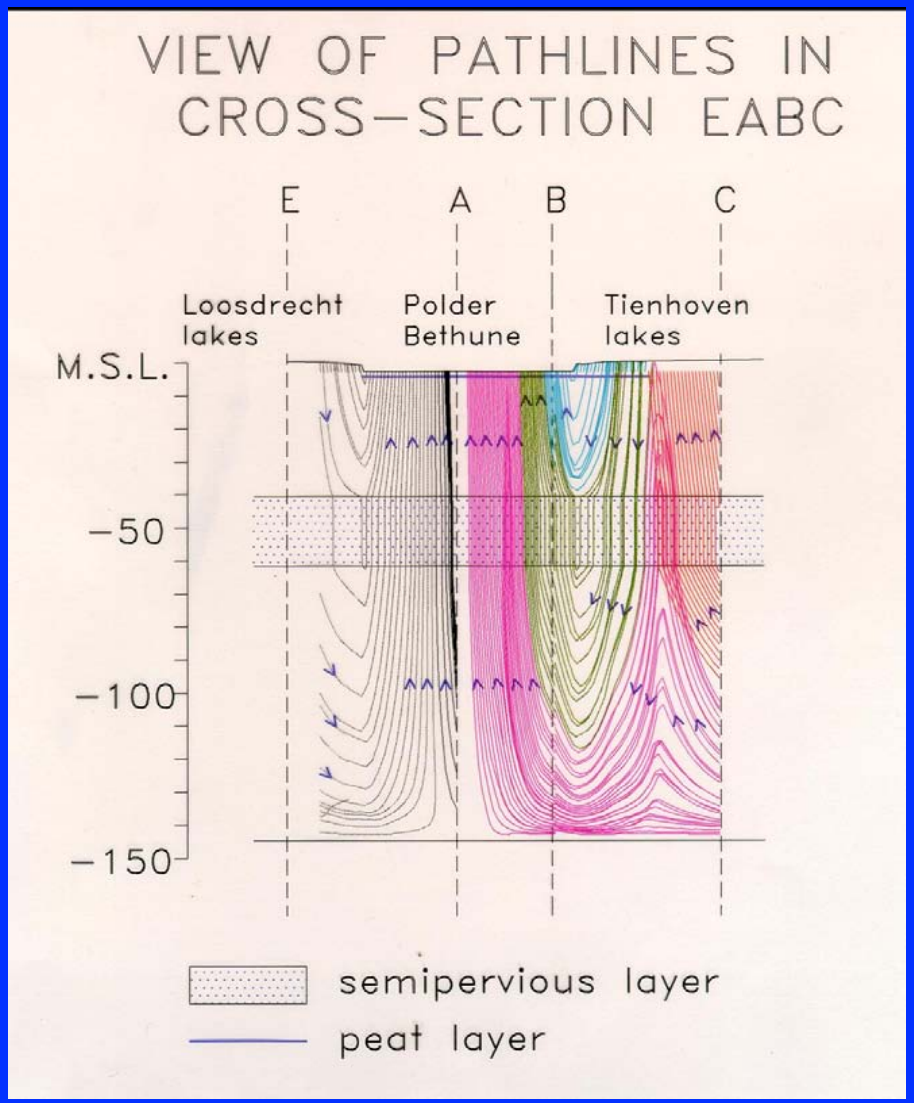
Environmental Concerns

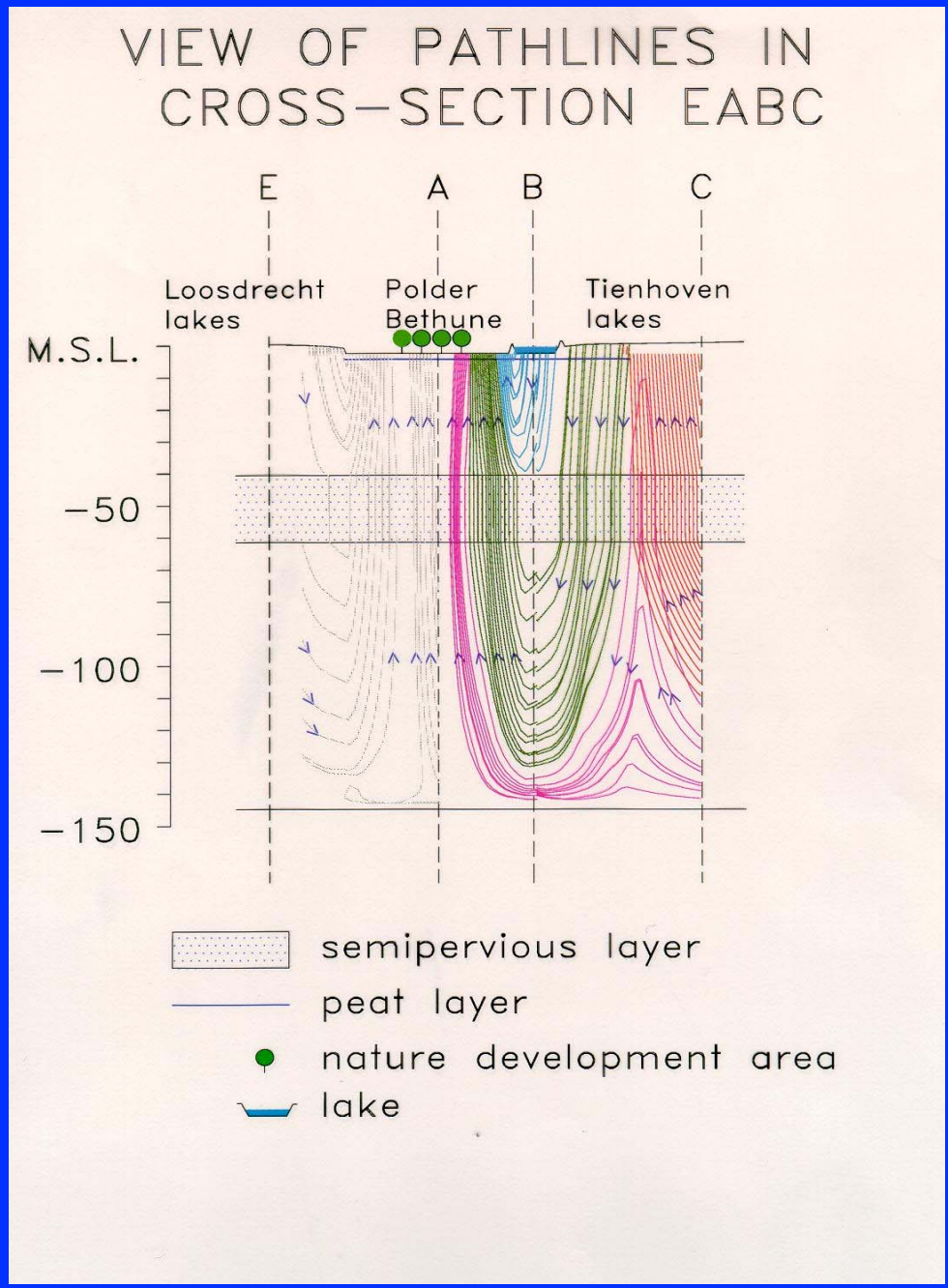
- Pumping large quantities of water from the Polder Bethune and infiltrating river water in the lakes surrounding it may jeopardize rare vibrating peats (‘trilvenen’) and floating peats (‘drijvende venen’) in surrounding nature reserves.
- Defense: only (infiltrated) surface water is being pumped (di^3 erence in cost: 0.37 Dfl/m^3).

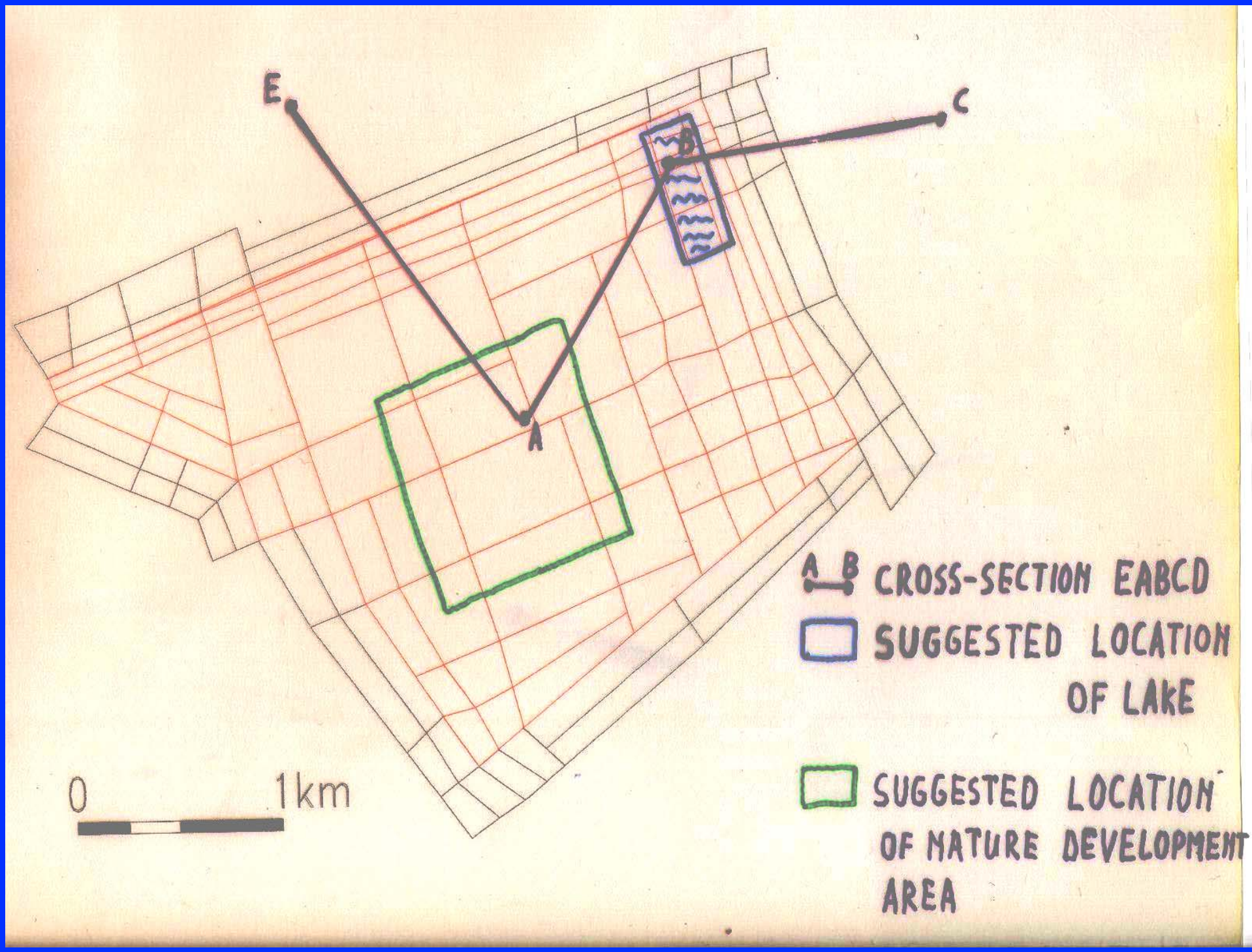
Questions to be answered by the project

- Does pumping a^3 ect the protected nature areas (peats)?
- Where does the water pumped from the Polder Bethune originate?

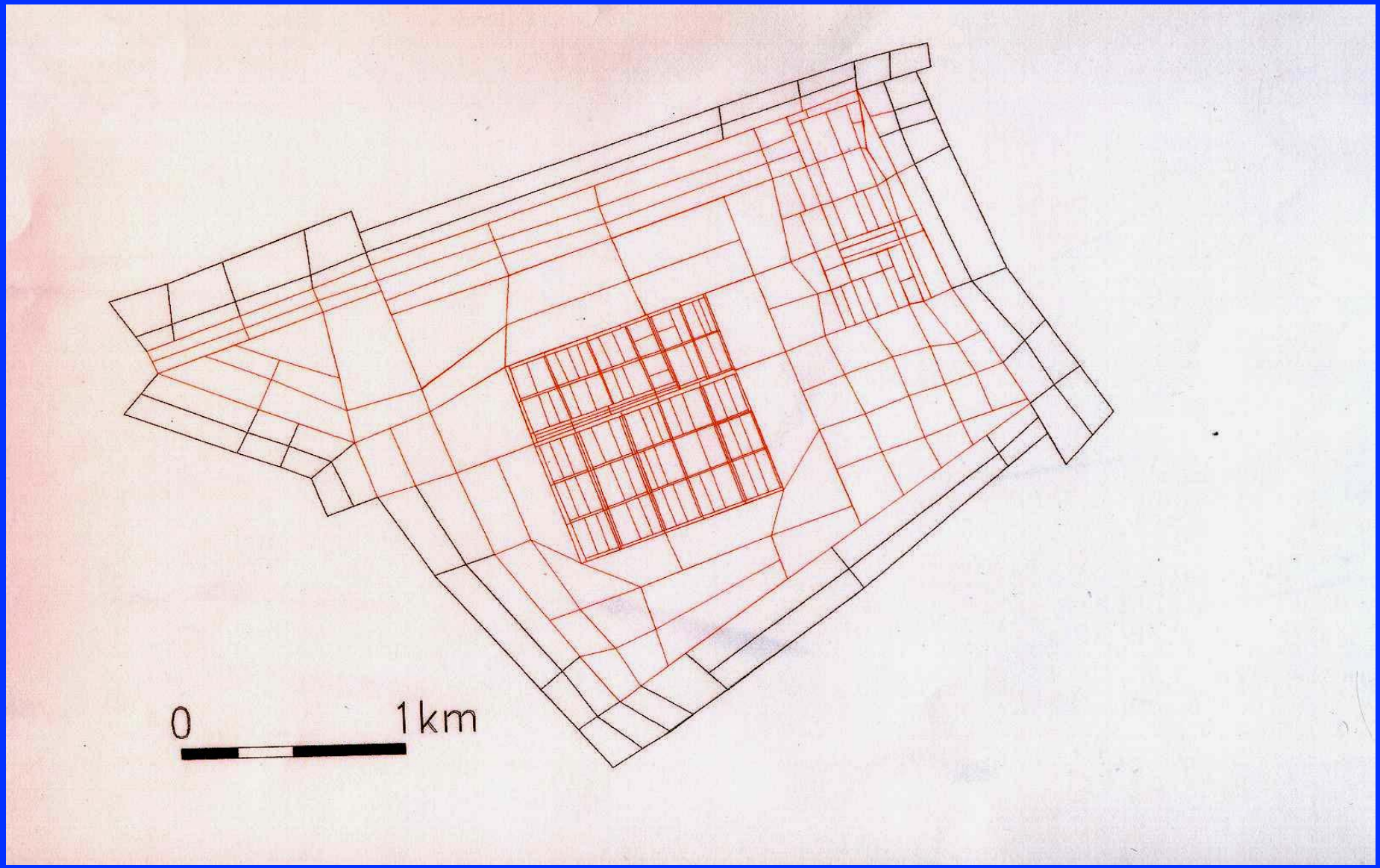

GROUNDWATER FLOW SYSTEMS
SUBREGIONAL AND LOCAL
0 1 2 3 4 5 6 KM
SUBREGIONAL SEEPAGE
LOCAL SEEPAGE
HET GOOI
AMSTERDAM RIJN CANAL
VECHT
PUMPING STATION
NIEUW LOOSDRECHT
UTRECHTSE HEUVELRUG
PUMPING STATION
GROENEKAN
UTRECHT
POLDER BETHUNE
E
B
C
D
A


VIEW OF PATHLINES IN CROSS-SECTION EABC
E
A
B
C
Loosdrecht lakes
Polder Bethune
Tienhoven lakes
M.S.L.
-50
-100
-150
semipervious layer
peat layer

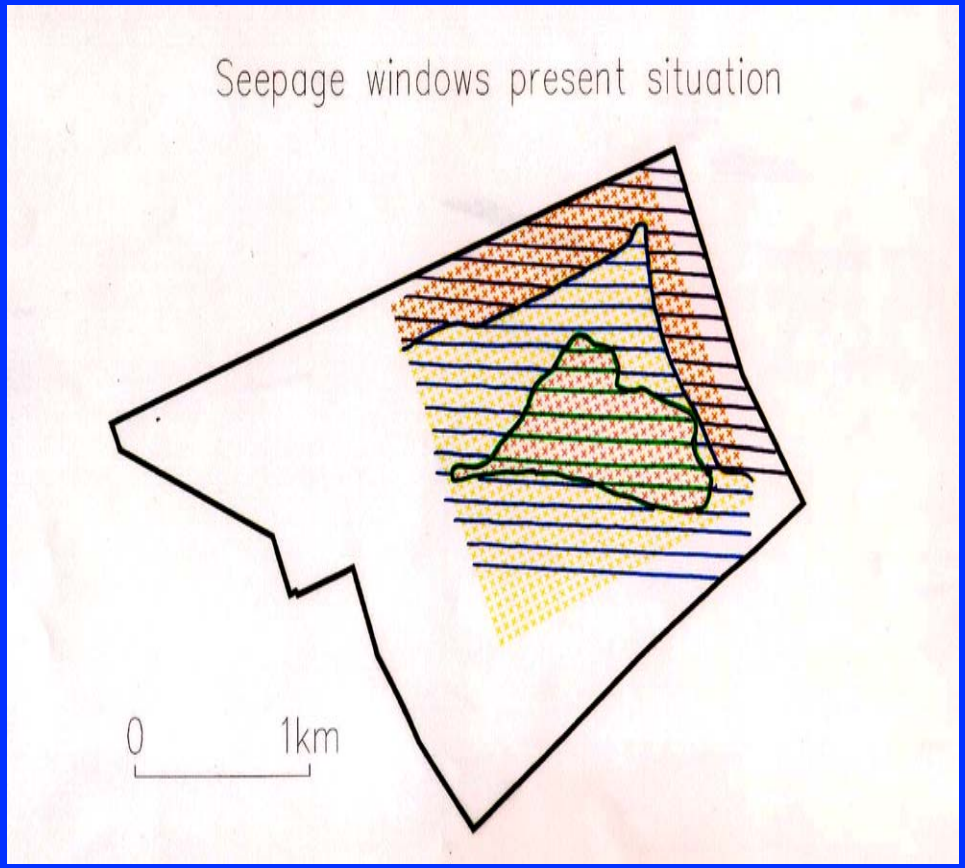

VIEW OF PATHLINES IN CROSS-SECTION EABC
E
A
B
C
Loosdrecht lakes
Polder Bethune
Tienhoven lakes
M.S.L.
-50
-100
-150
semipervious layer
peat layer
nature development area
lake

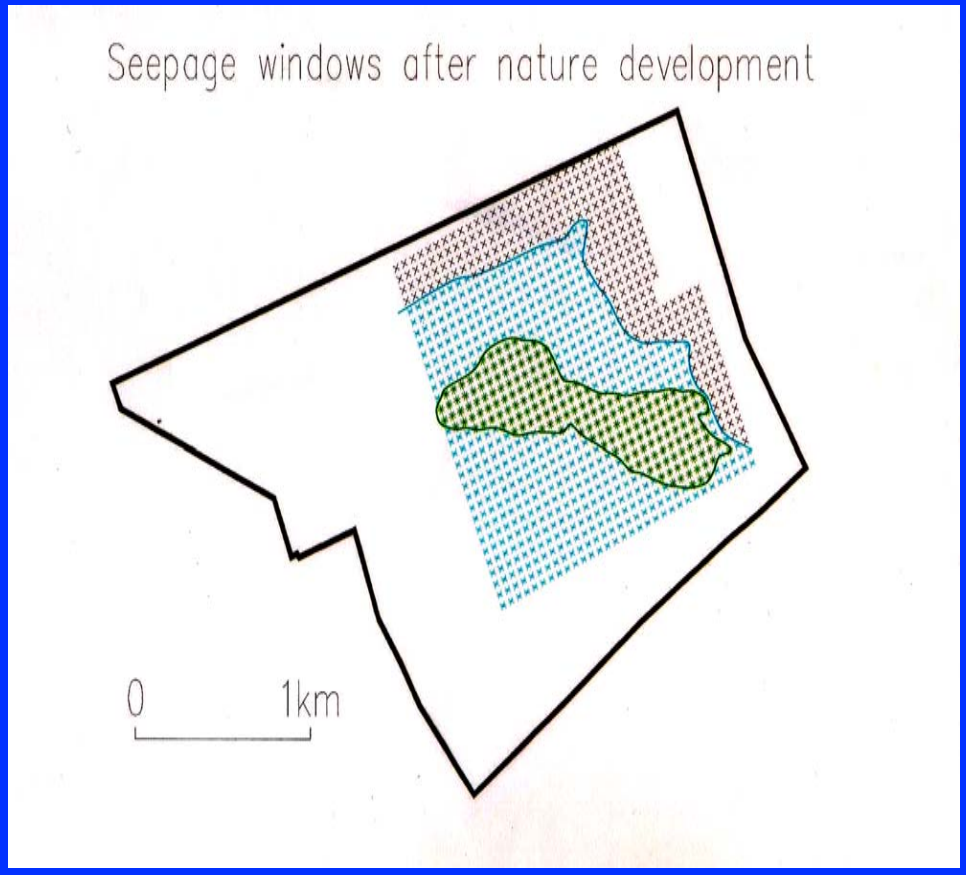

E
C
B
A
A B CROSS-SECTION EABCD
SUGGESTED LOCATION OF LAKE
SUGGESTED LOCATION OF NATURE DEVELOPMENT AREA
0
1km

Refined area-element grid



Comparison of seepage windows before and after refinement.





CONCLUSIONS

- MLAEM made it possible to simulate steep gradients and subtle changes from infiltration to seepage in an outstanding manner
- The e³ ect of the nature development could be studied e³ ectively by filling the related parts of the model with smaller elements in an easy way.
- Three-dimensional pathline calculations showed that the regional flow system is overlain by infiltration-discharge systems.