Diffuse pollution of groundwater in urban areas

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Catchment Science Centre

# Outline

- The message:
  - Multiple urban sources ≡ diffuse pollution
- Outline:
  - Urban recharge
  - Urban groundwater pollution
  - Nitrate loads in Nottingham
  - Organic sources and risks
  - Summary

Urban pathways for precipitation

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Evapo-transpiration

Precipitation

Evaporation

Roofs

Surface runoff

Storm sewers

Urban recharge

Direct recharge

Sewer leakage

Roof soakaways

Infiltration systems

Urban supply pathways

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Consumptive use

Imported water supply

Local groundwater

Sewers

Mains leakage

Irrigation excess

Septic tanks

Sewer leakage

Urban recharge

Lerner, 2002, *Hydrogeology Journal*, 10, 143-152
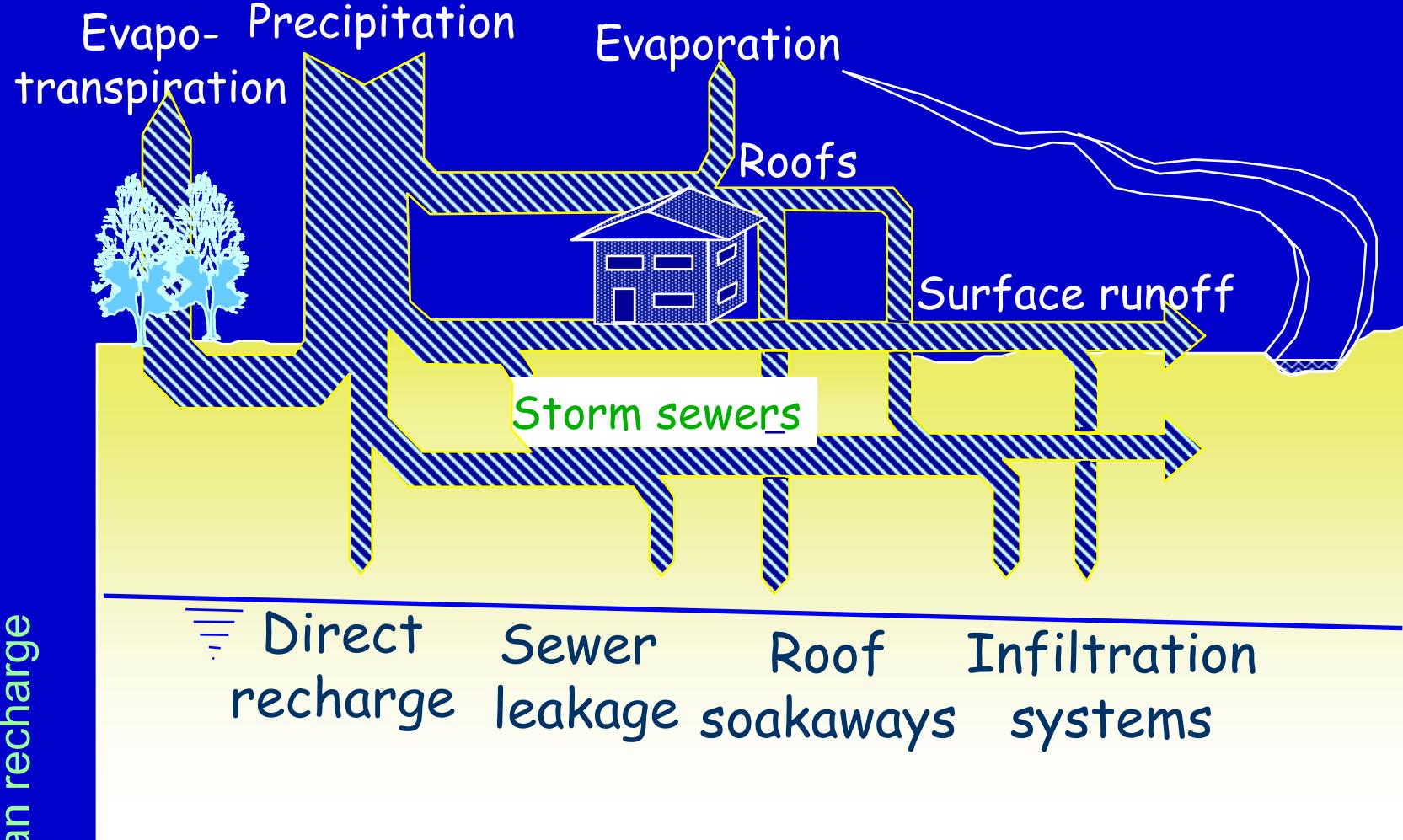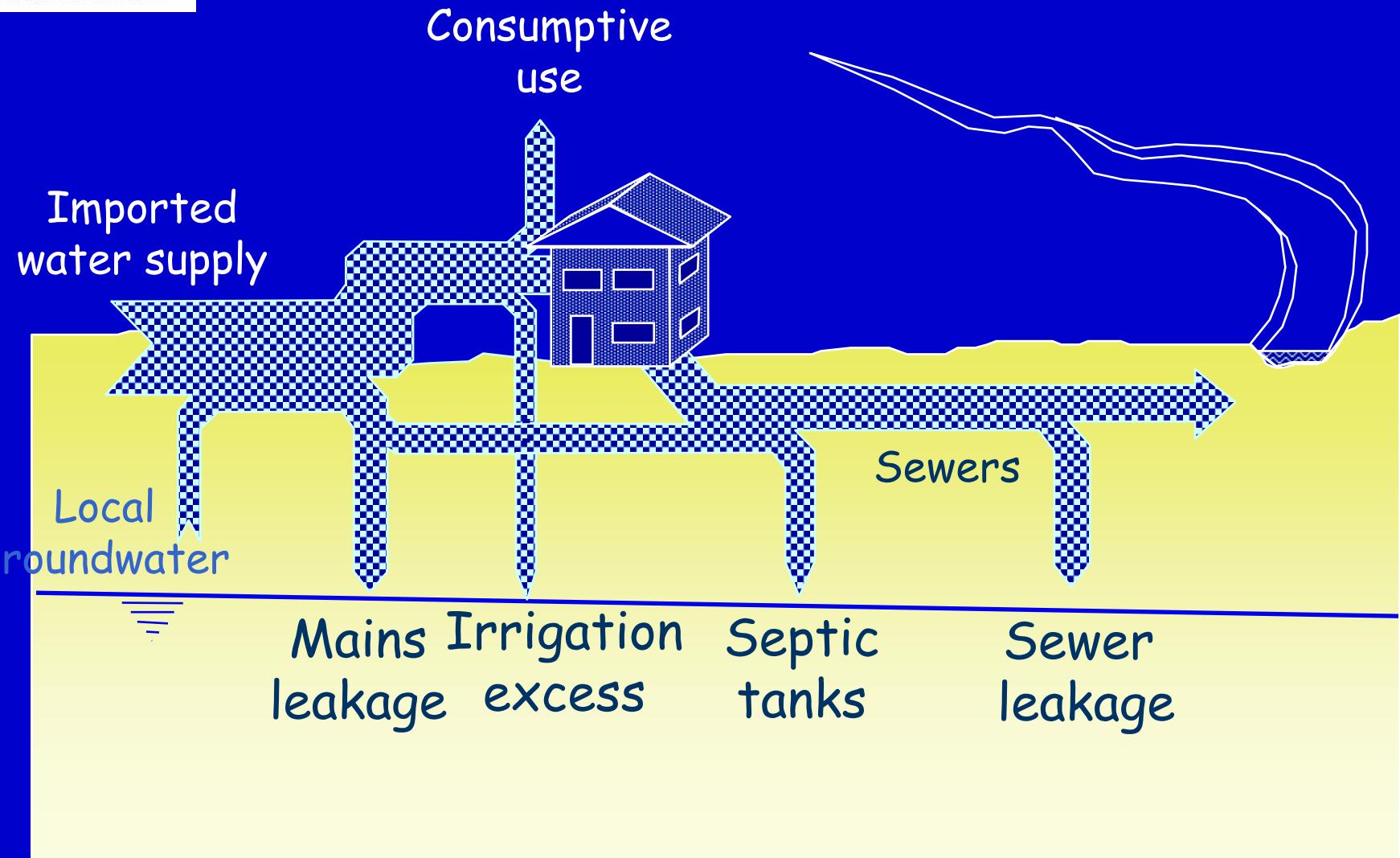
Water supply and rainfall to selected cities

Urban recharge

| City	Rainfall (mm/y)	Water supply (mm/y)	Leakage (%)
Nottingham	700	600	25 ↓
Lima, Peru (1979)	<10	1650	~50
Hong Kong (1980)	2000	280+1250	<10

Urban recharge, Nottingham

Urban recharge

Yang et al. 1999, *Environmental Geology*, 38, 183-198
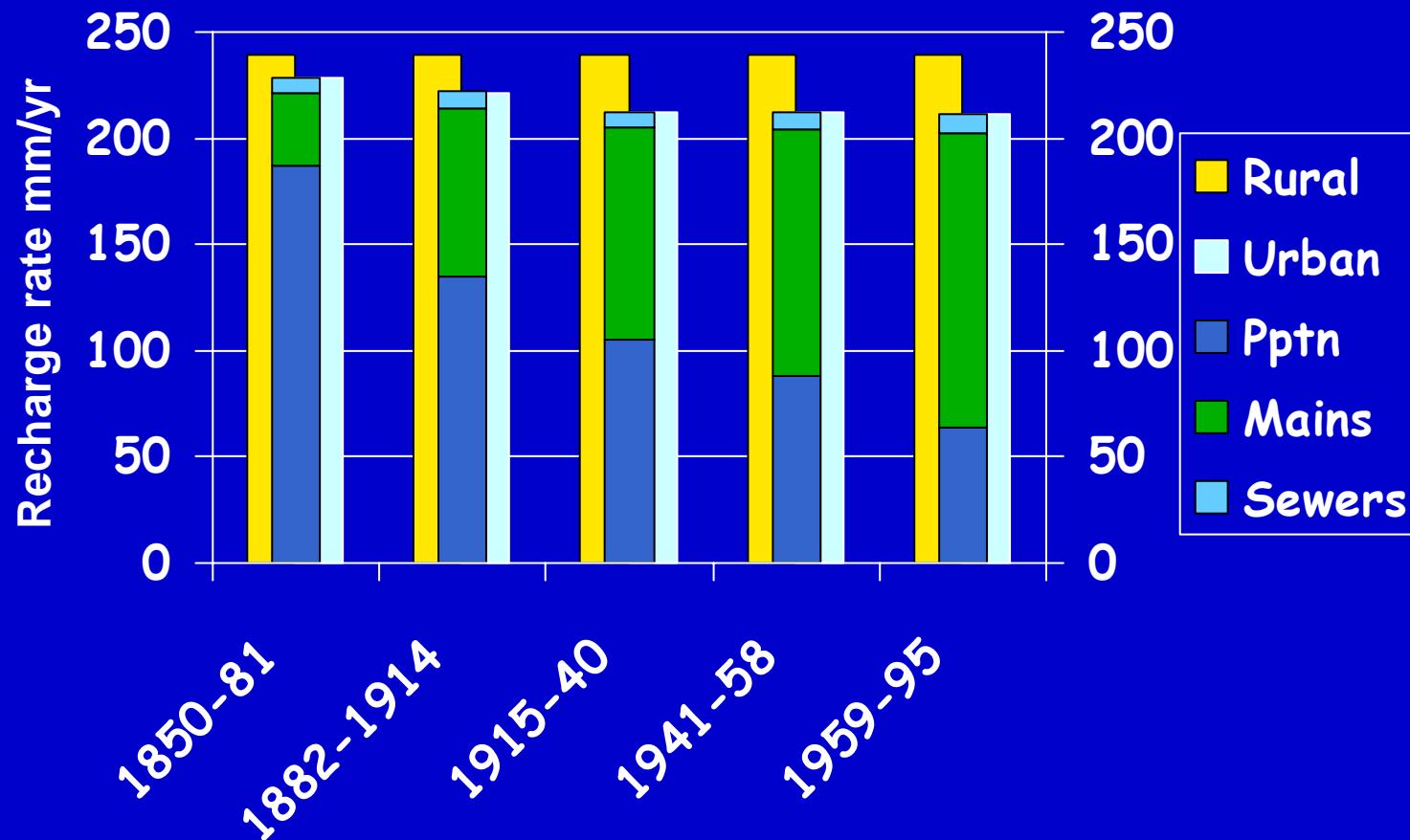
Chlorinated solvents in urban groundwater

Chlorinated hydrocarbon	%age of pumped boreholes over 1 μg/l	
	Coventry	Birmingham
Trichloroethene	72	74
Tetrachloroethene	40	40
Trichloroethane	52	22
Chloroform	43	17
Carbon Tetrachloride	31	2

Rivett et al. 1990, *Journal of Hydrology*, **113**, 307-323
Burston et al. 1993, *Journal of Hydrology*, **149**, 137-161

Urban groundwater pollution

Sewage in groundwater, Meadows, Nottingham

Borehole	$\delta^{15}N$	Microbiological[1]			limonene	Sewage impact
A- park	?	?	?	?	*x*	?
B - park	✓	✓	?	?	*x*	✓✓✓
C - park	✓	?	?	?	*x*	✓
D - park	✓	✓	?	?	✓	✓✓✓
E - 1970s	✓	✓	?	✓	*x*	✓✓✓
F - 1970s	✓	?	?	✓	✓	✓✓✓
G - 1970s	✓	✓	✓	✓	*x*	✓✓✓
H - 1970s	✓	✓	✓	✓	*x*	✓✓✓
I - 1970s	?	?	?	?	*x*	✓
J - 1970s	?	?	?	?	✓	✓
K - C19th	✓	✓	?	✓	*x*	✓

[1] Total coliforms, E. Coli, F. Streptococci

- Meadows, like all UK urban areas, is fully sewered

Urban groundwater pollution

Barrett et al. 1999. *Water Research*. **33**(14), 3083-3097

Road salt in groundwater

Location	Roads (10^3 km)	Salt (10^3 t in 86-87)
UK	347	2000
Germany	40	627

Toronto

Salt applied	>100x10^3 t/year
Cl in groundwater near Toronto highways	2000 – 13000 mg/l
Cl in springs on Toronto lakefront	400 mg/l

Howard & Haynes, 1993 *Geoscience Canada,* **20**, 1-8
Howard & Beck, 1993 *JCH*, **12**, 245-268

Urban groundwater pollution

N in Nottingham groundwater

Urban groundwater pollution

Location of sampled boreholes	NO$_3$-N		NH$_4$-N	
	Detects %	Mean mg/l	Detects %	Mean mg/l
Deep rural	100	12	75	0.35
Deep urban	100	13	27	0.3
Shallow urban	100	10	45	0.2

Nottingham case study

Nitrate loads in Nottingham

Magnesian Lst

Permo-Triassic Sst

Scottish L. Palaeozoic

Sheffield

Nottingham

Papplewick

Oxton

Calverton

Thurgarton

Butlers Hill

Epperstone

Dorket Head Woodborough

Gonalston

Lowdham

Kneeton

Redhill

Bulwell

Arnold

Lambley

Caythorpe

Highbury Vale

Old Basford

Burton Joyce

Gedling

Shelford

Carlton

Netherfield Stoke Bardolph

Nottingham

Colwick

Holme Pierrepont

West Bridgford

Meadows

N

2   0   2   4 Kilometers

N

Hydrogeological map of Nottingham

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Nitrate loads in Nottingham

N

Multi-level sampler

Meadows

Nottingham

Groundwater level
River
Mercia Mudstone
Triassic Sandstone
L. Magnesian Lst.
Glacial drift
Alluvium

10   0   10   20 Km
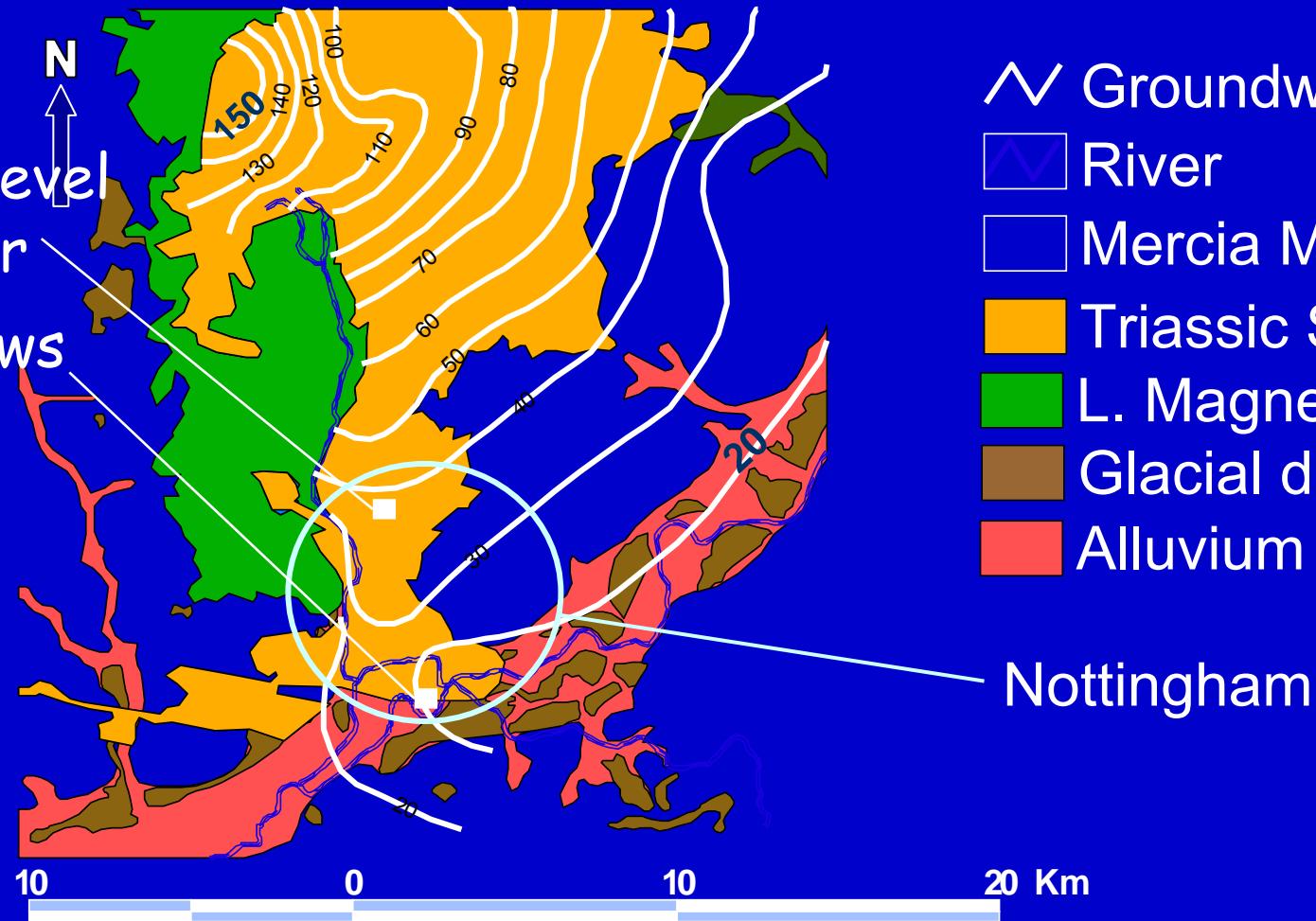
Recharge rates from solutes

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$Cl:N:SO_4$ $Cl:N:SO_4$ $Cl:N:SO_4$

Rain   Water Mains   Sewers

$Cl:N:SO_4$

Nitrate loads in Nottingham
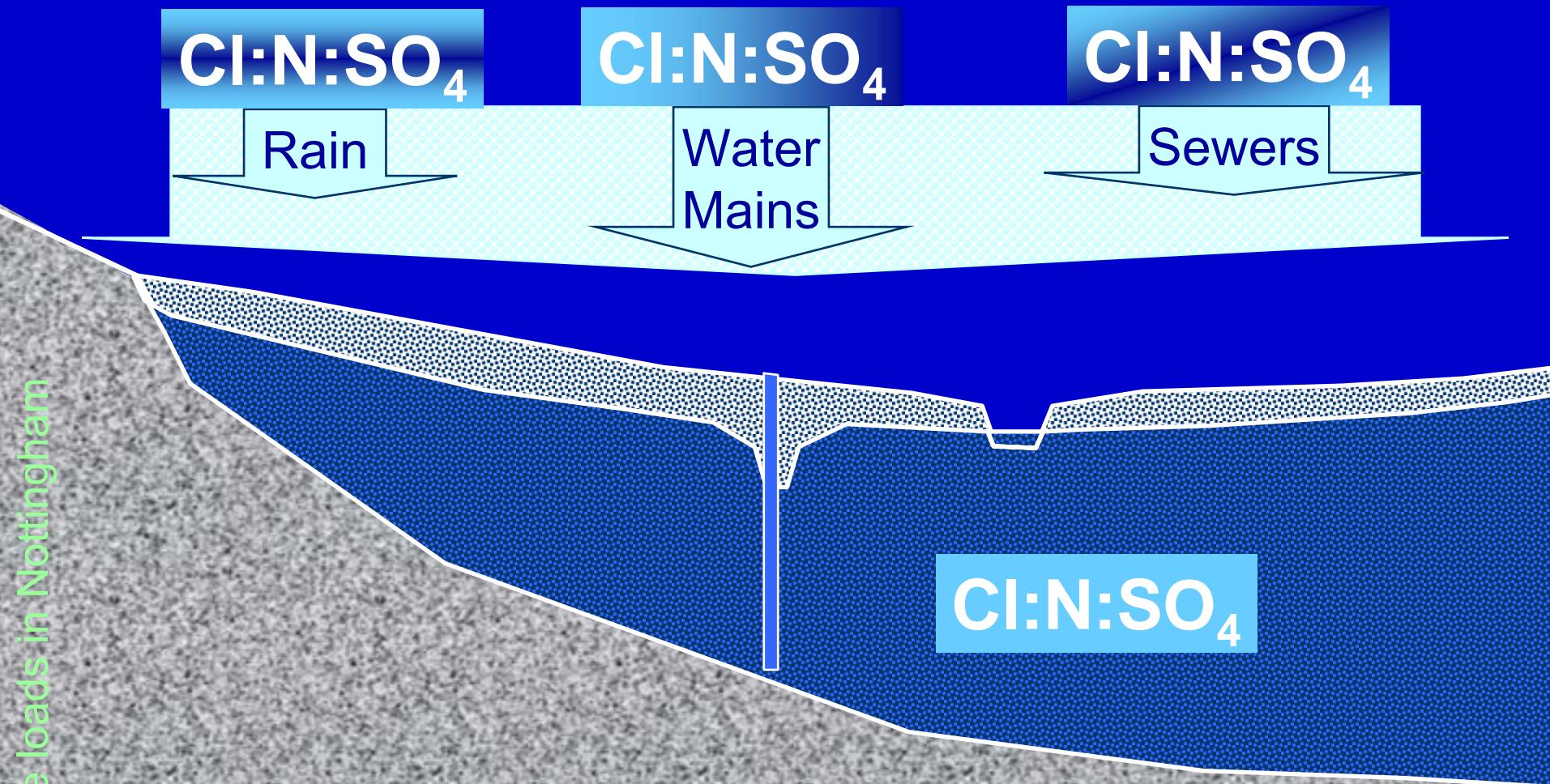
Process for estimating recharge and loads

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Nitrate loads in Nottingham

Conceptual aquifer model

Groundwater flow model

No **Calibrated heads?** Yes

START

TOTAL RECHARGE

Transport models for Cl, SO$_4$, N

Calibrated concentrations? Yes

No

No

Yes **Change flow model?**

De-convolute

RECHARGES LOADS
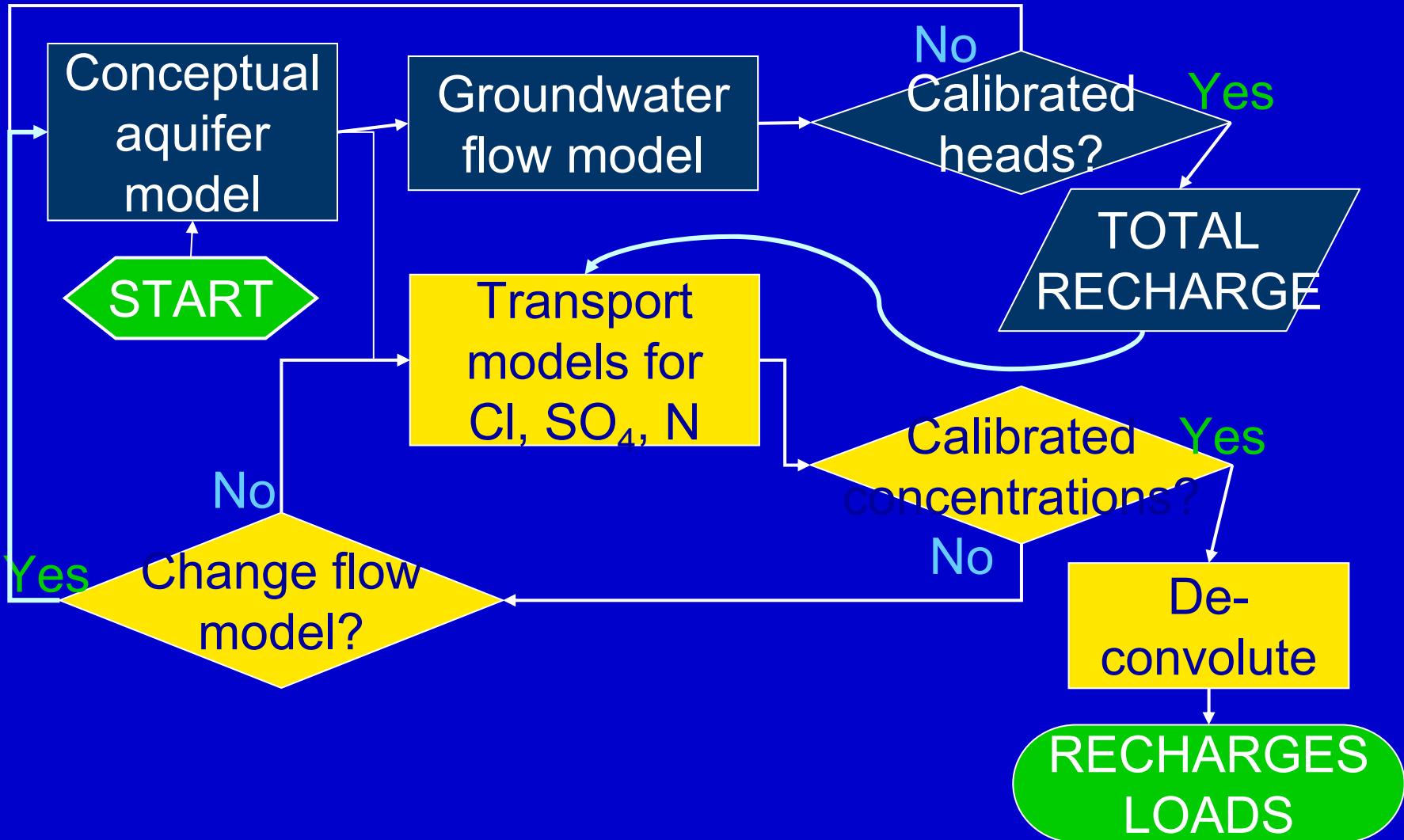
Time and space division of 4 mass balance models

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Nitrate loads in Nottingham

1850   1900   1950   2000

River Leen

River Trent

- 20 km N-S

- 16 km W-E

- standard spacing 500m

- 1 layer

- MODFLOW
  &
  MT3D
  in Visual MODFLOW
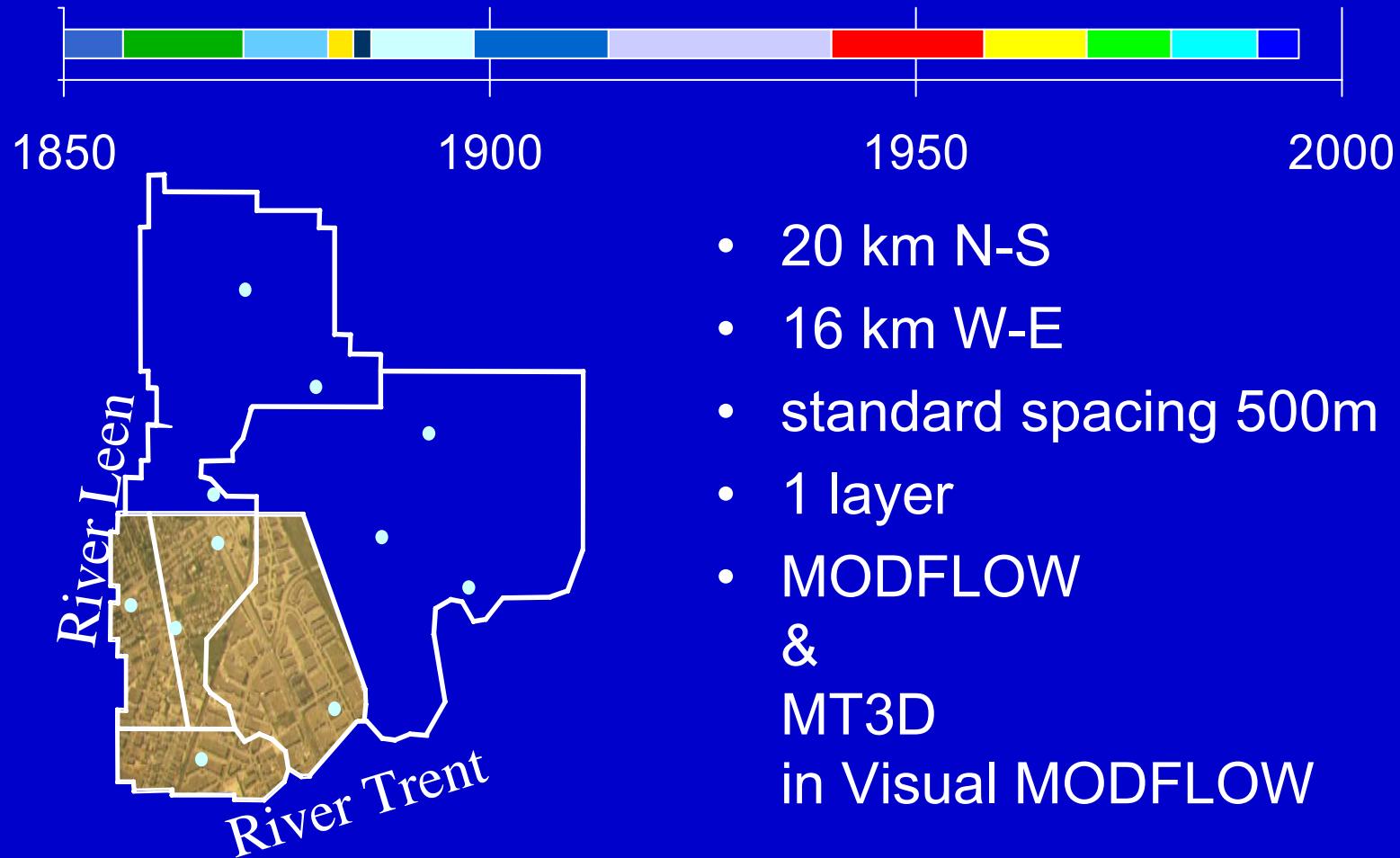
N loads to Nottingham groundwater

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Nitrate loads in Nottingham

N load kg/ha/yr

Period	N load
1850-1881	~9.7
1882-1914	~12.2
1915-1940	~13.5
1941-1958	~17.5
1958-1995	~21
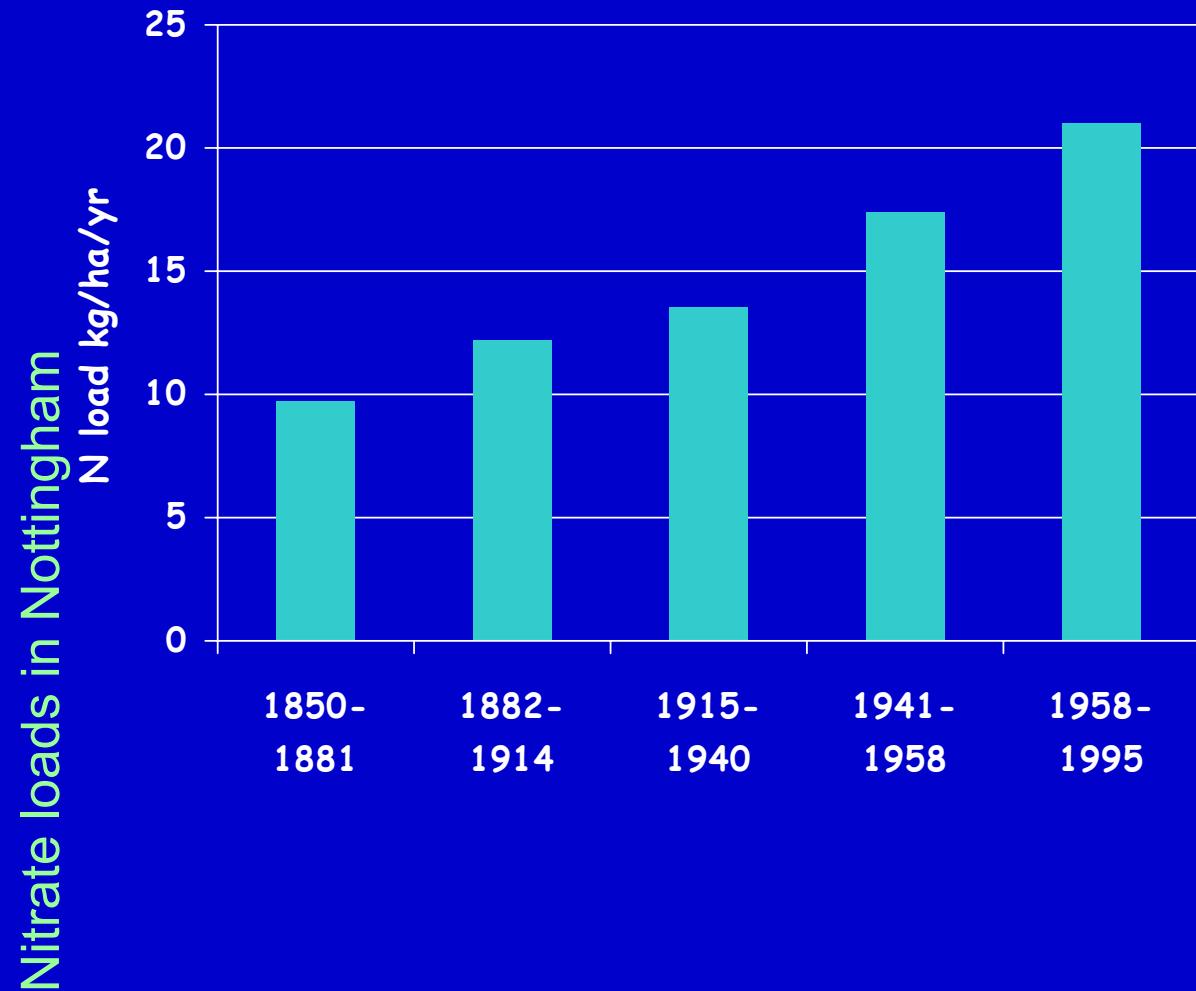
- 1990s urban load 21 kg/ha/y
- Comparable to intensive arable load
- Where from?

Urban fertilisers

Location	Loading (kg N/ha/y)
Perth, Australia	100
USA	1-55

Nitrate loads in Nottingham

Wakida & Lerner, 2005, *Water Research*, 29 3-16

Leaking sewers

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Nitrate loads in Nottingham

Septic tank systems
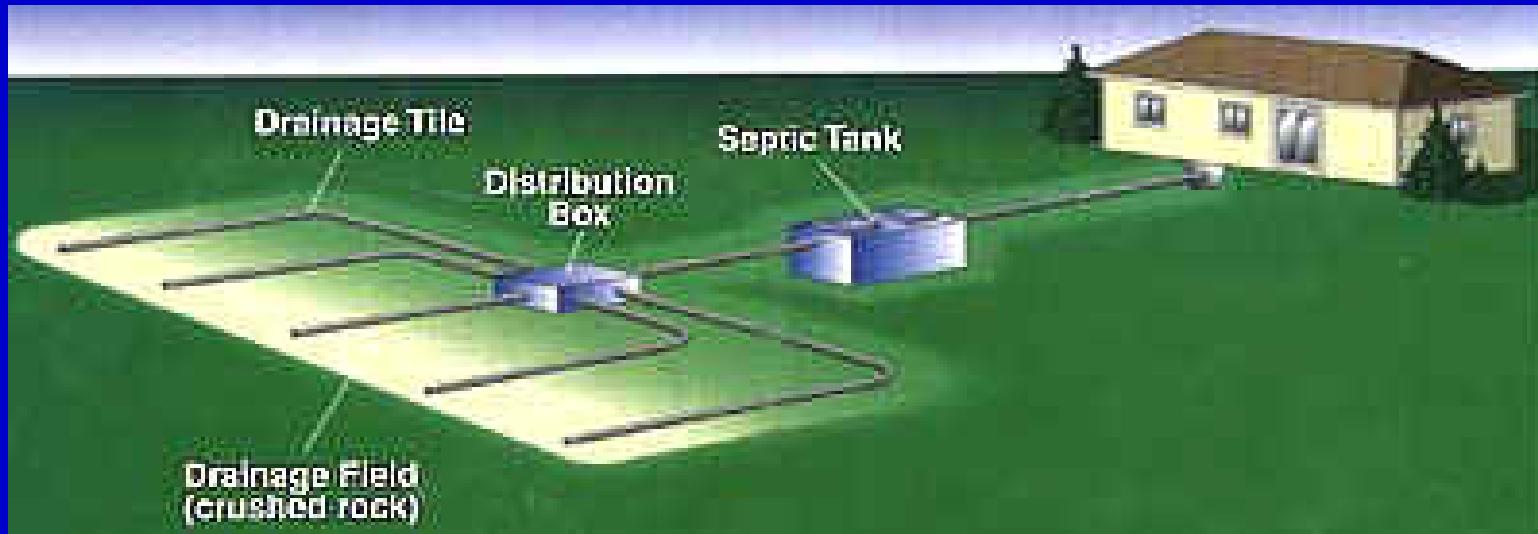
Location	N load from septic tanks (kg N/ha/y)
Merida, Mexico	100
New England	48

Wakida & Lerner, 2005, *Water Research*, 29 3-16

Nitrate loads in Nottingham

Housing and house building

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Nitrate loads in Nottingham

Industrial use and spillage

Nitrate loads in Nottingham

# Ammonium plume from Rexco
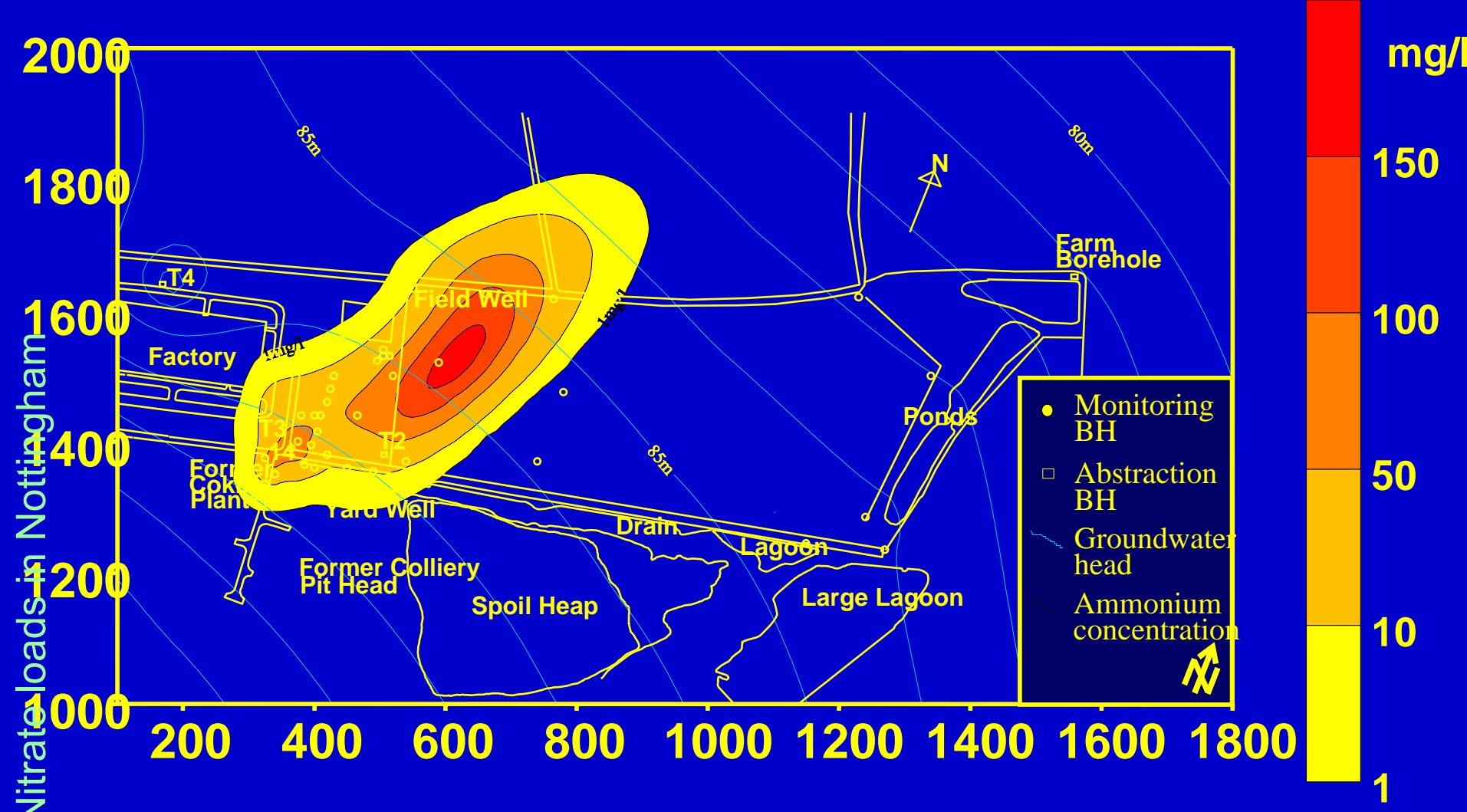
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Landfills

- NH_4 in leachate up to 1500 mg/l
- >10 000 closed landfills in UK, mostly unlined
- Loads up to 4000 kg N/ha/y

Nitrate loads in Nottingham

N loads in Nottingham

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Nitrate loads in Nottingham

Total N load (kg/ha/yr) vs **Recharge period**

Legend:
- Con. Land
- House building
- Soil N
- Sewers
- Mains

Recharge periods: 1850-1881, 1882-1914, 1915-1940, 1941-1958, 1958-1995

Wakida & Lerner, 2005, *Water Research*, 29 3-16
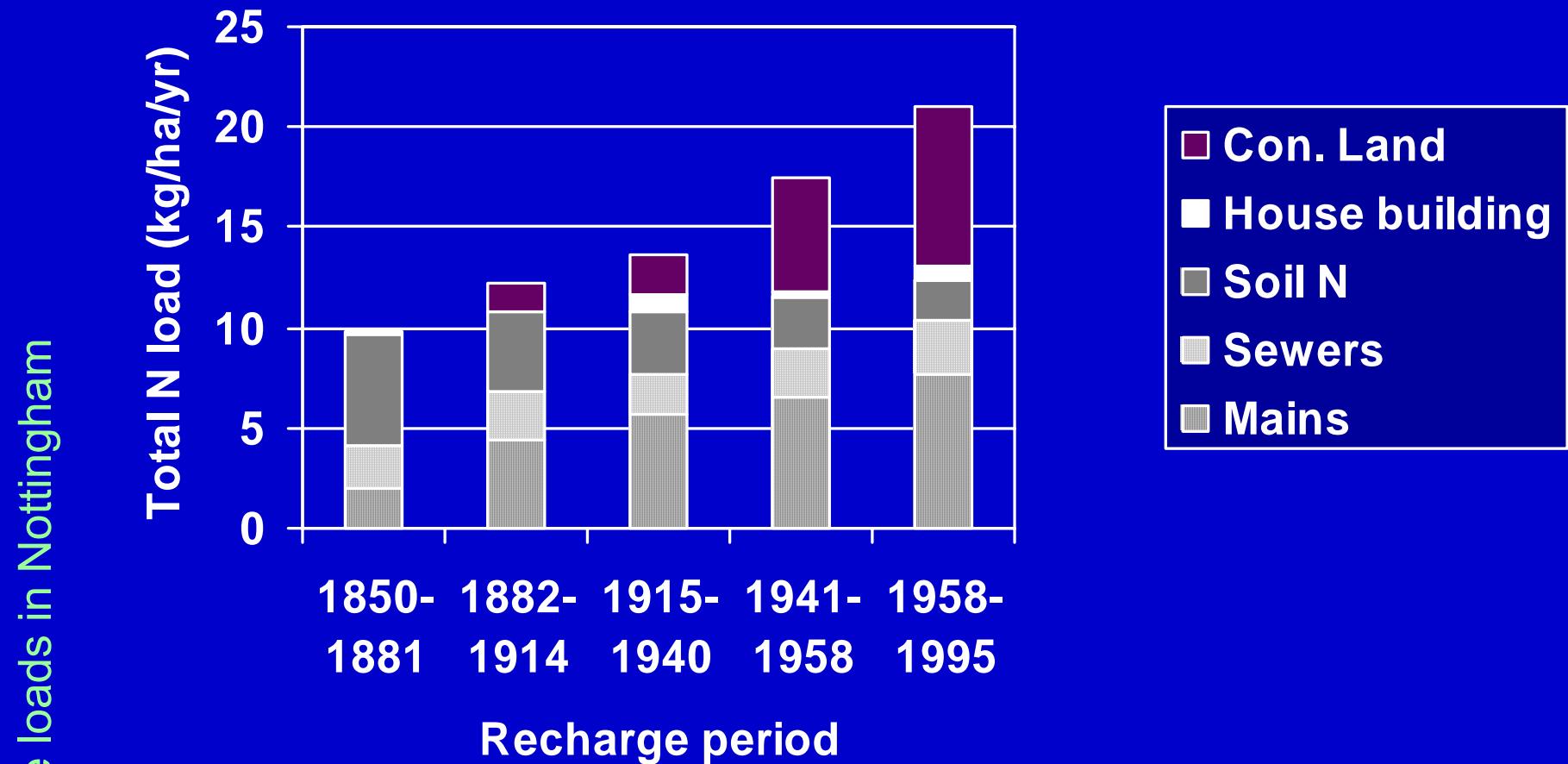
Organic sources and risks

- Density of sources
  - National
  - Nottingham
- Risks from urban sources
  - Nottingham
- Loads

Organic sources

Chlorinated solvent industry database Tait et al. 2004

Industry	Sector	Sites	Data Analysis
Engineering	• Transport • Mechanical • Machine Tools • Plant Machinery • Precision • Aerospace • Defence	50,000	• 75,000 industries • 60,000 manufacturing sites • Postcodes give 100m resolution[1]
Electronics	• Electrical Eng. • Electronic Eng.	12,000	
Chemical	• Paints • Varnishes • Inks • Pesticides • Adhesives / Sealants • Rubber	3,500	• Bartholomew digital map data[2] • Geoplan digital postcode map[3]
Metal	• Finishing	2,000	
Textile	• Pretreatment • Dry Cleaning	7,000	[1]University of Essex, [2]University of Manchester, [3]University of Greenwich

Density of chlorinated solvent users

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Density scale: sites/km²

Organic sources

> 100

< 10

Sheffield
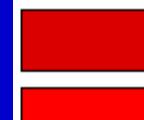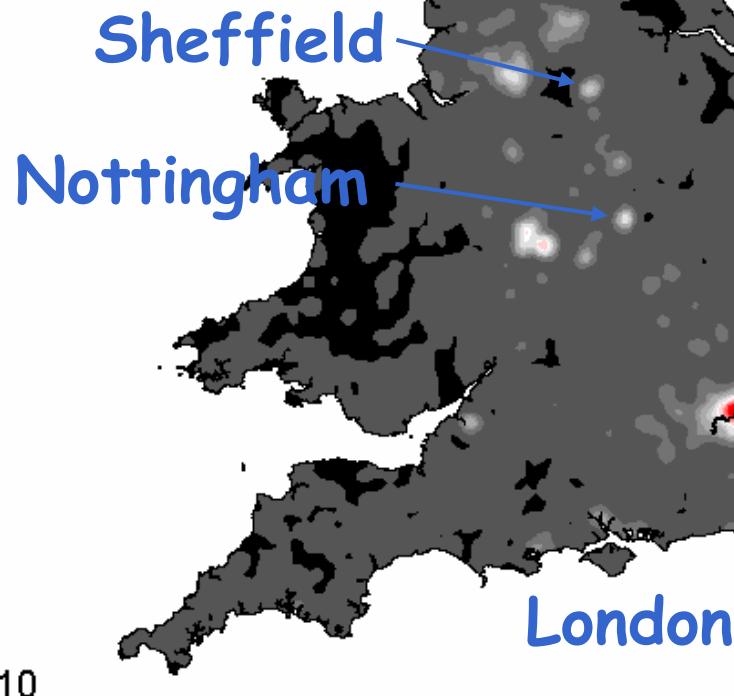
Nottingham

London

- 75 000 current sites
- London - 2,500 dry cleaning outlets

Tait et al. 2004, *SOTTE* 319, 77-98

# Nottingham: point or diffuse sources?

Potential TCE sources

Organic sources
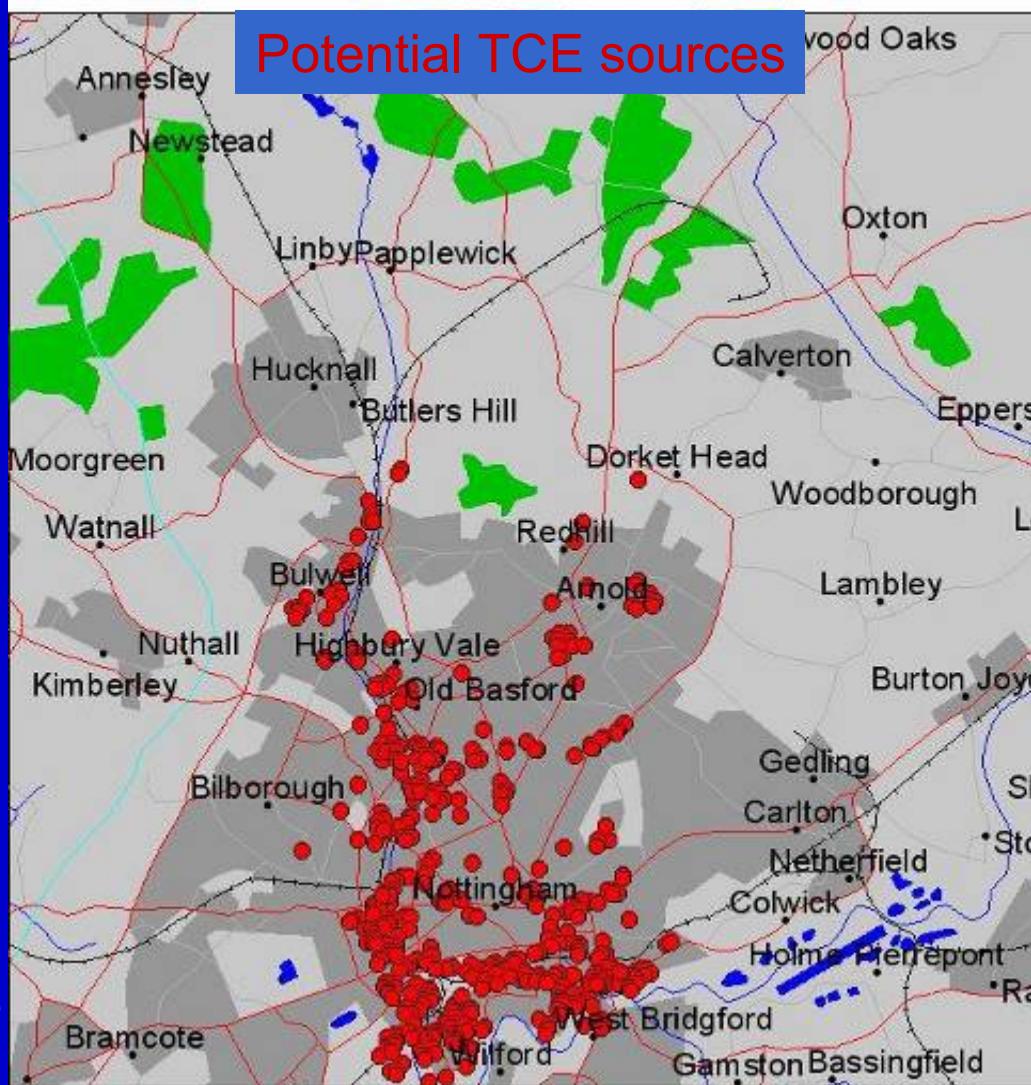
- Potential TCE sources in Nottingham
  - 1991
  - Unconfined aquifer
- How dense a pattern to become diffuse pollution?

Petrol station

Garage

Dry cleaners

Engineering works 1940-1980

Bleaching & dyeing works 1900-1995

Petrol station

BH

WATER TABLE

Sources

Pathways

Receptor

Organic sources
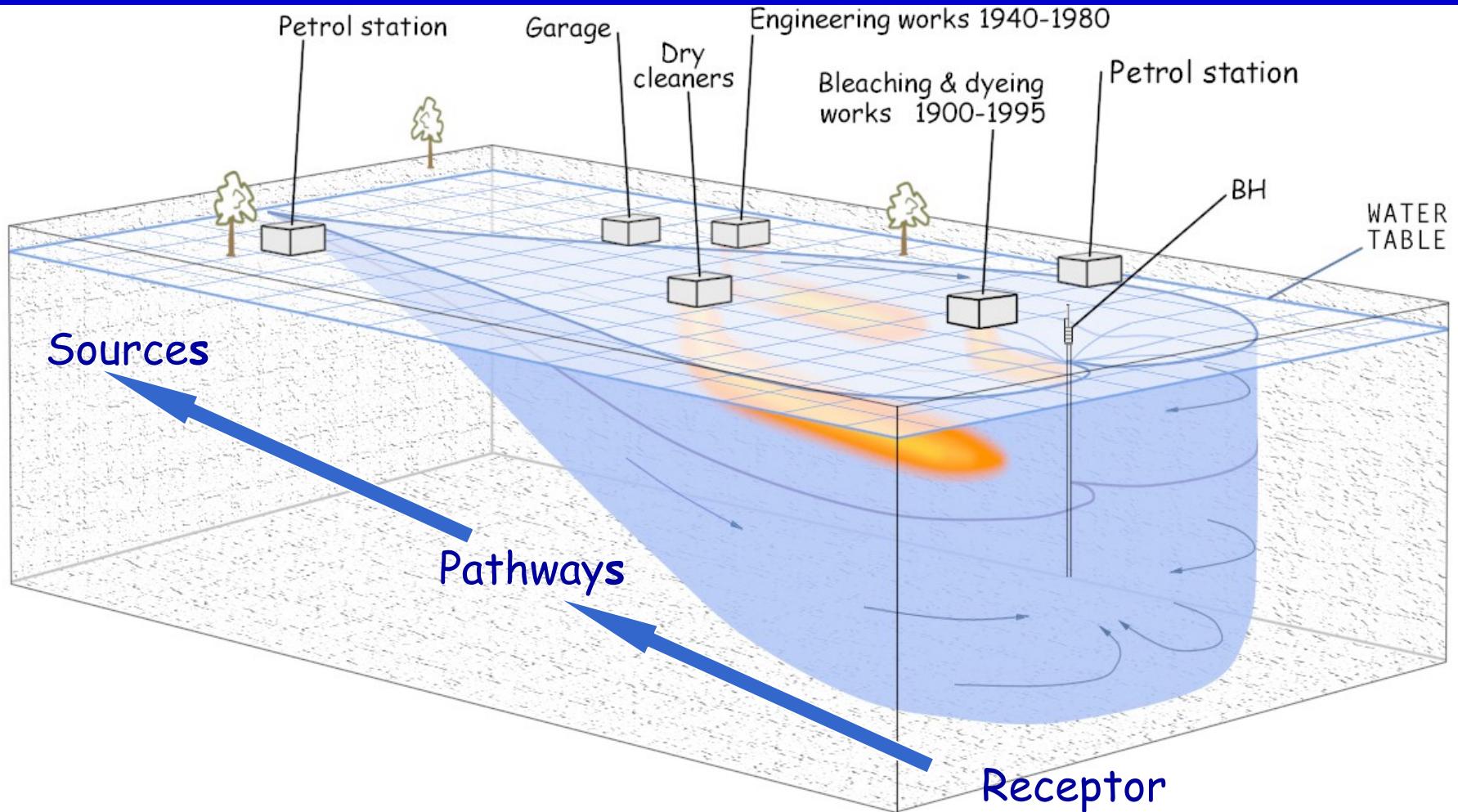
BOS: the model components

Groundwater flow model

Catchment zone tool

Landuse analysis

Databases

Pollution risk model

GUI

Organic sources

Cait et al., 2004, Environmental Modelling and Software, 19, 1111-1124
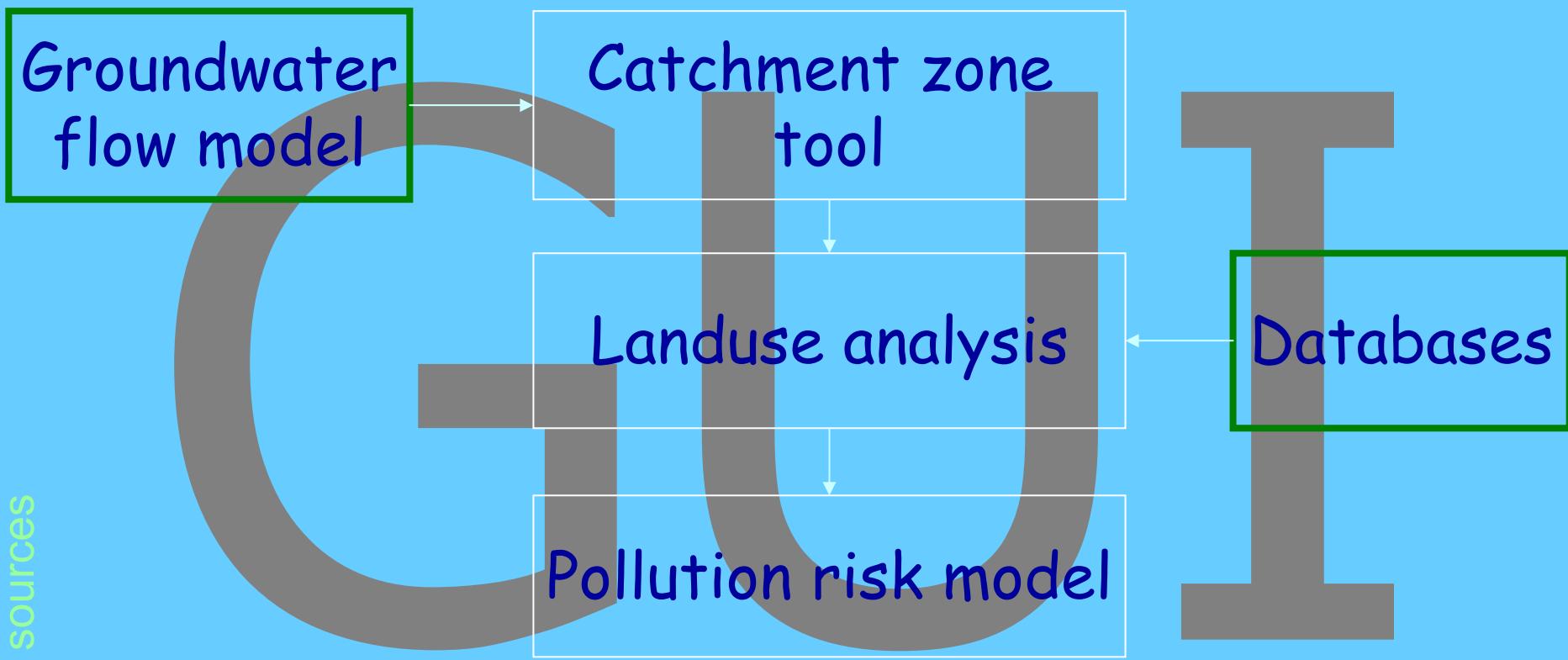
The catchment zone model

- Stochastic MODPATH
- 1 particle per node
- Monte Carlo simulations
  - E.g., recharge, permeability
- Frequency of arrival gives probability of node in capture zone

Organic sources
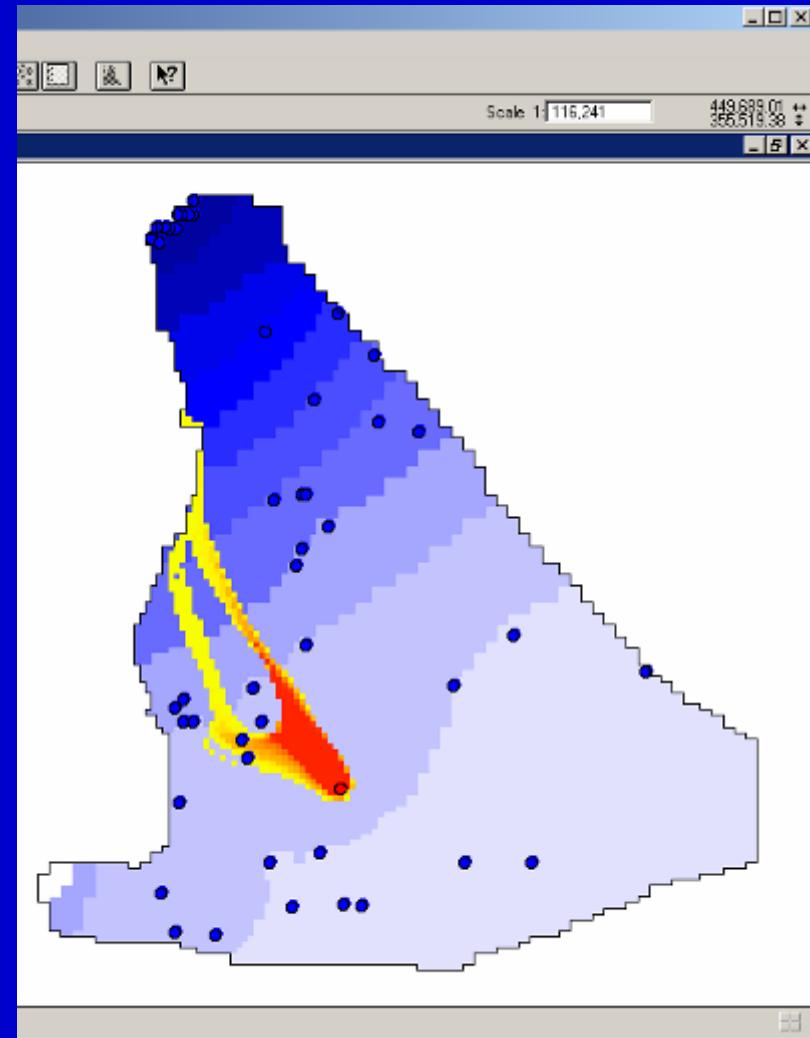
Landuse GIS

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Organic sources

1991 landuse

- Residential
- Recreational
- Institutional
- **Industry**
- Agricultural
- Commercial
- Waste
- Transport
- Water
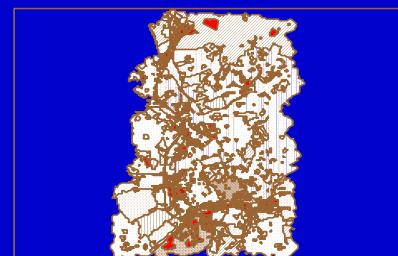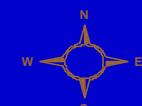
0.9   0   0.9   1.8   Kilometers

Specific industry databases

Microsoft Access - [specific industry data : Table]

File Edit View Insert Format Records Tools Window Help

Industry n	Start date	Stop date	Industry type	Known contam	Industry name	Details
1	1921	1974	41		Barton's buses	Originally a garage that developed into barton's buses. Part of the site has been an iron found... d an e
2	1901	1939	2		Shawl factory	Shawl factory and lace finishing
3	1901	1974	42		Neville Brothers	A lace makers since 1881, after 1930 the factory was gradually taken over by myford machin... ers
4	1954	1974	2		Nuart Lace	Lace making factory
5	1954	1974	3		Barwin Works	Hosiery factory
6	1901	1974	43	1	Silk mill	Factory has been occupied by a silk mill, lace making, bleaching and dyeing works

Microsoft Access - [general indusrty : Table]

File Edit View Insert Format Records Tools Window Help

Industry type	Industry name	Cont	Conta	Conta	Cont	Cont	Conta	Conta	Conta	Conta
1	Transport and haulage	1	2	3	4	6	7	8	9	
2	Textile manufacture	5	6							
3	Hosiery	5	6							

Microsoft Access

File Edit View Insert Format Records Tools Window Help

contaminant properties : Table

Contaminant	Contaminant	KOC	Half life mean	Half life SD	Aqueous solub	Mole fractio
1	Benzene	38	0.00375	0.0027	1750	
2	Toluene	135	0.0218	0.053	515	
3	Ethylbenzene	95	0.0093	0.015	152	

Organic sources

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New unconfined catchment

Raw predicted catchment
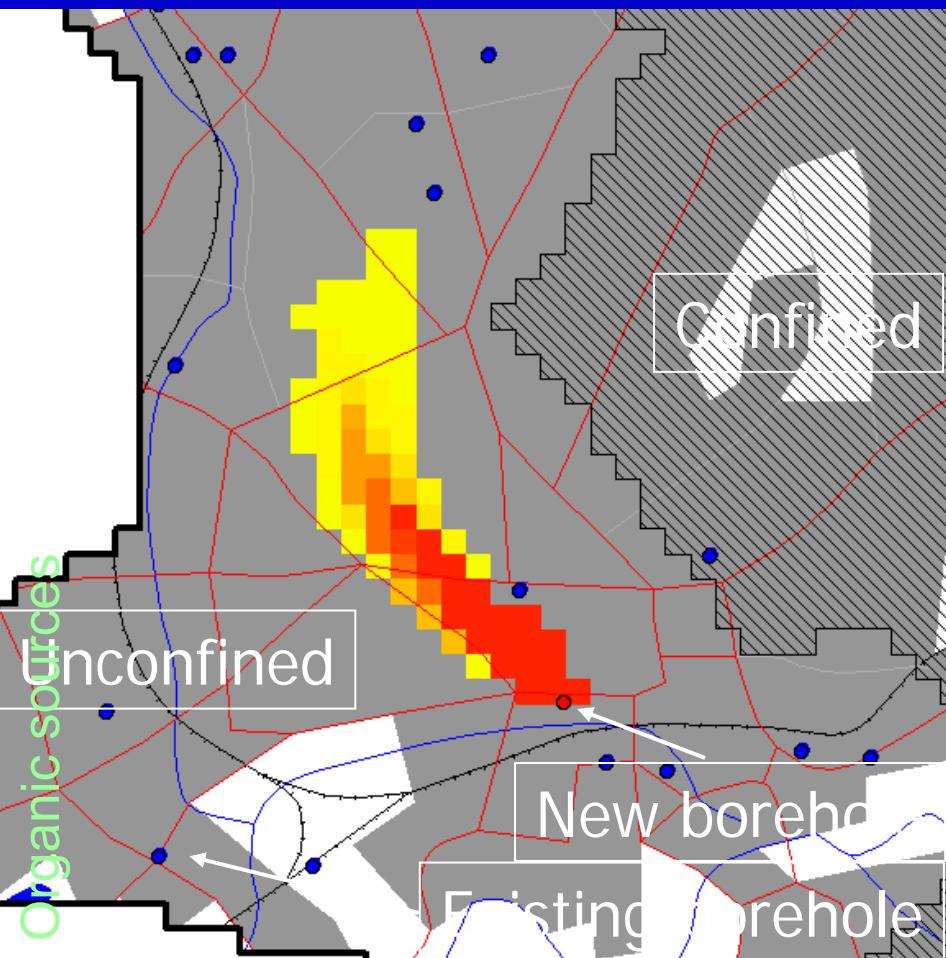
Probability contoured catchment with industries

Confined

Unconfined

Organic sources

New borehole

Existing borehole

Industries
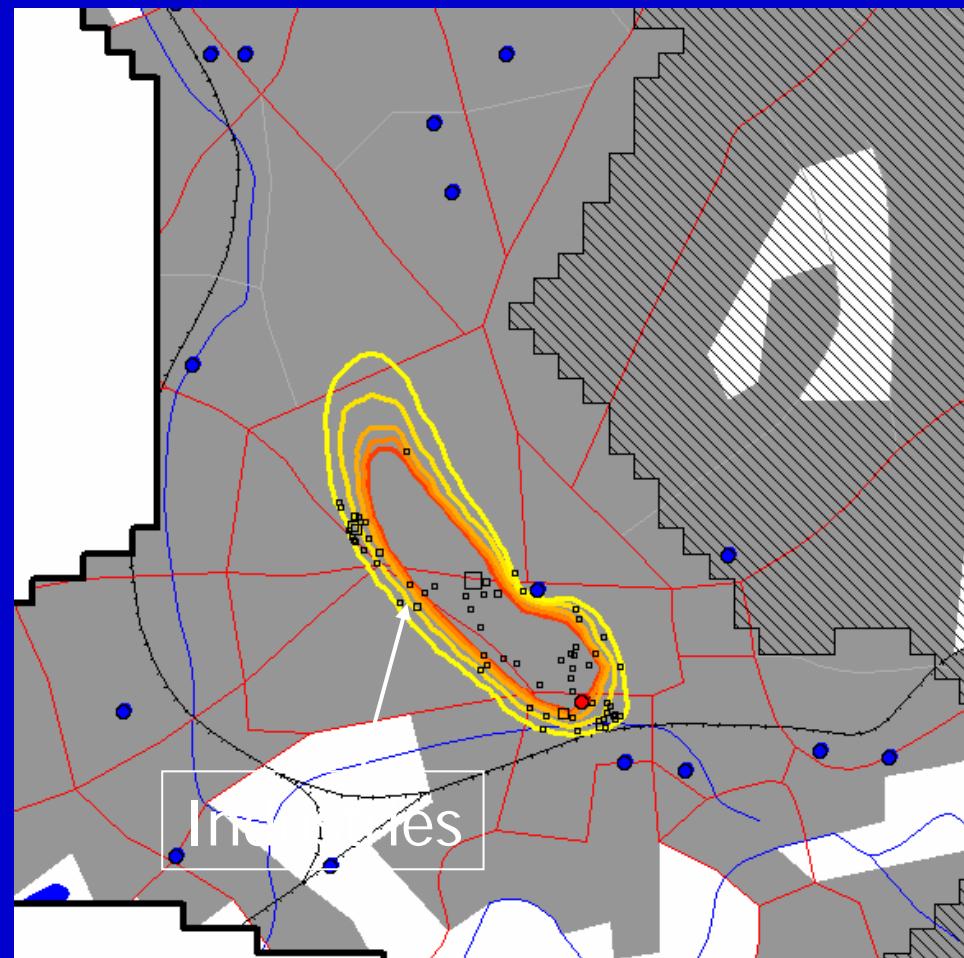
The pollution risk component

recharge → source → initial flux

SOURCE — **PATHWAY** — **TARGET**

pumping borehole

vadose zone migration of contaminants

dissolution

biodegradation

contaminant flux at the bottom of vadose zone

vadose zone

water table

advection of contaminants

biodegradation

sorption

dilution by groundwater at pumping borehole

groundwater flow

Organic sources
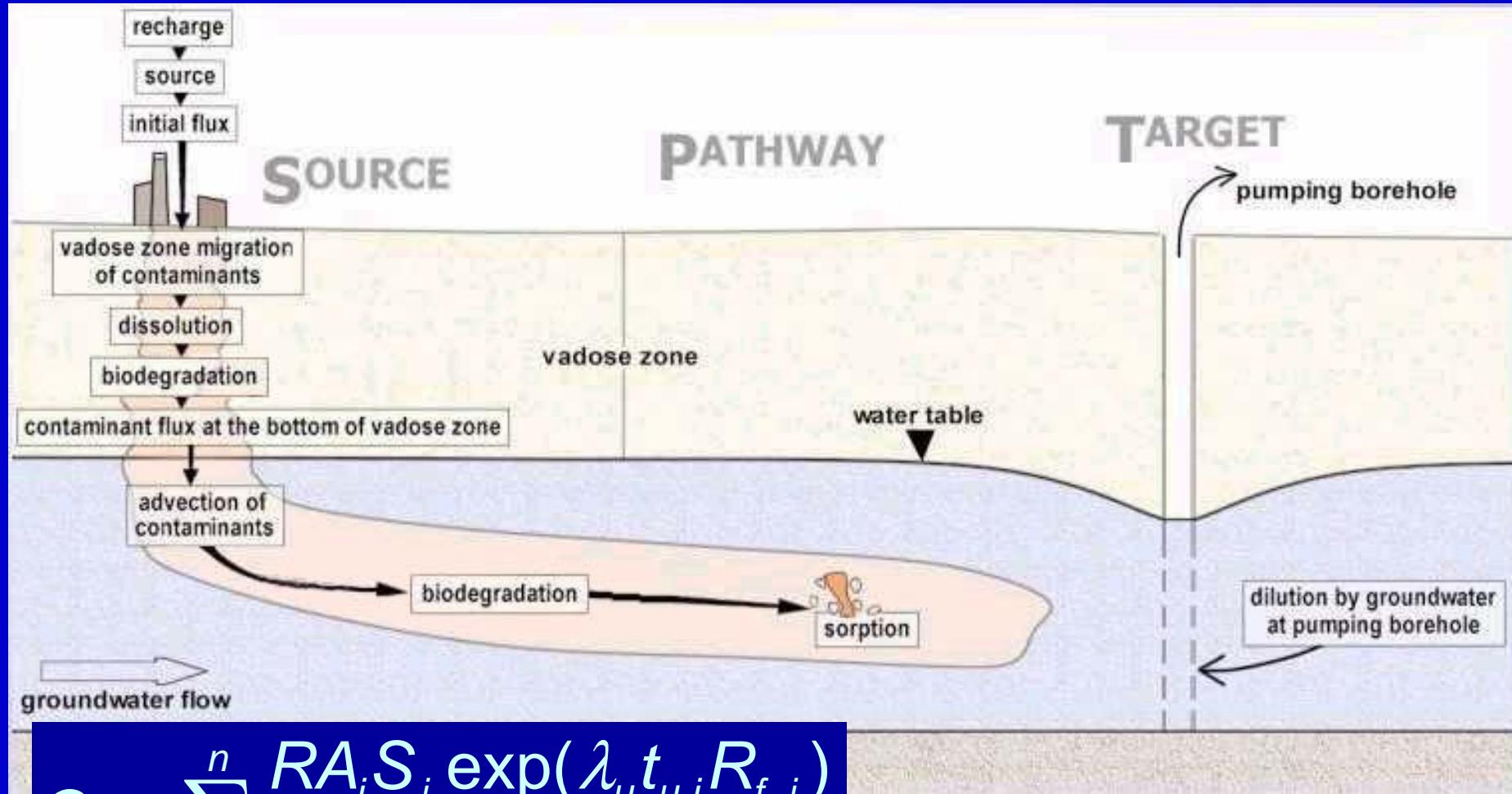
$$C_j = \sum_{i=1}^{n} \frac{RA_i S_j \exp(\lambda_u t_{u,i} R_{f,j})}{Q \exp(\lambda_s t_{s,i} R_{f,j})}$$

• Monte Carlo analysis

Predicted concentrations

Organic sources
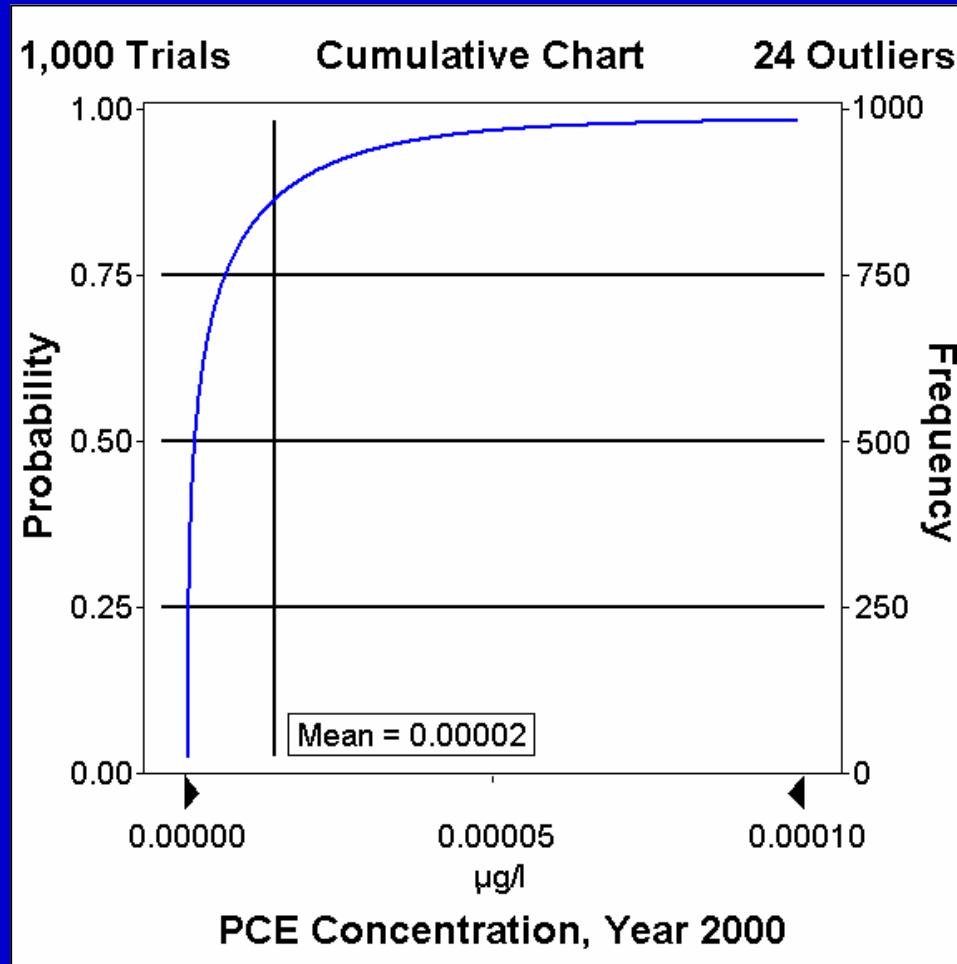
Validation

- Risk models are rarely validated
- Construct and believe
- Attempted validation against field data
  - 2 wells ⟩ 14 (not independent)
  - 7 contaminants measurements

- Also national MTBE observations (not shown)

Organic sources

Validation

Organic sources

| Parameter	Drinking Water Std (µg/l)	Borehole 1		Borehole 2	
		Field (µg/l)	Model (µg/l)	Field (µg/l)	Model (µg/l)
TCE	30	140	230	100	220
1,1,1 TCA	30	4	9	5	13
PCE	10	260	360	320	400
Benzene	1	bql	0.07	bql	0
Toluene	<10	bql	0.03	bql	0
Ethylbenzene	<10	bql	0.05	bql	0.1
Xylene	<10	bql	0.001	12	0.1

bql = below quantification limit

- 13/14 predictions within a factor of 2

Predicted PCE concentrations

50%ile log(C_{PCE}), 2005

Borehole Simulation Location

Study Area

Organic sources
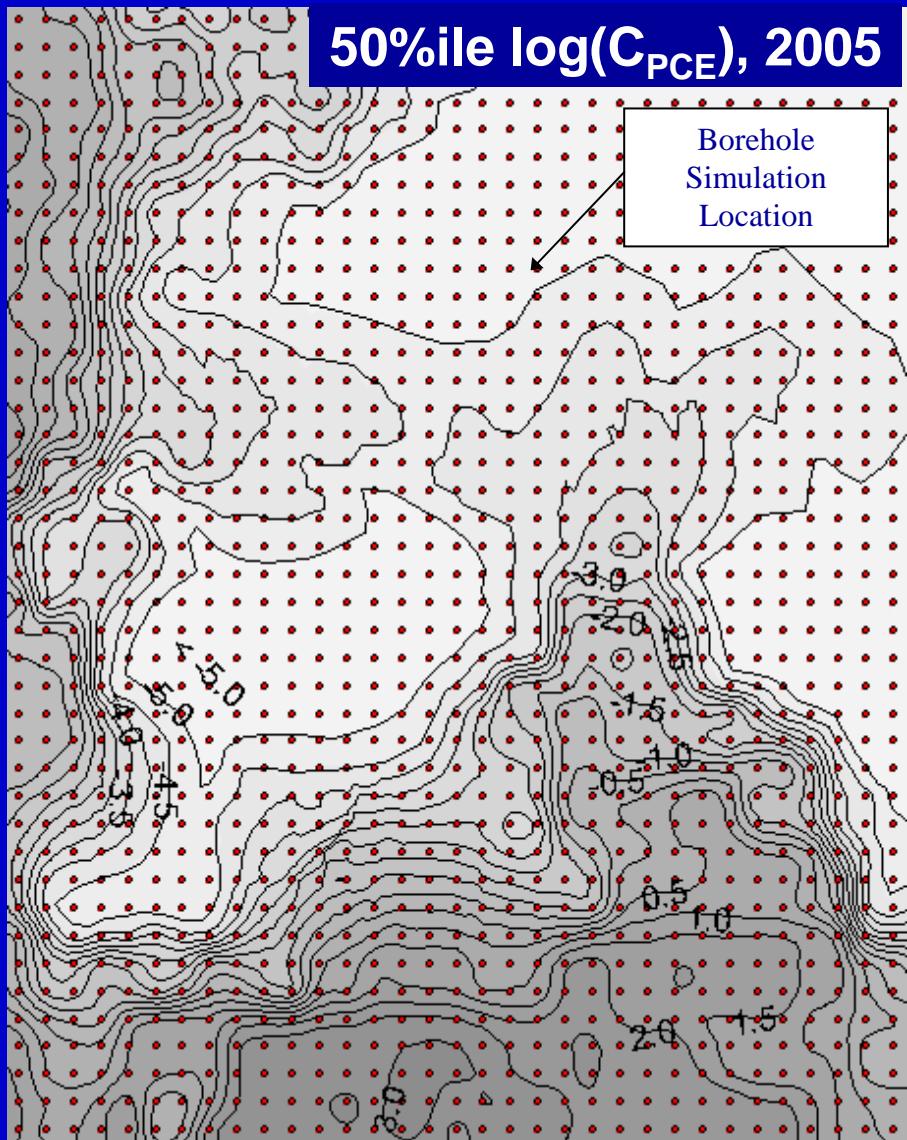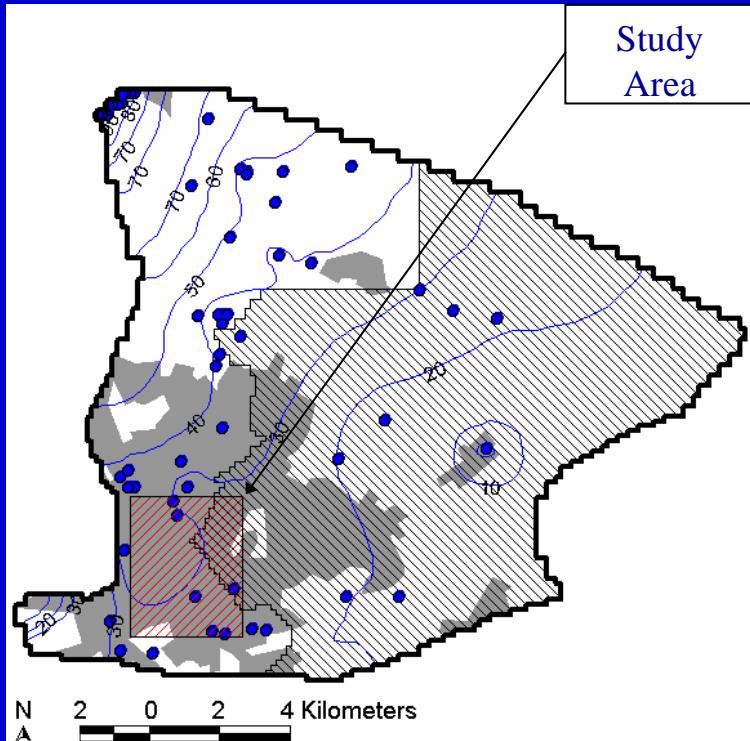
Tait et al., submitted, Environmental Modelling and Software

Risks from leaking sewers

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Organic sources

- Nottingham sewer network
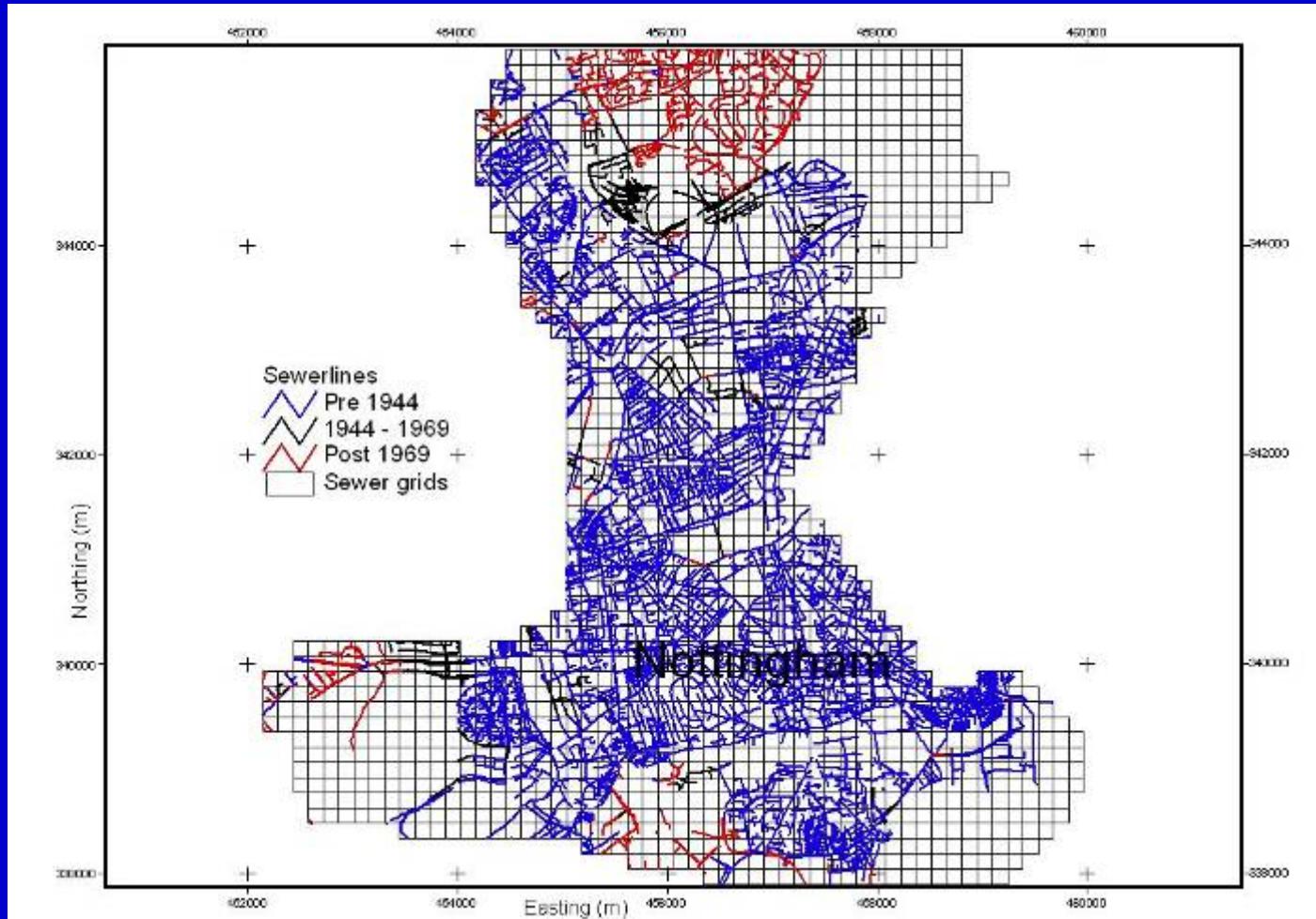
Nottingham: Potential MTBE load

Potential MTBE sources

Organic sources
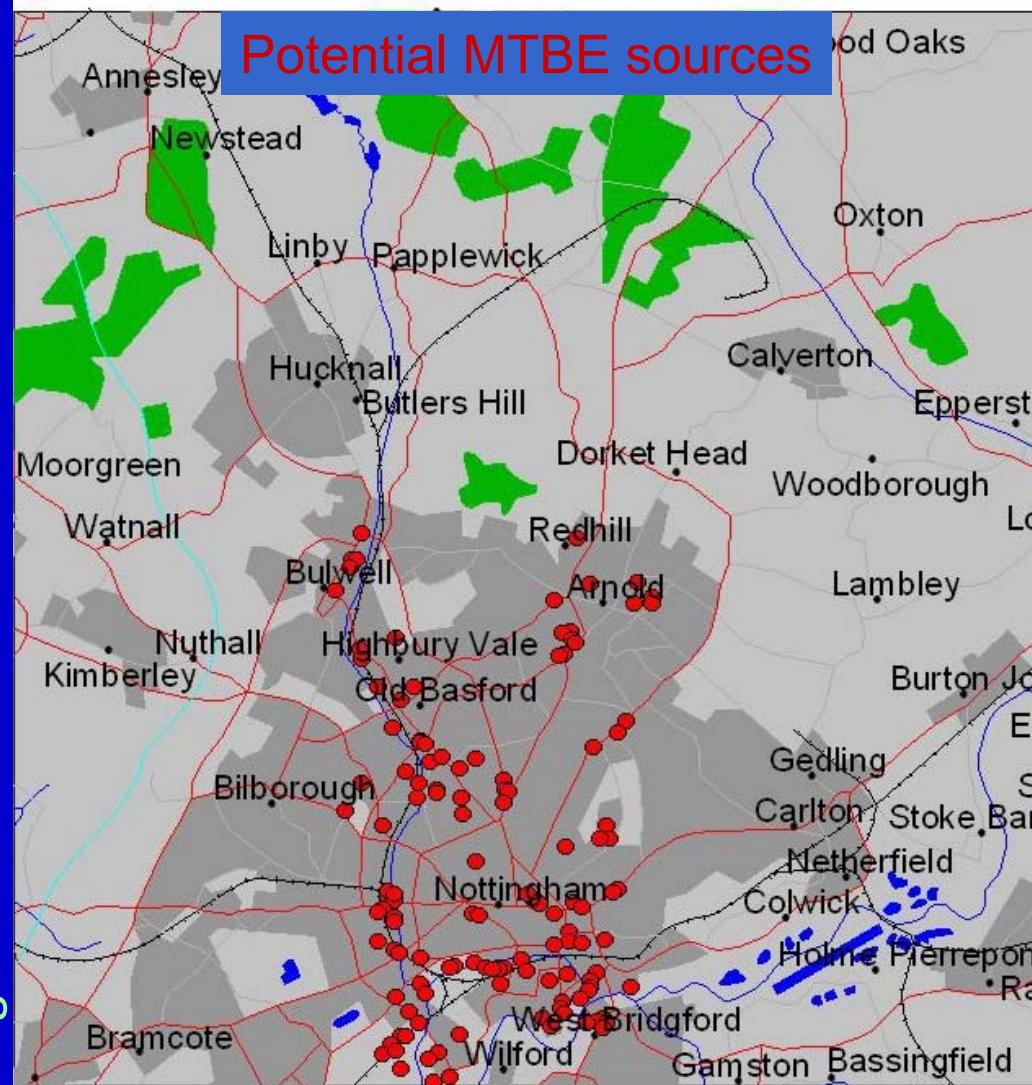
- Summing sources in Nottingham risk analysis
- Load ~10 kg/ha/yr
- Probably too high

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Chlorinated solvent load in Birmingham aquifer
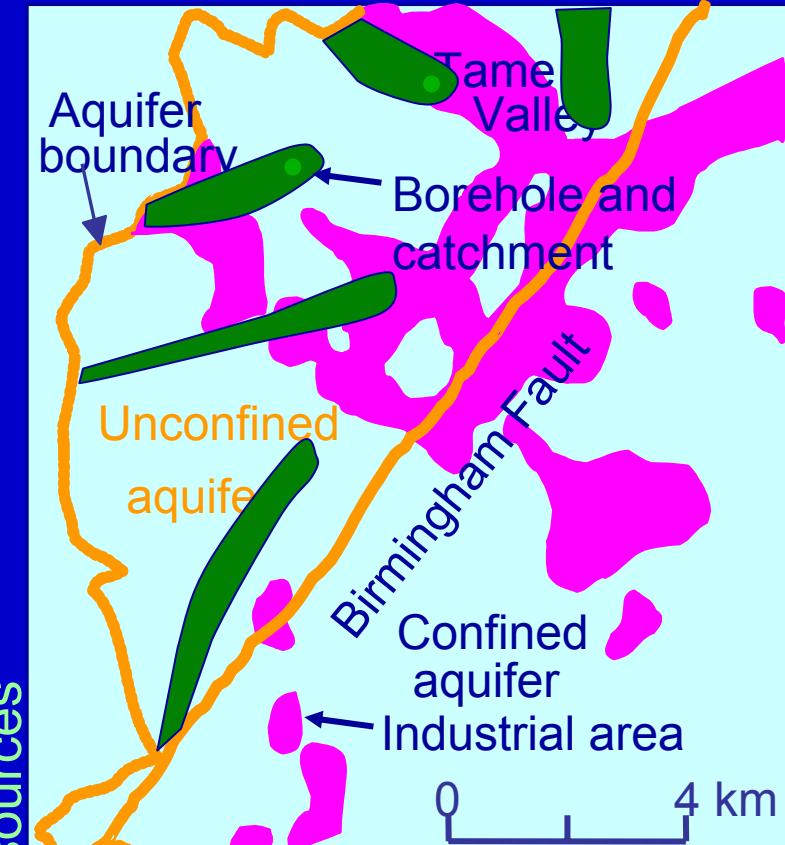
Year	% recharge pumped	Mass removed (kg/yr)[1]	Load (kg/ha/yr)
1987	43	1811	0.4
1998	5	228	~1

[1] from Rivett et al. 2005 *QJEGH* 38, 337-250

Assume:
- Steady state
- Boreholes are pumping representative concentrations of TCE, PCE, etc

Reminder of the story

- Urban recharge
  - plenty in cities
- Urban groundwater pollution
  - N, organics, sewage, salt, etc
- Nitrate loads in Nottingham
  - 21 kg/ha/yr from contaminated land, sewers, mains
- Organic sources and risks
  - Many sources, significant risks
- The message:
  - Multiple urban sources ≡ diffuse pollution

Summary

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Selected Nottingham references

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F.T. Wakida & D.N. Lerner, 2006. Potential nitrate leaching to groundwater from house building. *Hydrological Processes*, **20**(9):2077-2081.

B.N. Chisala, N.G. Tait and D.N. Lerner, *in press* . Evaluating the risk of methyl tertiary-butyl ether (MTBE) to urban groundwater at city scale: Nottingham case study. *Journal of Contaminant Hydrology*, December 2005.

N. G. Tait, R. M. Davison, S. A. Leharne and D. N. Lerner. Borehole Optimisation System (BOS) - Assessing the Potential Value of Urban Groundwater in Nottingham. Submitted, January 2006.

Also papers led by R Taylor, K Powell and S Trowsdale.

Summary