Assessing Exposure and Effects for Aquatic Environmental Risk Assessment: The Challenge of Engineered Nanoparticles

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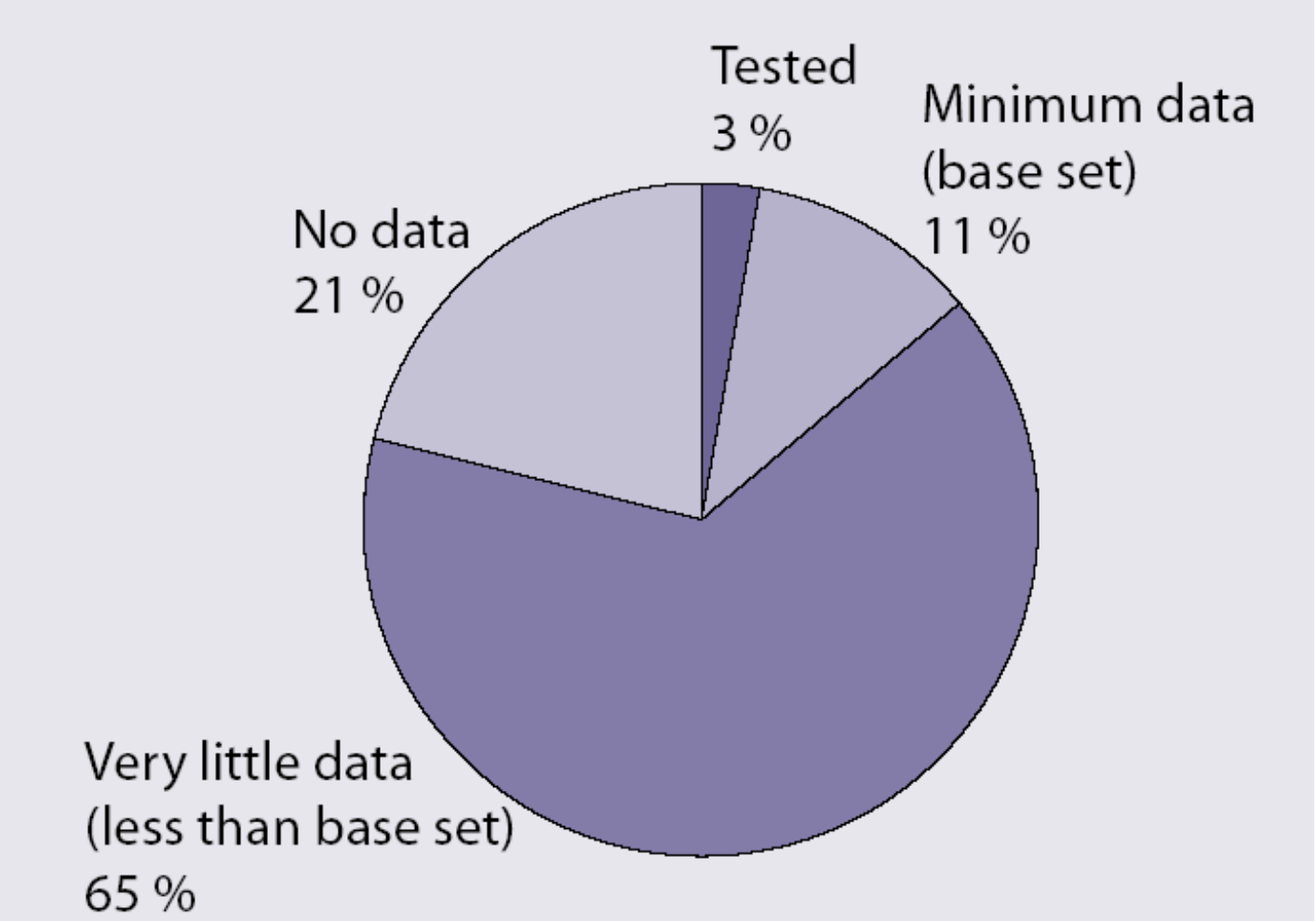
Outline

- Requirements for environmental risk assessment
- What is risk?
- Characterising risk
- Case study
- The challenge of nanoparticles

Requirements to assess environmental risks

Proportion of chemicals with data



REACH – a new chemicals policy for Europe

Registration, **E**valuation & **A**uthorisation of **CH**emicals

Registration:

Chemicals imported/produced in volume of ≥1 tonne per producer (equivalent to ~30,000 substances), have to be registered with a new EU Chemical Agency.

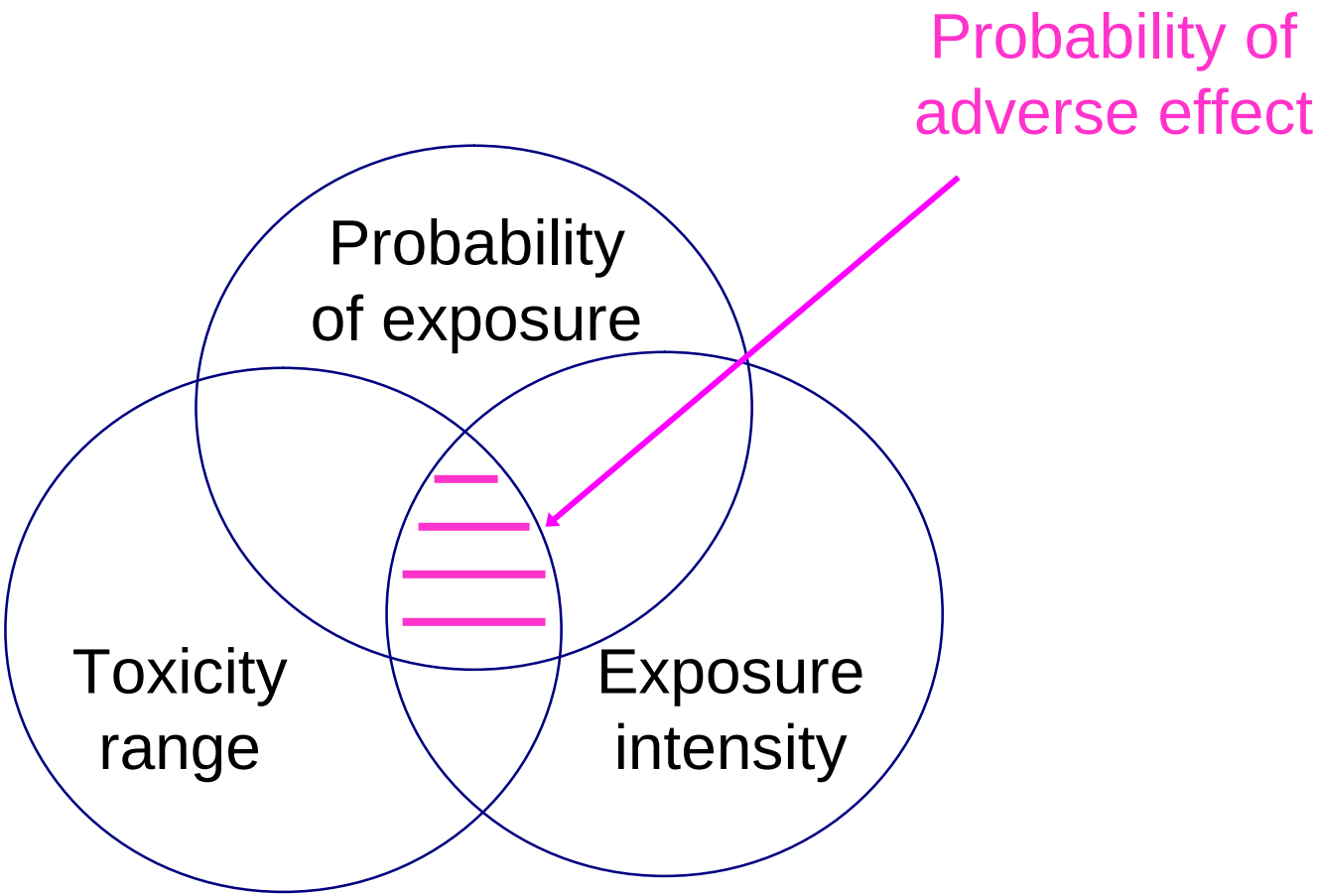
Evaluation:

Evaluation of the registered information (and other) by the EU Chemical Agency and Member States authorities to determine hazards and risks.

Authorisation:

Authorisation requirements imposed on substances of very high concern (e.g., carcinogens, mutagens and EDCs), including in some cases their replacement.

Characterising risk



Tiered approach

From first tiers...

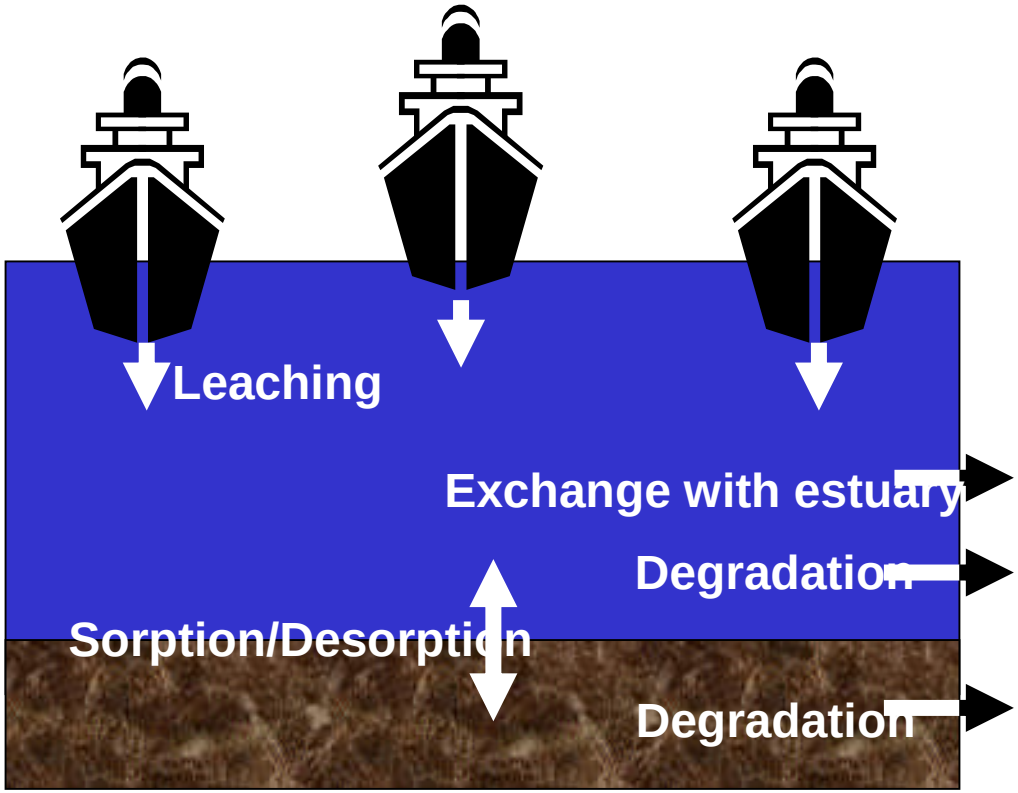
Simple, rapid
Guidelines available, little expertise needed
Help identify where there is potential risk
Incorporate simple, worst-case assumptions

to higher tiers

complex mathematical models
Provides a more realistic assessment of exposure
few guidelines available, expertise and experience needed

Assessing exposure

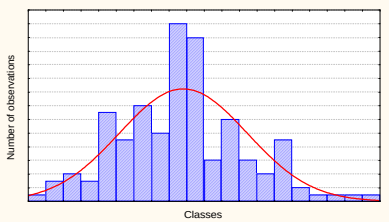
Monitoring

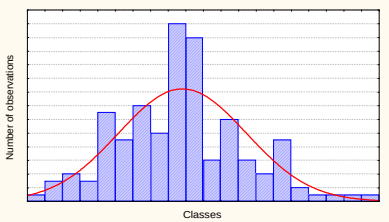


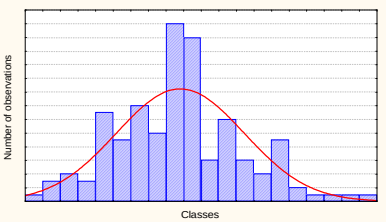
Modelling

Standard approach to modelling exposure

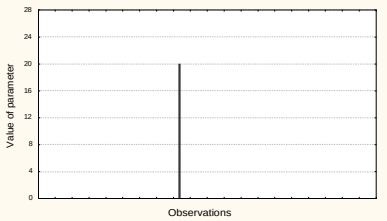
Distribution of input parameters

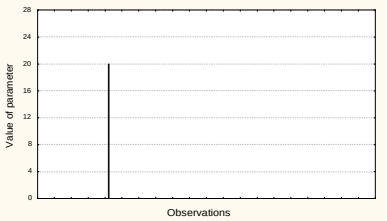


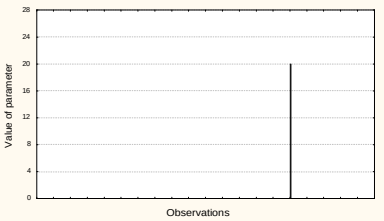




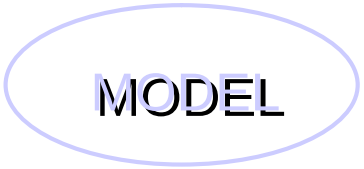
Choice of input parameters





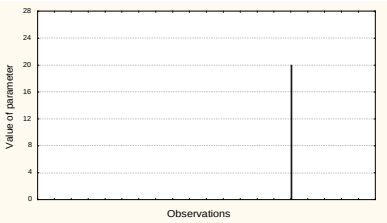


Single model run



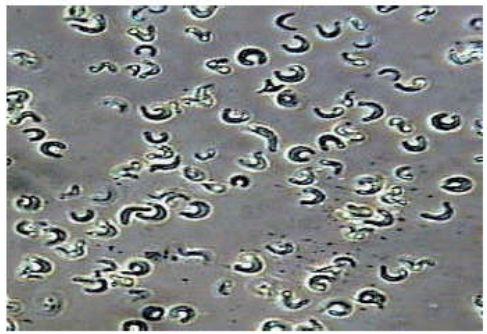
Single model output

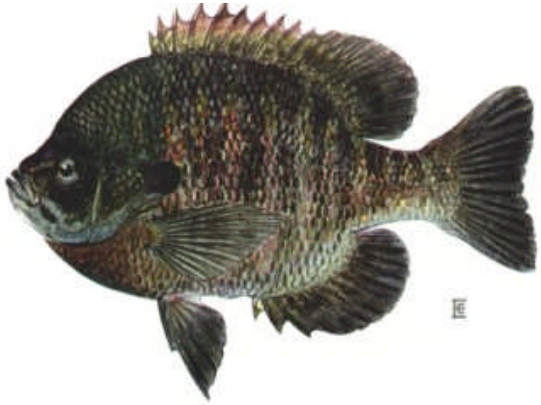
Deterministic



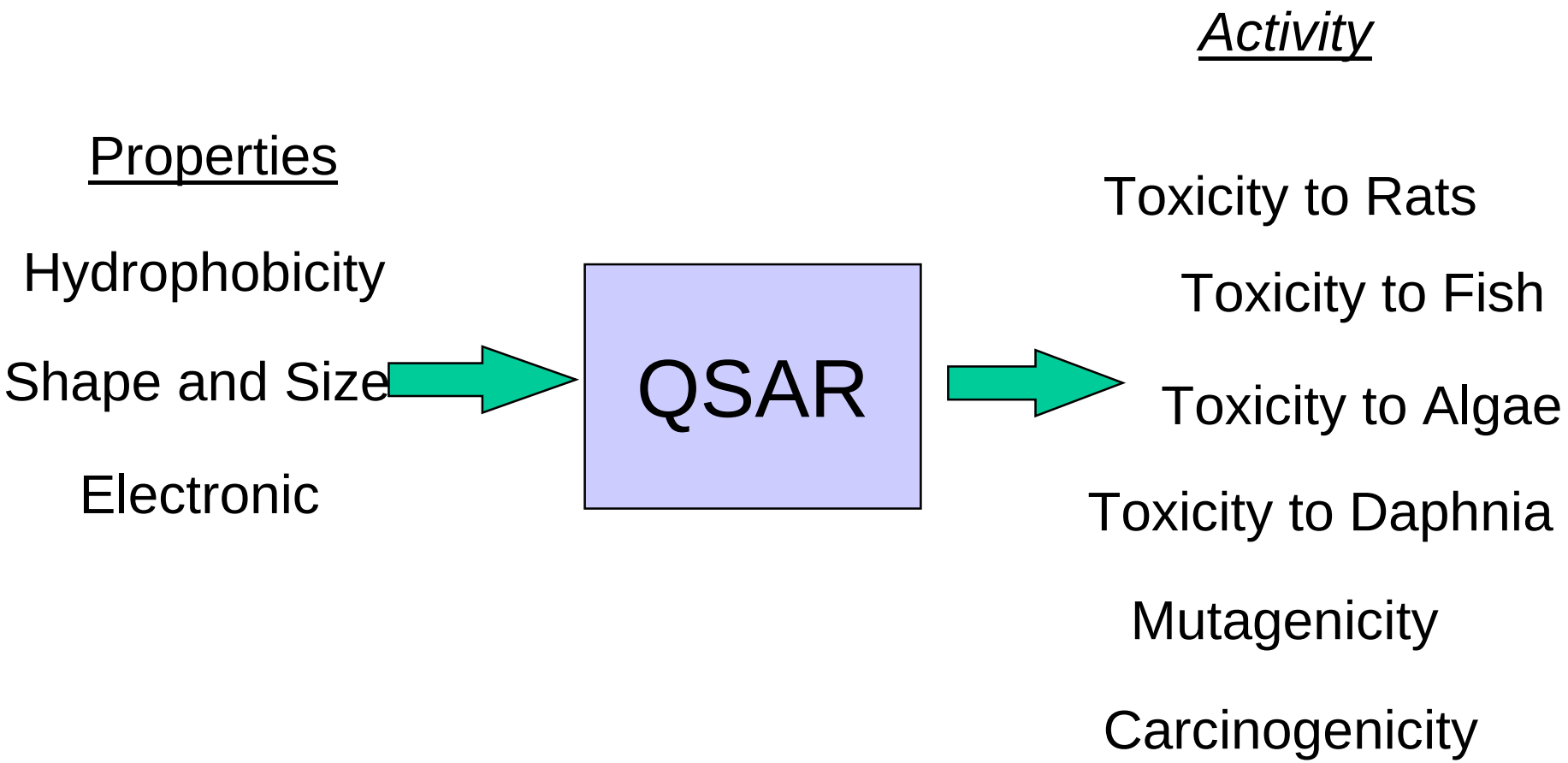
Regulatory Tests

- Fish
  - 96 h LC50
  - Chronic ELS
  - Full life cycle
- Invertebrates
  - Daphnia 48 h EC50
  - Daphnia 21 d Study
- Algae 96 h EC50





Predictive methods will also play a role

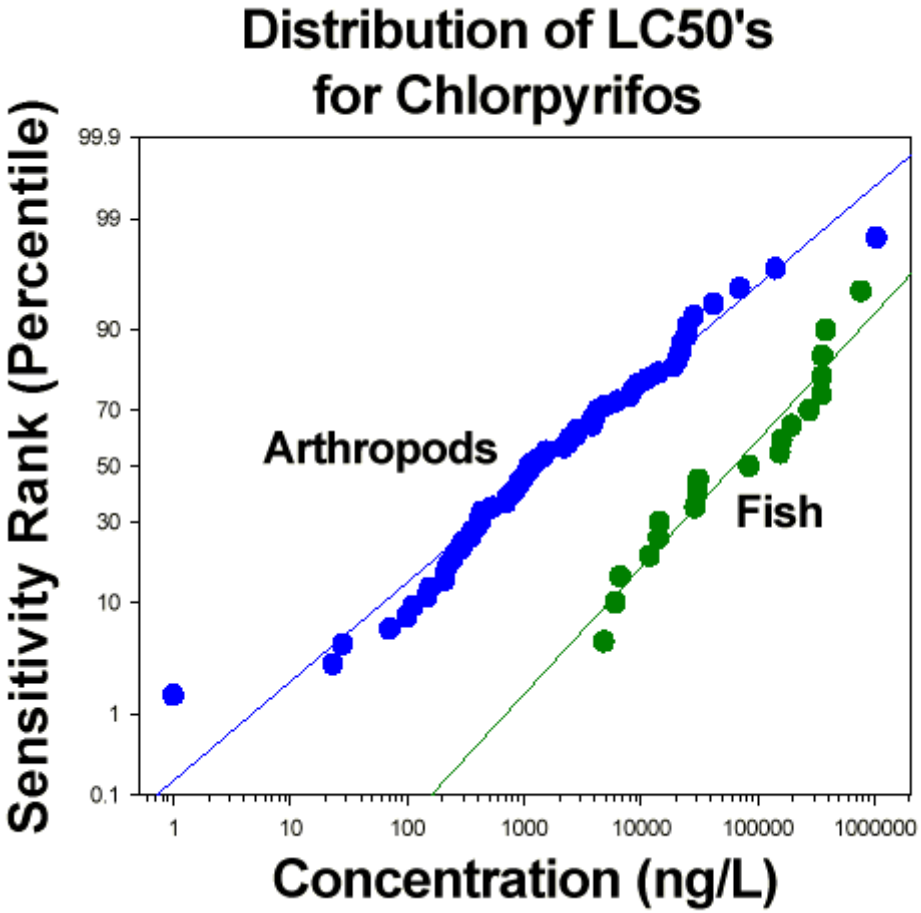


Uncertainties in effects testing

- Tests performed at constant concentrations
- Relative sensitivity of test species not known
- Time to effects not known in relation to exposure profile
- Effects characterised for single organisms not populations

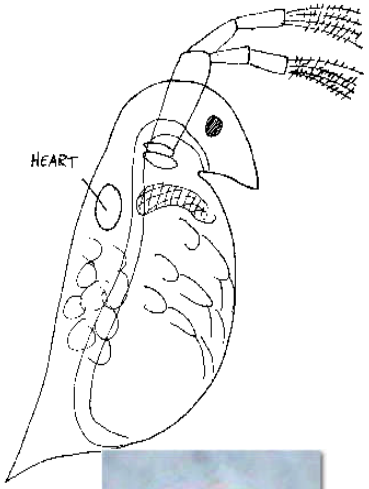
Apply a protective safety factor

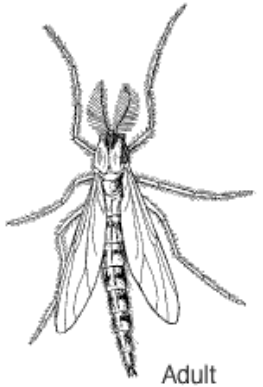
Distribution of effects

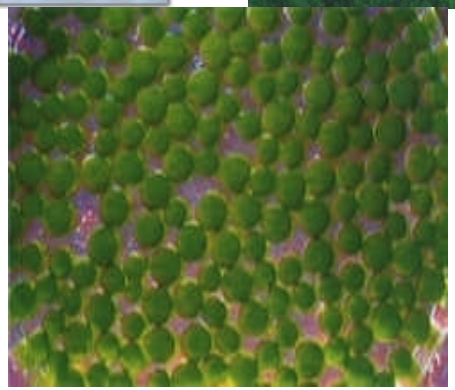


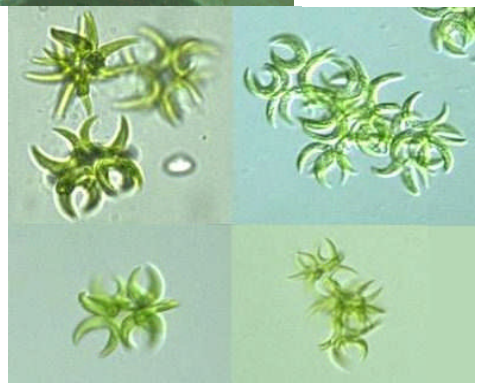
Source: ECOFRAM

Mesocosms









Coping with the uncertainties

$$PNEC = ECx/AF$$

Endpoint type	Assessment factor
QSAR	1000
Acute	100
Chronic	10
Mesocosm	1

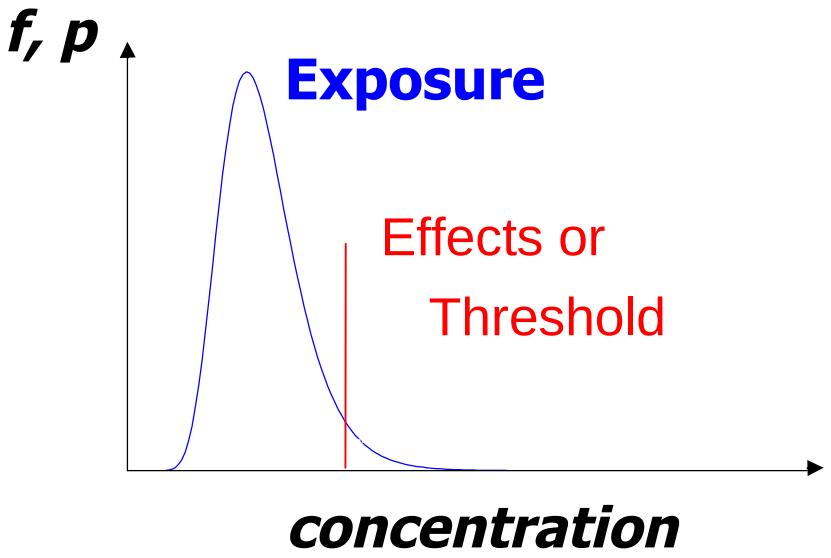
Characterising risk

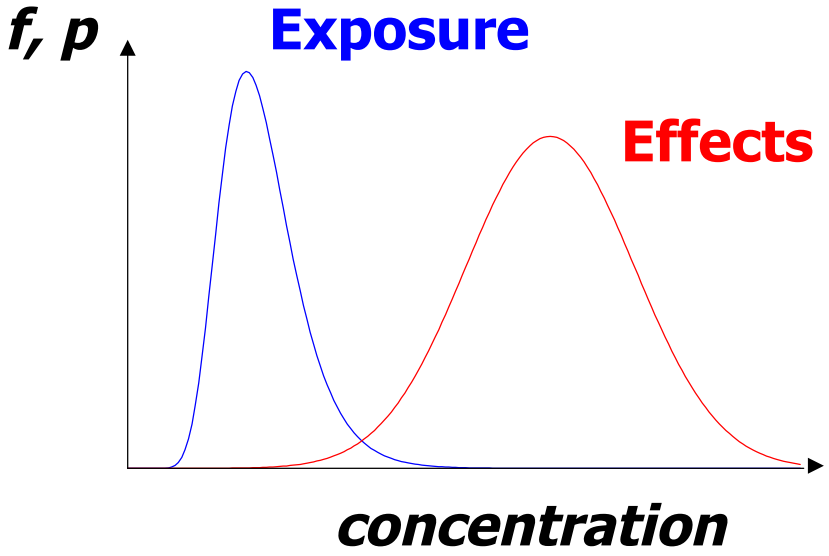
$$\text{Risk Characterisation Ratio} = \frac{\text{Exposure Concentration}}{\text{Predicted no-effect concentration}}$$

RCR > 1 = unacceptable risk

RCR < 1 = acceptable risk

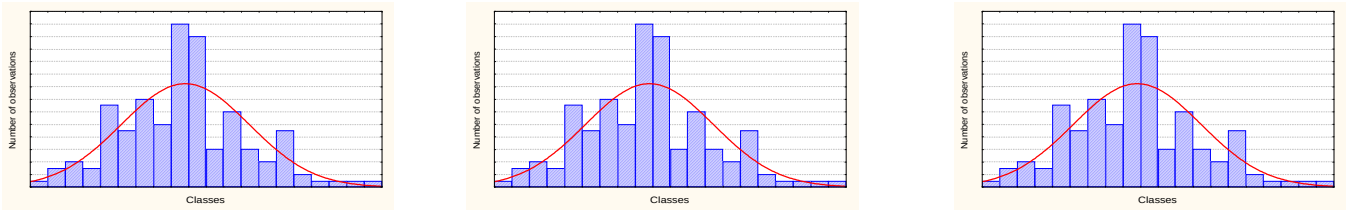
Becoming probabilistic



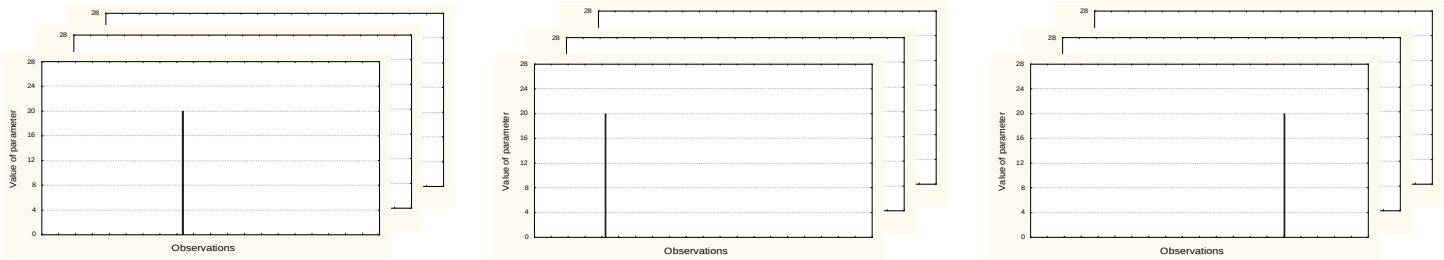


Monte-Carlo Approach

Distribution of input parameters



Sampling of input parameters

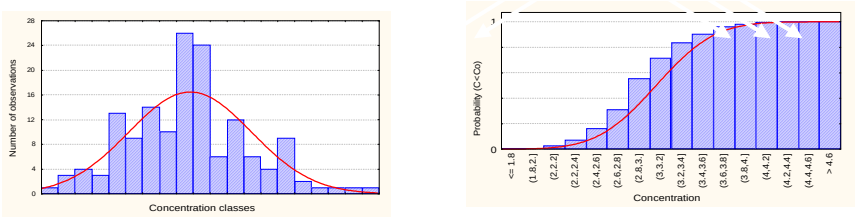


Multiple model runs

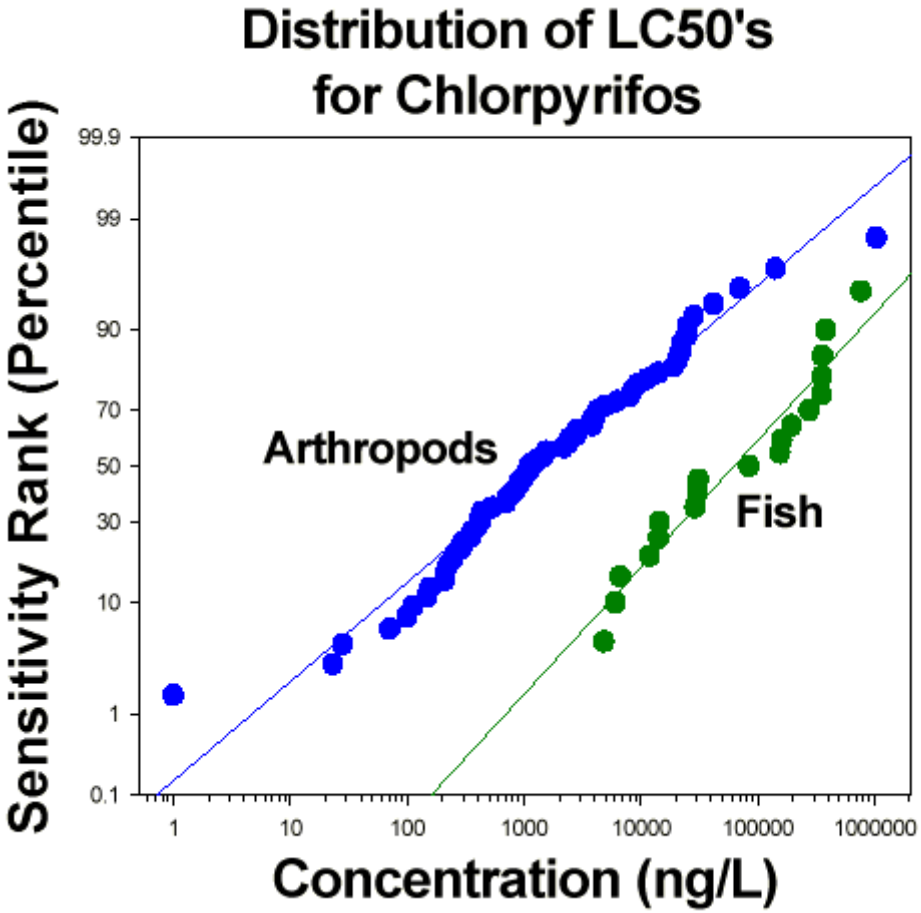
MODEL

Stochastic

Distribution of Model output

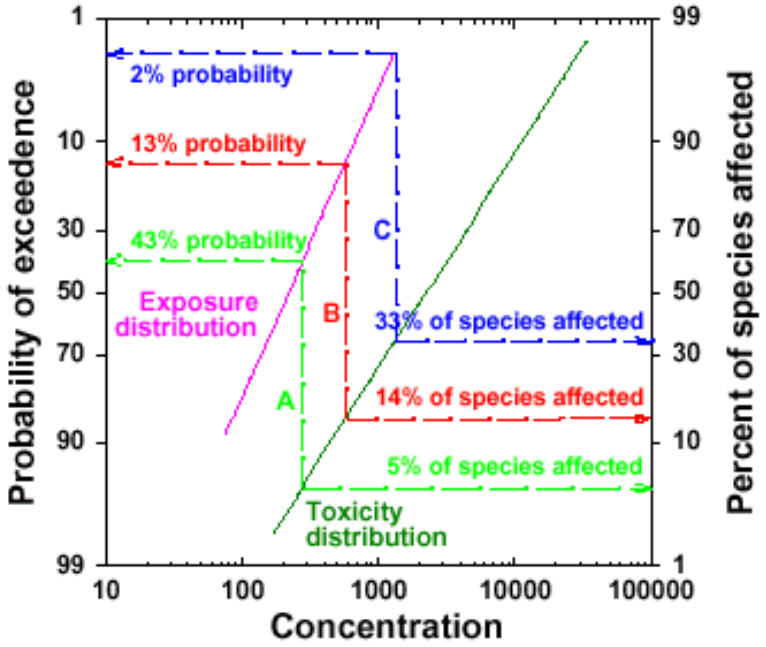


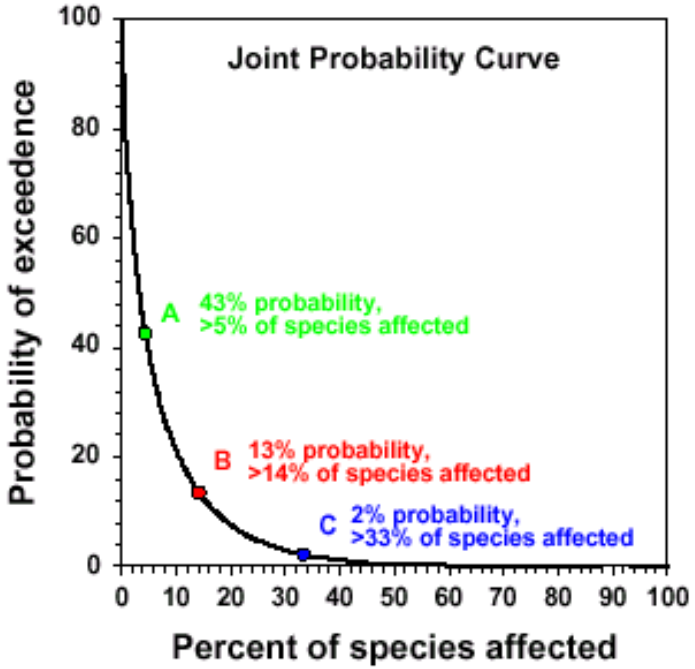
SSD's



Source: ECOFRAM

Joint probability curves





Case study: higher tier modelling for a pesticide

- Winter wheat herbicide for use in the UK
- Acidic – relatively mobile – impersistent
- Potential for leaching from fields to surface waters via artificial drains

Potential impacts on higher aquatic plants

48-hr no observed effect conc (NOEC) for Lemna = 1.0 μg l^{-1}

First-tier concentration in drainflow = 0.63 μg l^{-1}

Toxicity:exposure ratio

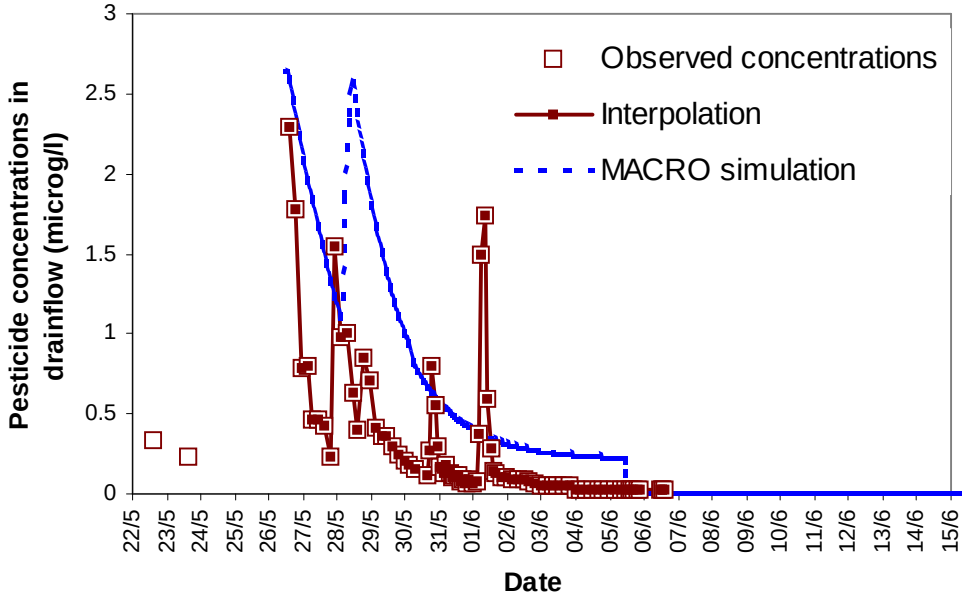
= effects conc / exposure conc

= 1.0 / 0.63 = 1.6

('Safe' threshold is >10)

Field study

Monitor pesticide in drainflow and an adjacent stream at a representative site

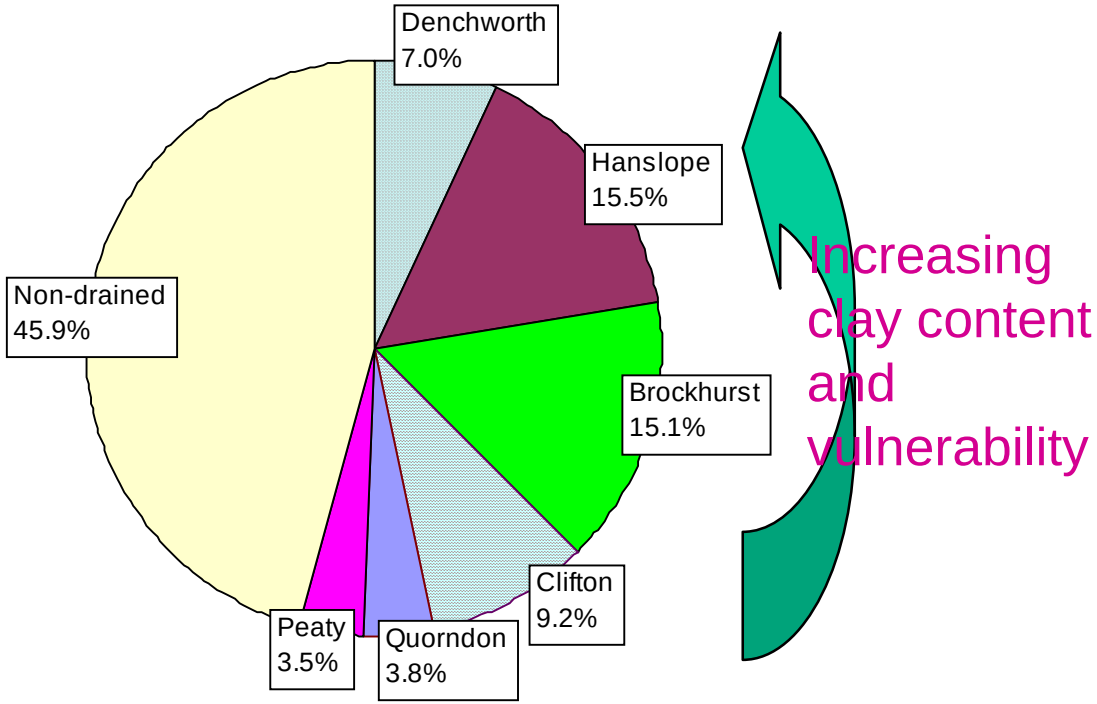


Test model in predictive mode

Simulated maximum within 12% of observed

Probabilistic exposure assessment

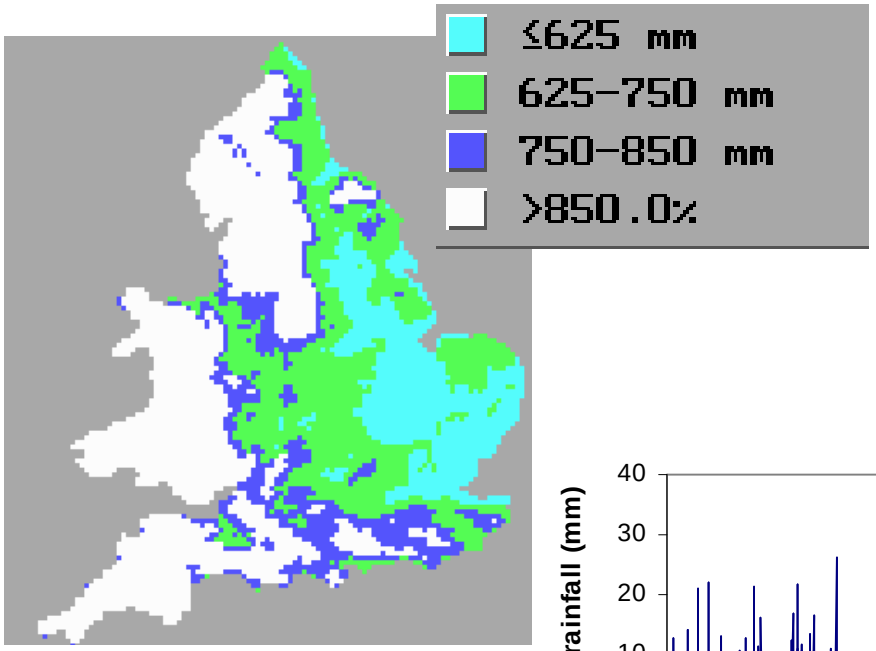
Wheat area divided into seven soil classes



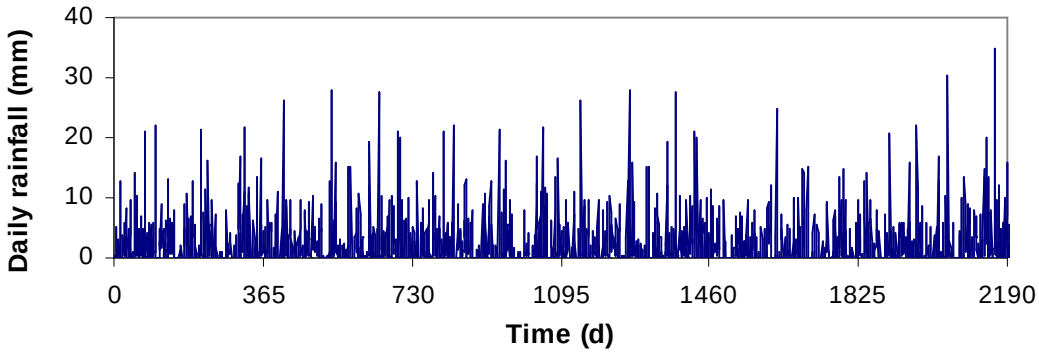
Model parameterised for each of the mineral, drained soils

Probabilistic exposure assessment

Wheat area divided into three climatic classes



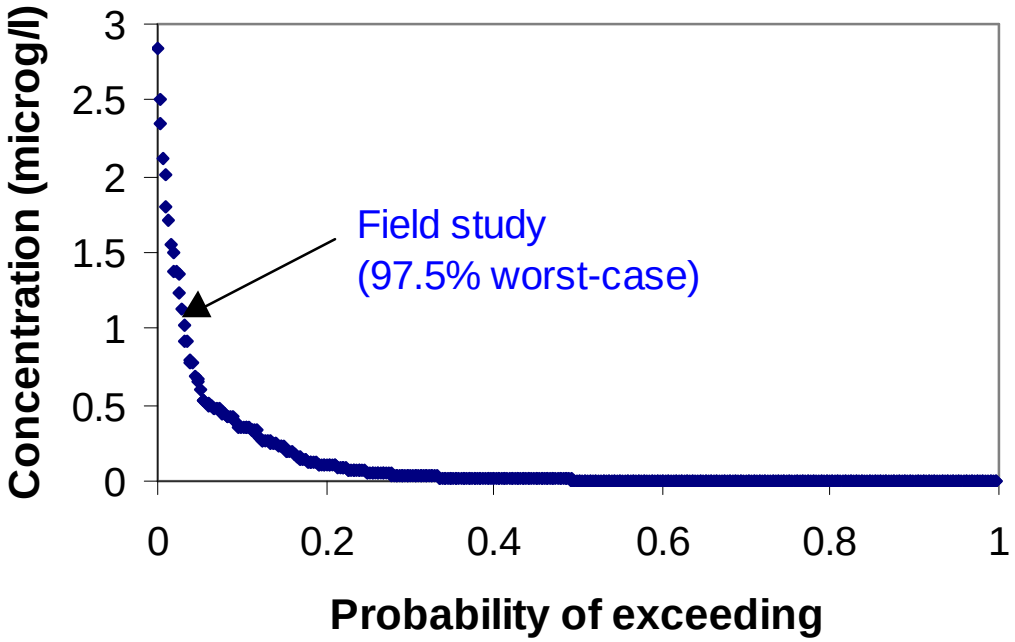
30 years' weather data for each



Probabilistic exposure assessment

30-year model runs for each of 15 soil-climate scenarios (~450 hours processing time in all)

Cumulative frequency distribution of maximum daily concentrations in each year simulated



450 data points

Probabilistic risk characterisation

***Lemna gibba* shown to be most sensitive species**

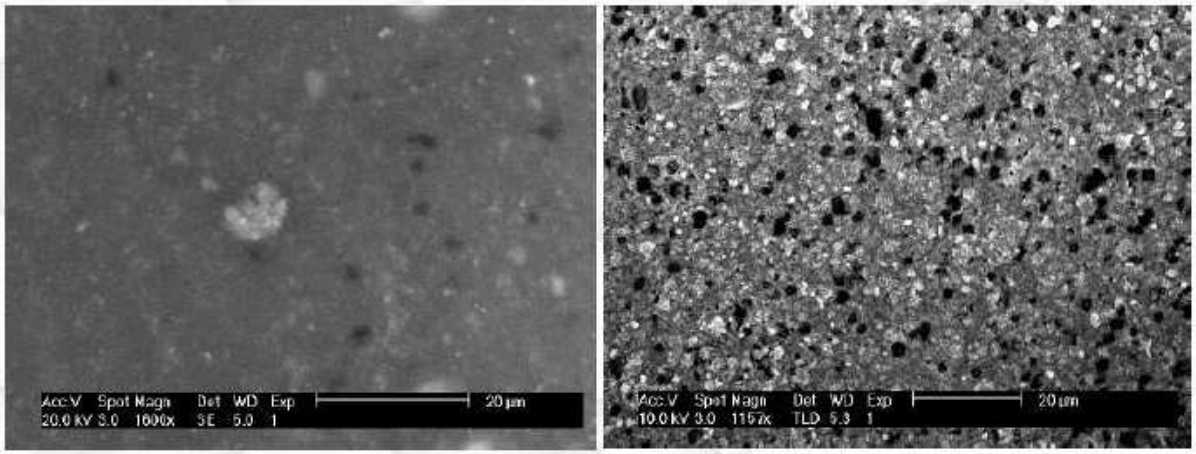
7-day EC50 = 2 μg/l; recovery within 14 days at concentrations up to 7 μg/l

Maximum exposure conc^{n}	Potential for effect	Potential for recovery	Relative abundance
<0.2 μg/l	Negligible	-	91.8%
0.2 - 2.0 μg/l	Very unlikely	Yes	7.1%
2.0 - 7.0 μg/l	Possible	Yes	1.1%
>7.0 μg/l	Possible	No	0%

Can we do this for an ENP?

Will we reach the right conclusion?

What do we assess?

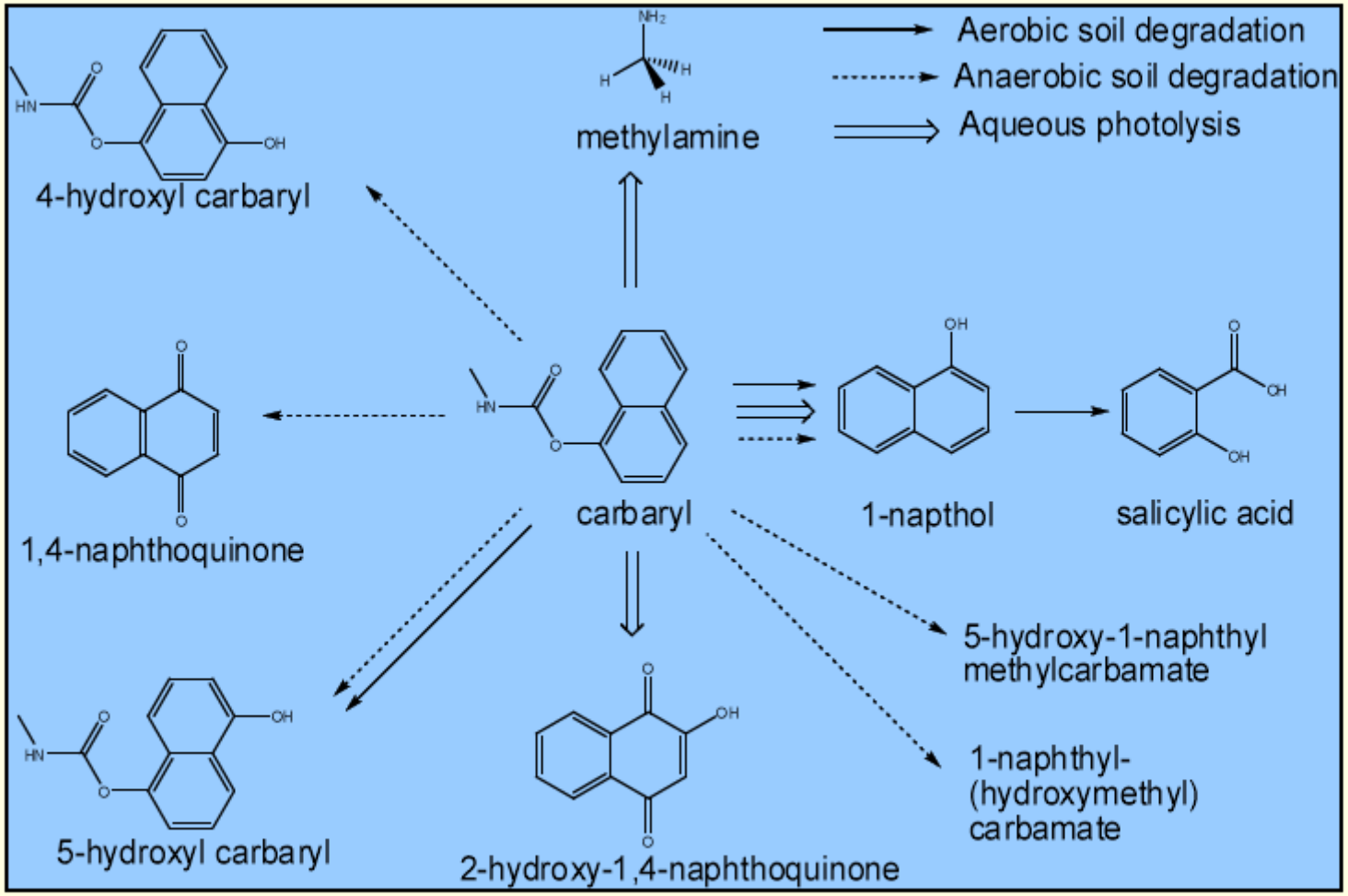


WetSEM SEM

- Raw ENP
- ENP in product
- Aggregate
- Ionic material
- Mixture of the above
- Infinite possibilities

In cooperation with Christiane Lorenz (ETH Zürich)

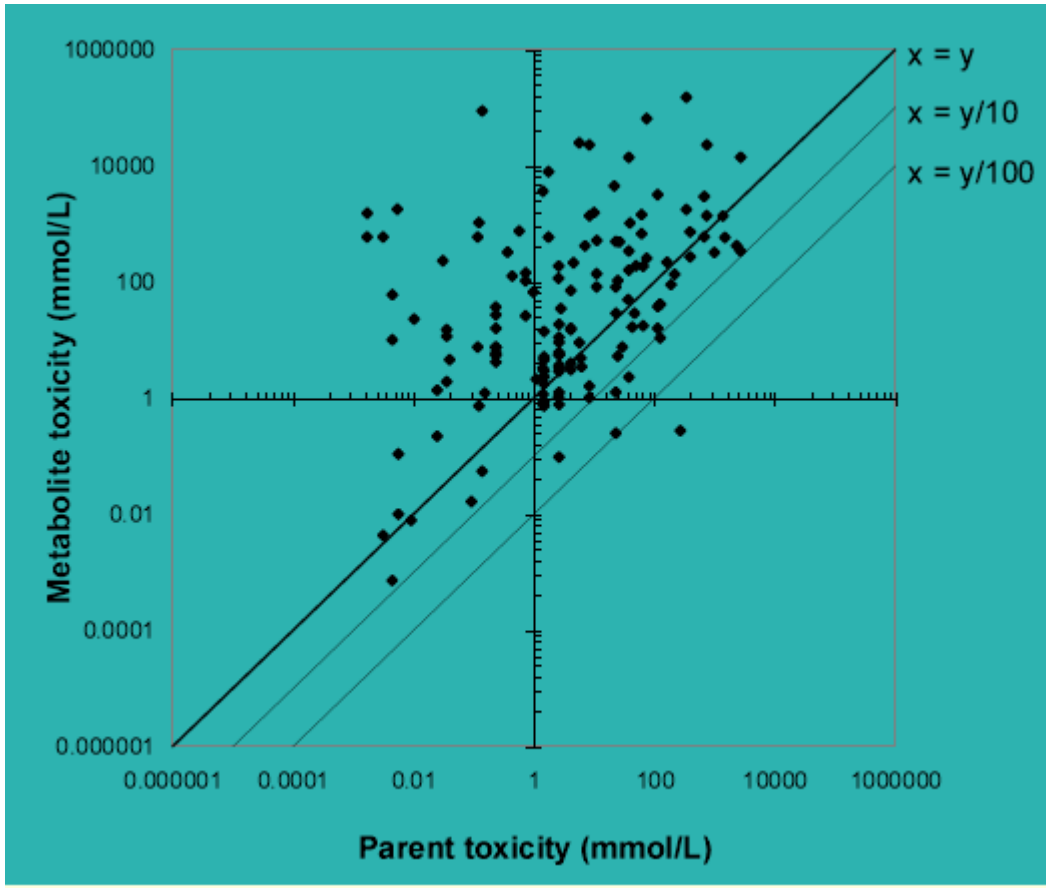
It’s not just a nano problem

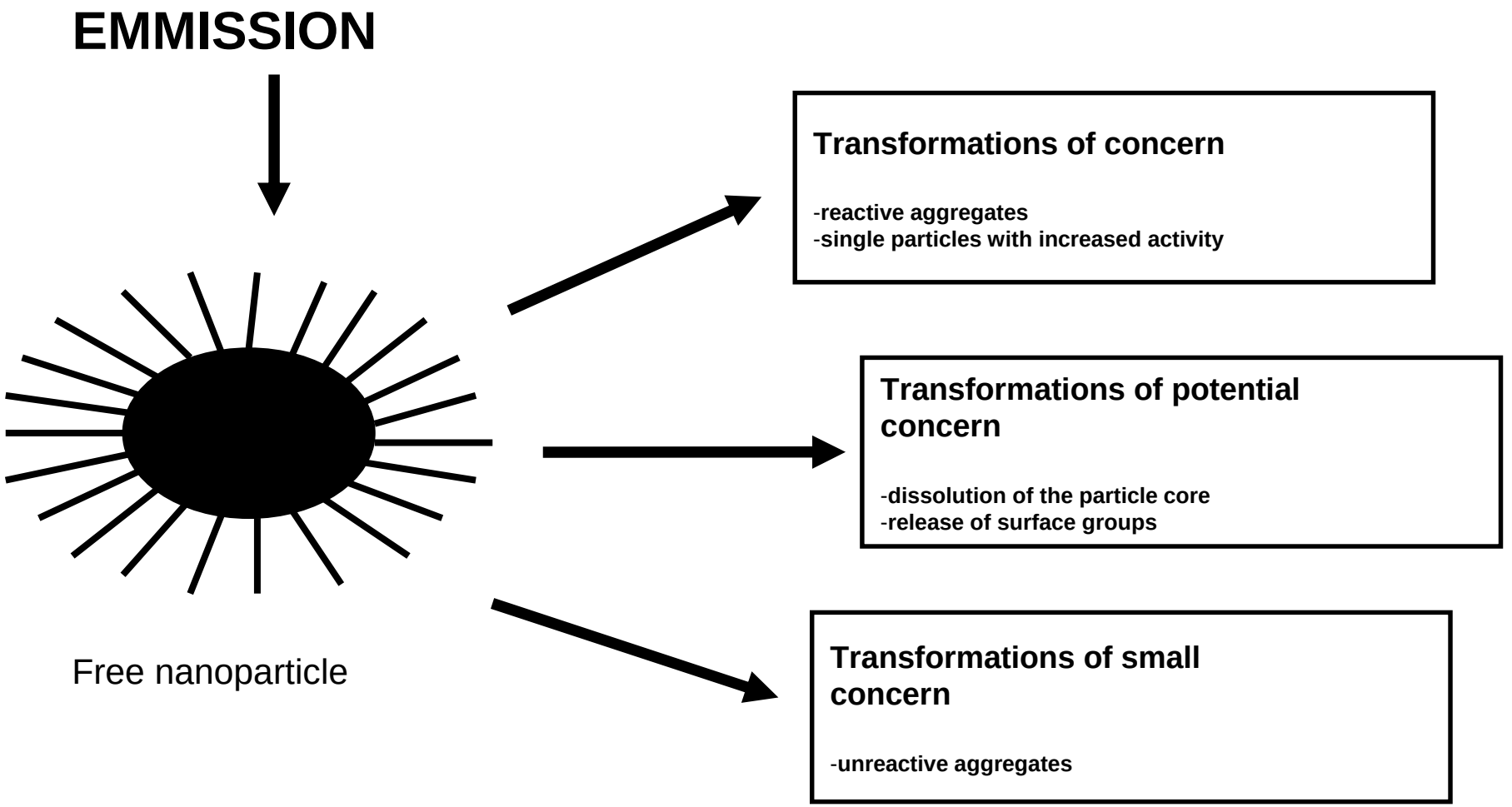


Derived from Roberts and Hutson 1999

Components assessed in traditional ERA

- Parent
- TPs > 10%
- 'Relevant' TPs
- Properties and functionality can be highly informative




EMMISSION
Free nanoparticle
Transformations of concern
-reactive aggregates
-single particles with increased activity
Transformations of potential concern
-dissolution of the particle core
-release of surface groups
Transformations of small concern
-unreactive aggregates

Exposure assessment?

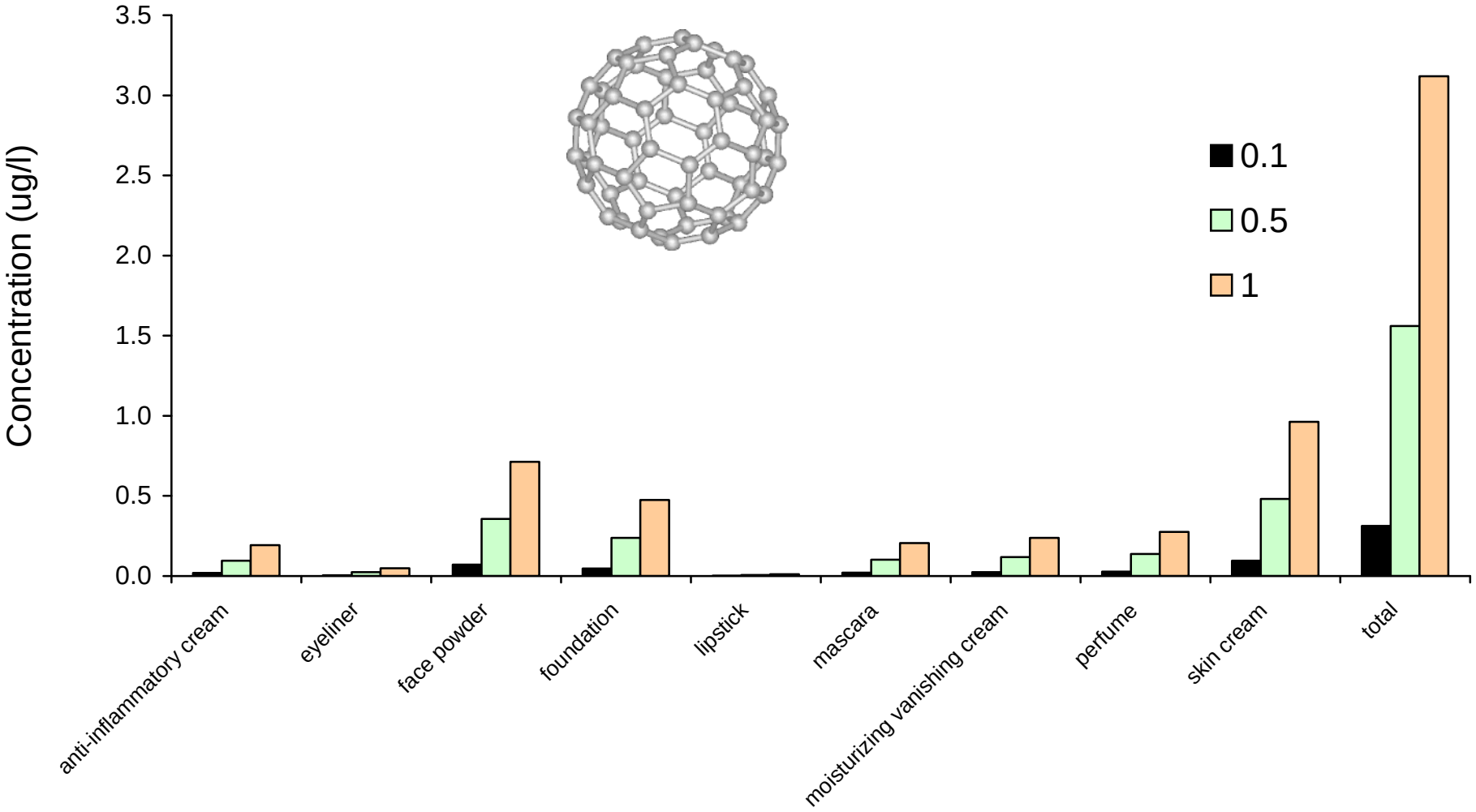
Cosmetics
Paints & coatings
Catalysts & lubricants
Water treatment
Security printing
Textiles & sports items
Medical & healthcare
Food/ food packaging
Plant protection products
Veterinary medicines
Construction materials
Electrical & electronics
Fuel cells & batteries
Paper manufacturing
Weapons & explosives

Cosmetics
Paints & coatings
Catalysts & lubricants
Water treatment
Food & food packaging
Plant protection products
Agrochemicals
Veterinary medicines

Applications

Application	Nanomaterial	Concentration (%)
Personal care products (sunscreens, toothpaste, soap, shampoo, face creams	TiO_2 Hydroxyapetite Ag Fullerene C_{60}	5 15 0.02 0.05 – 0.25
Paints and coatings	TiO_2 SiO_2 ZnO Alumina Silica/Alumina	5 15 1-10 0.5-5 7-10
Medical	Ag API	5 1-20
Food and packaging	nanoclay	5
Fuel catalysts	CeO2	5-10

Predicted Exposure to ENPs



Exposure predictions

	Water (μg/l)	Soil (μg/kg)	Air (mg/m^3)	Aggregate size (nm)
Ag	0.010	0.43	-	-
AlO_3	0.0002	0.01	-	-
Au	0.14	5.99	-	-
CeO_2	<0.0001	<0.01	6 x 10^{-7}	-
fullerenes	0.31	13.1	-	75 (25-500)
hydroxyapatite	10.1	422	-	-
latex	103	4307	-	-
organo-silica	0.0005	0.02	-	-
SiO_2	0.0007	0.03	-	205 (135-510)
TiO_2	24.5	1030	7	330 (175-810)
ZnO	76	3194	-	480 (420 – 640)

The real world is much more complex

- Aggregation
- Dissolution
- Abiotic and biotic degradation of cappings
- Association with other materials or substances in the environment
- Constantly changing system
- Experimental approaches now available for assessing fate in a particular medium

Fate in Wastewater Treatment

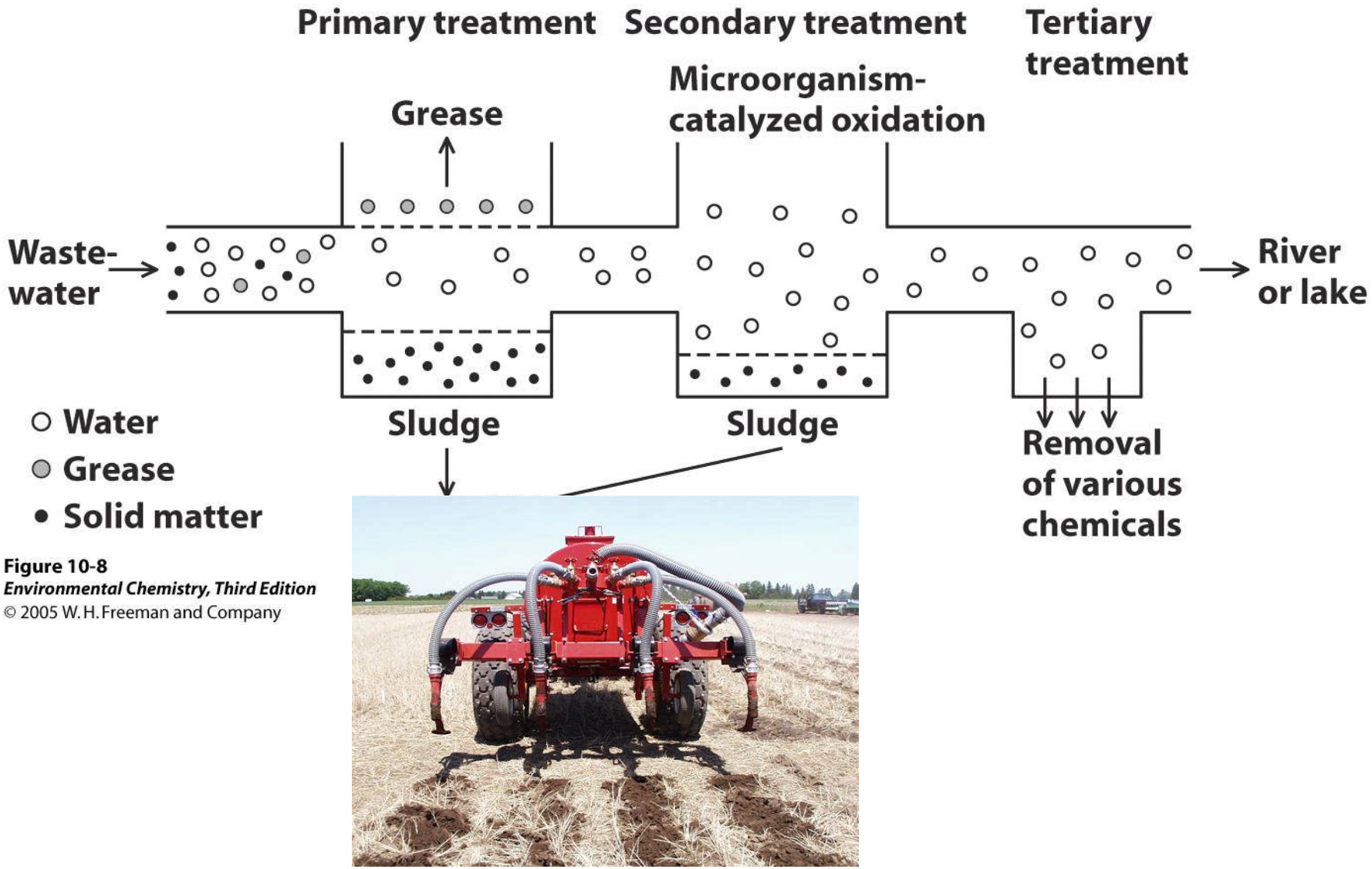


Figure 10-8
Environmental Chemistry, Third Edition

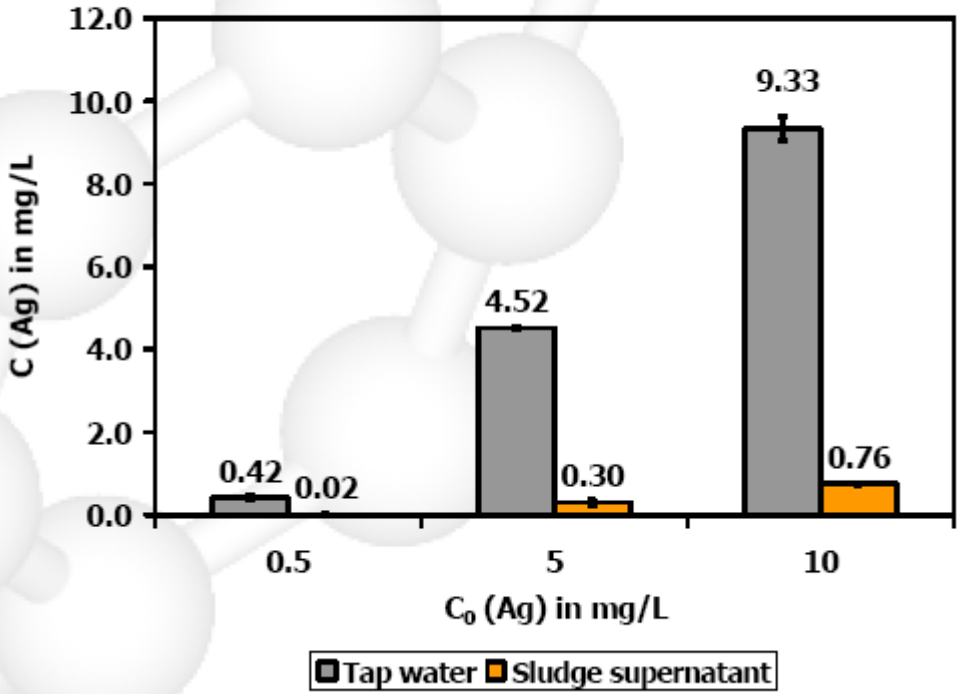
Fate in WWT

- Mixed liquor (mix of raw water & activated sludge), MLSS: 2 g/L, pH 7-7.5
- Tap water as reference, pH 7.8
- Spiked with Ag nanoparticles (Sigma Aldrich, < 100 nm): 0.5, 5, 10 mg/L (3 replicates, blanks, controls)
- 6h on shaker, left to settle
- Ag totals analysed by ICP-MS
- Size analysis by DLS, TEM, HDC-ICP-MS

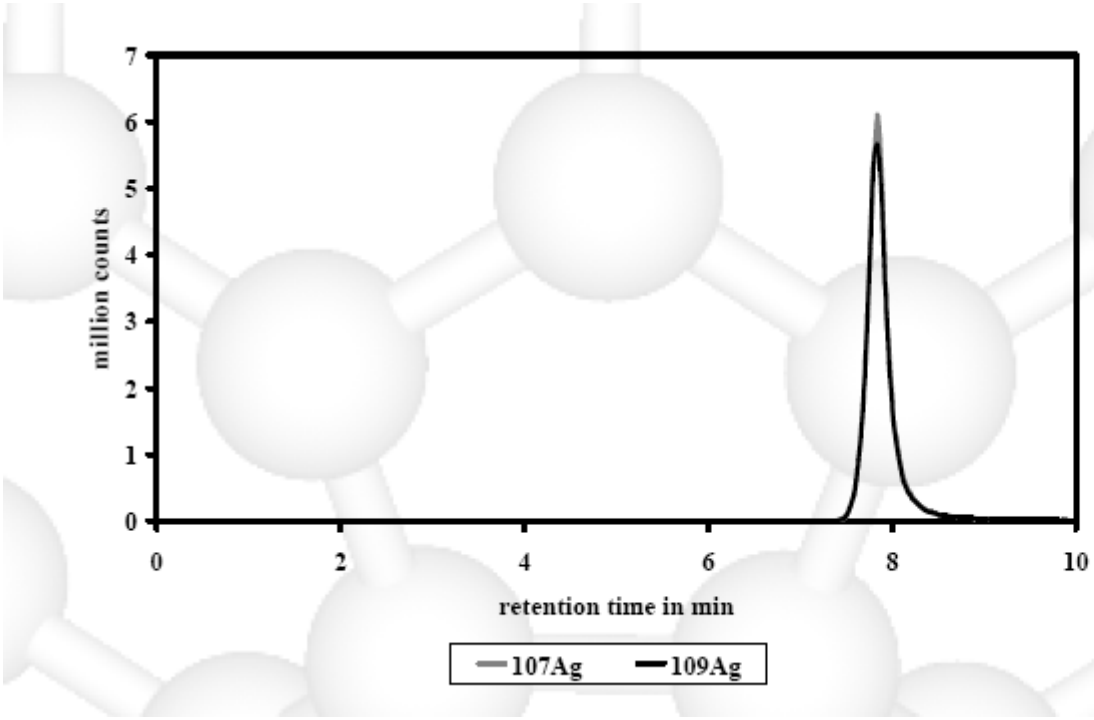
Broadholme Sewage Treatment Works near Northampton

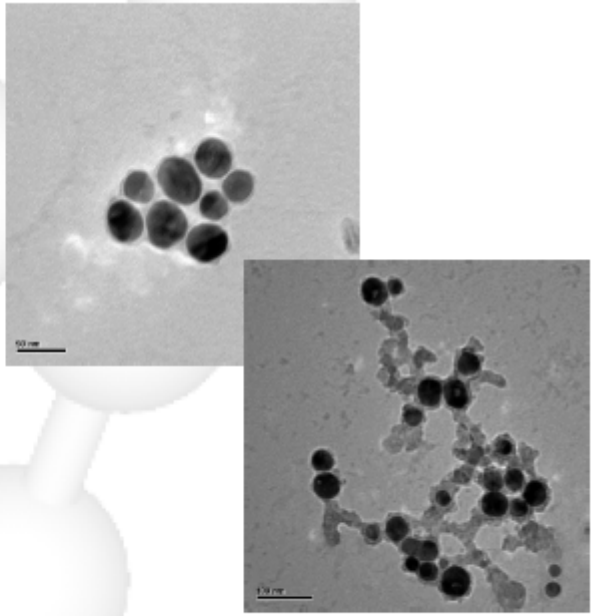
Fate in WWT

- Recovery for Ag in tap water ~ 90%
- Recovery for Ag in sludge supernatant ~ 5 %
- Most of Ag seems to partition to biomass
- Speciation of Ag in supernatant?

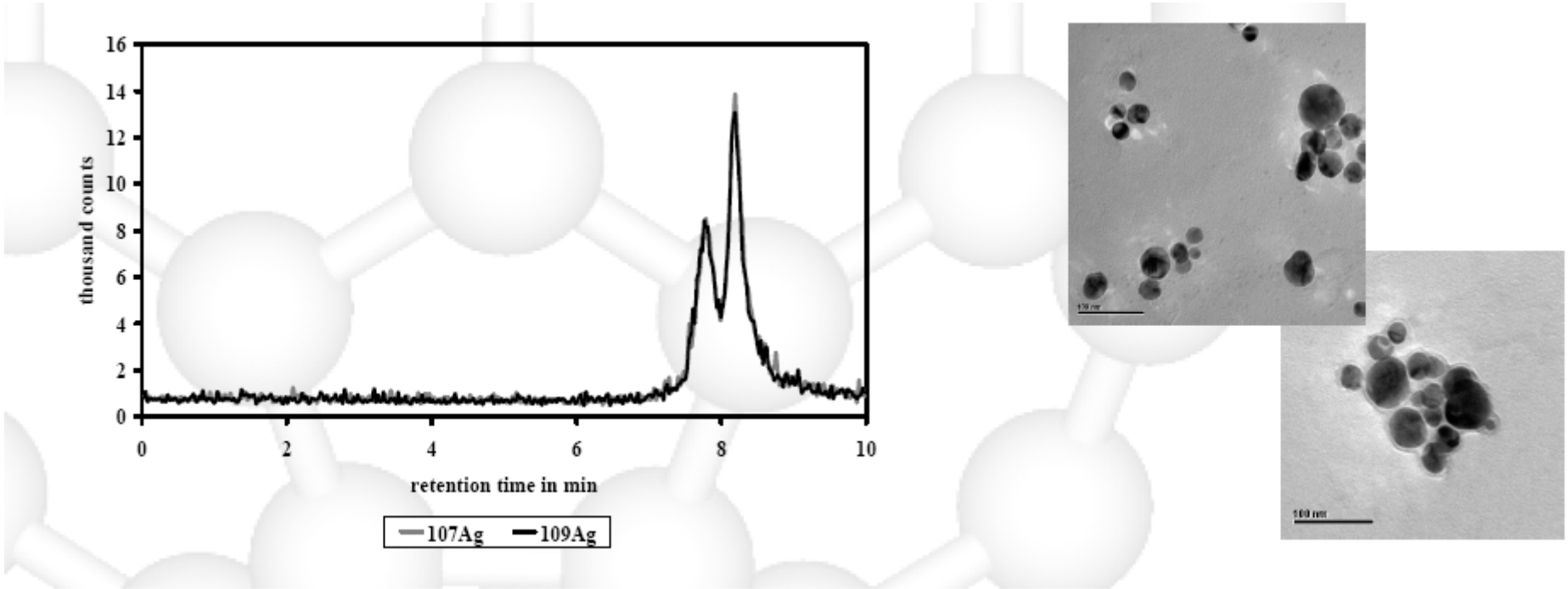


Analysis – Tap Water

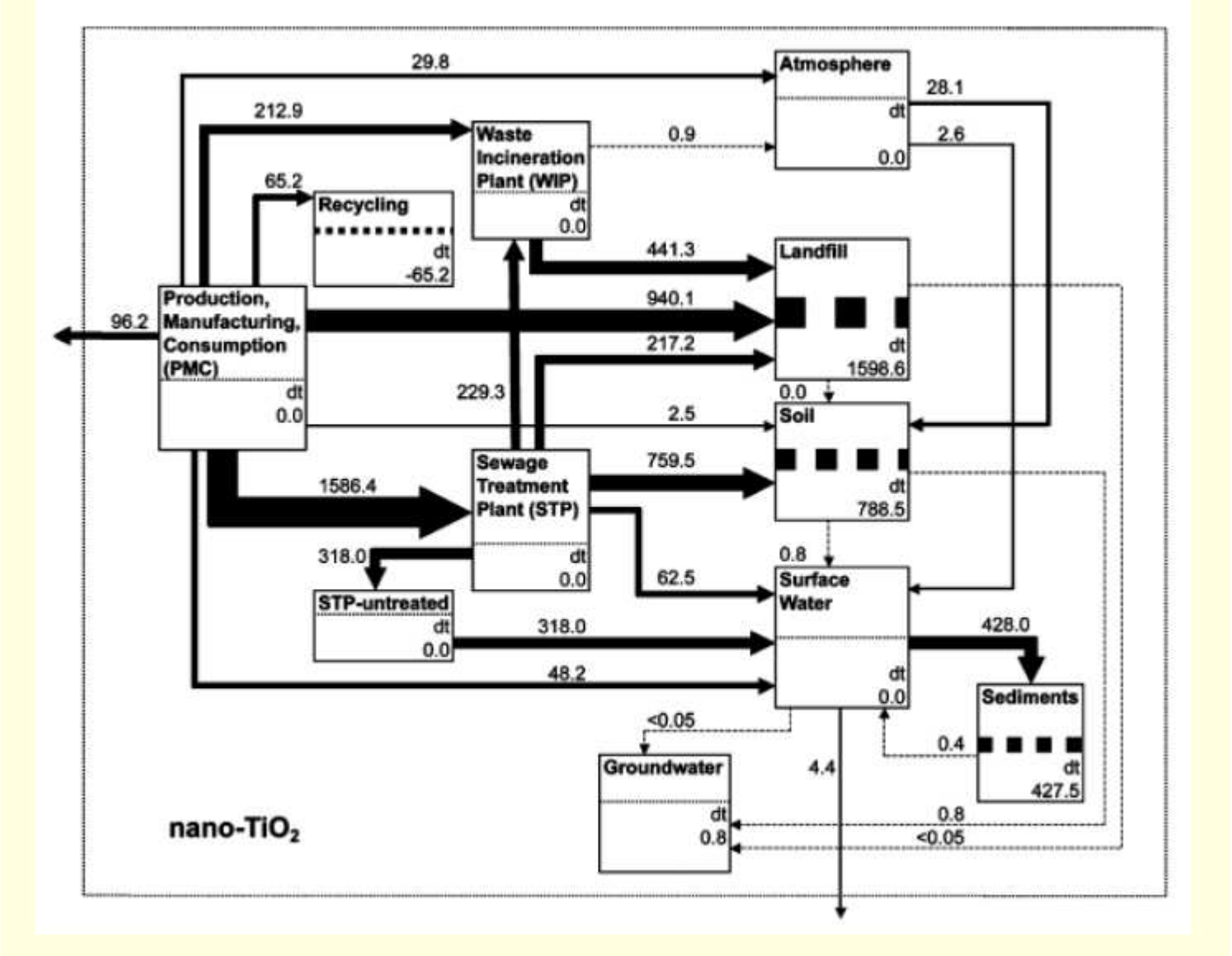




Analysis – sludge supernatant



More realistic modelling – Gottschalk et al

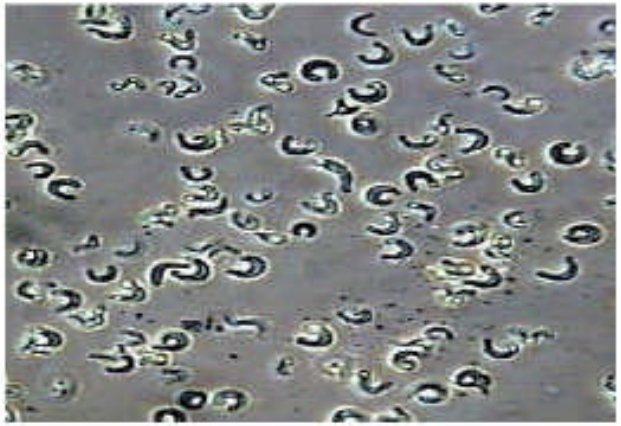


Exposure predictions

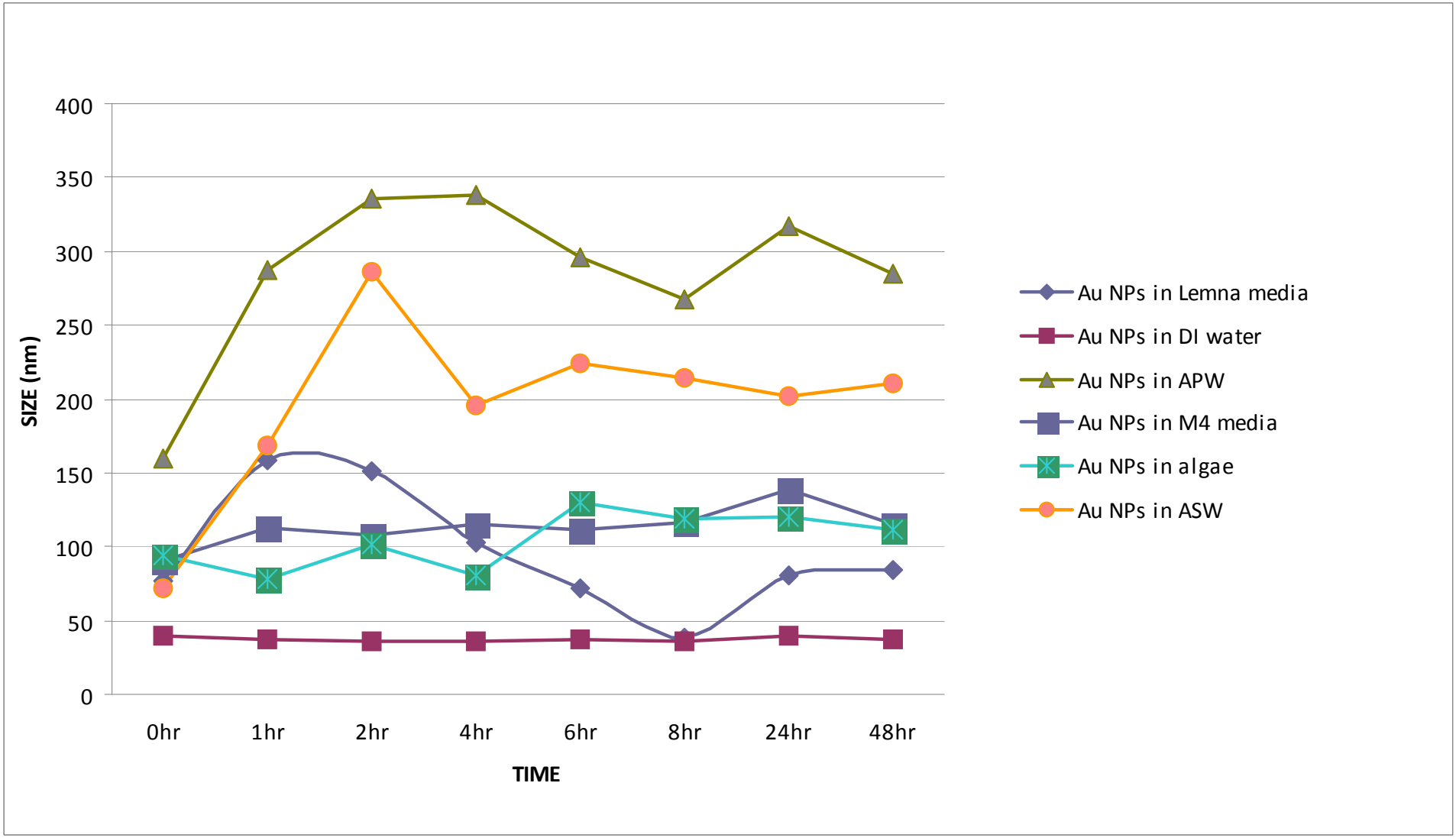
	Europe	US	Switzerland
TiO_2	0.015	0.002	0.28
ZnO	0.010	0.001	0.013
Ag	0.764	0.116	0.428
CNT	0.004	0.001	0.003

- Lower tier modelling of ENPs is possible
- Empirical data can be used to refine predictions
- Long way off having higher tier models

Are the effects tests appropriate?



Behaviour in standard media



Challenges

- Studies are done in standard media – speciation in the environment may be totally different
- The challenge will be to catch the toxic component
- May need to use media that are more 'natural' and representative
- In longer term we may need to develop approaches that allow us to assess the toxicity of different species

Bioaccumulation

- PBT assessment now incorporated into many ERA processes
- Bioaccumulation potential assessed based on Log Kow
- Probably not relevant for ENPs

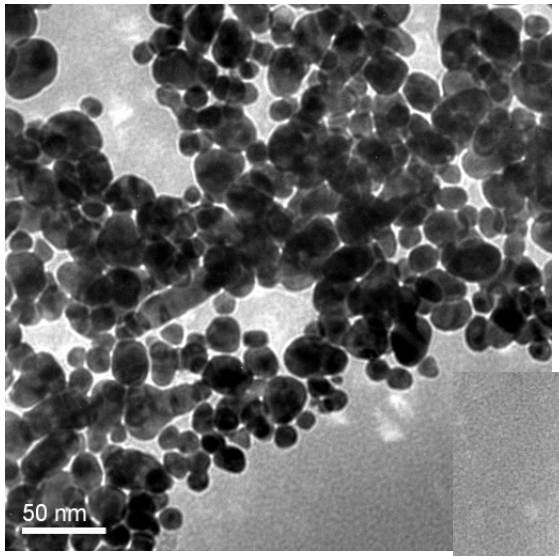

Size
matters

Uptake and particle properties

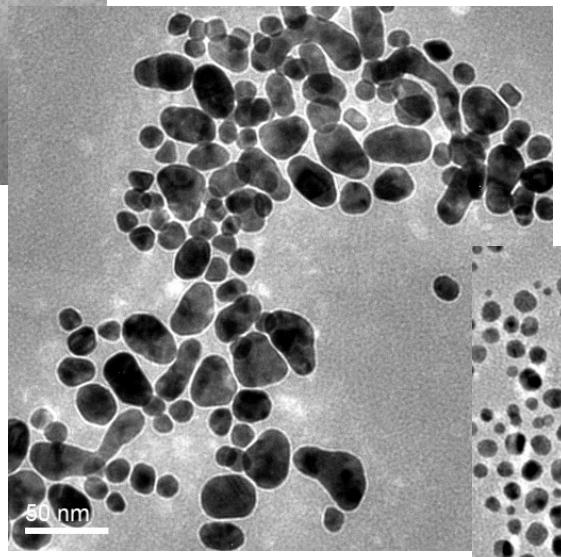
- Model Au particles synthesised by University of Alberta – 5 and 30 nm citrate or mercaptoundecanoic acid capped
- Uptake studies with *Daphnia magna* and *Lumbriculus variegatus*
- X-ray fluorescence analysis of the organisms at ANKA, Karlsruhe

Lumbriculus

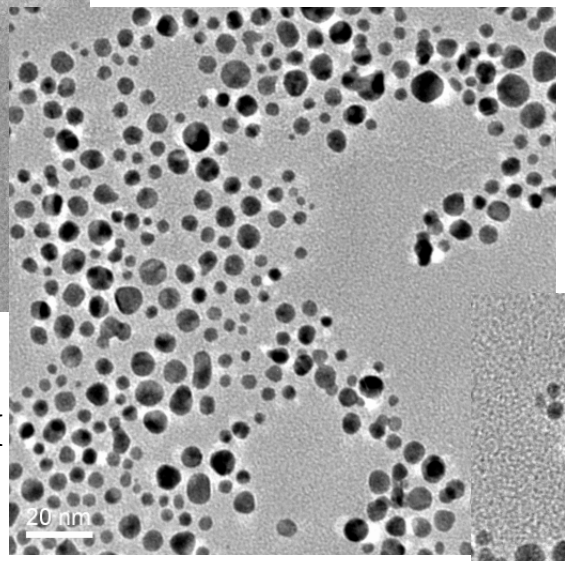
Model Au particles



30 nm, Citric

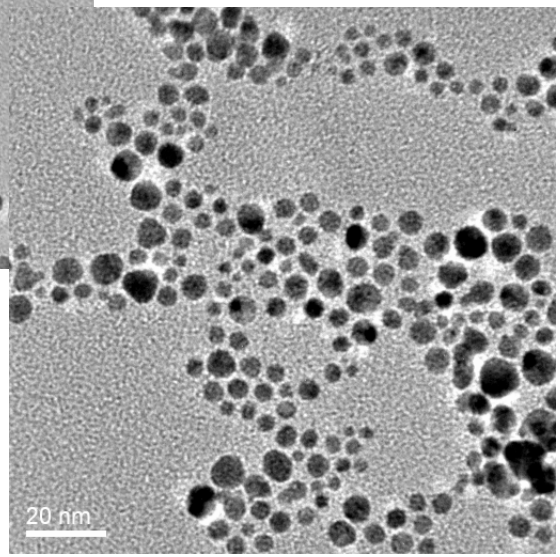


30 nm
SH(CH2)10COOH

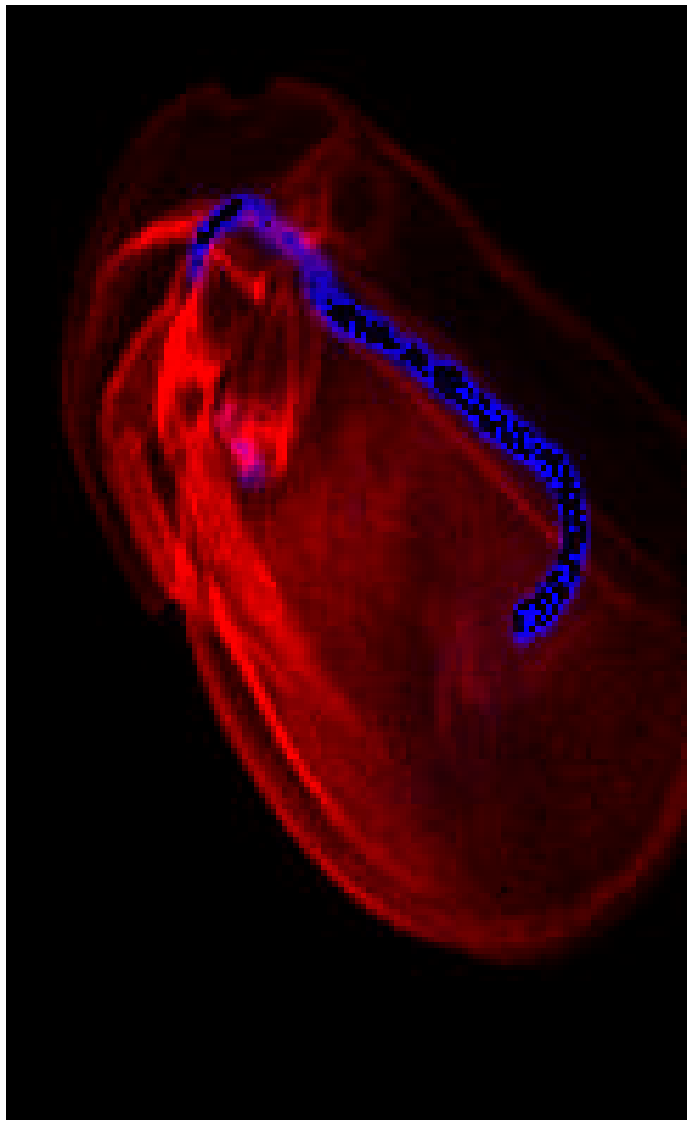


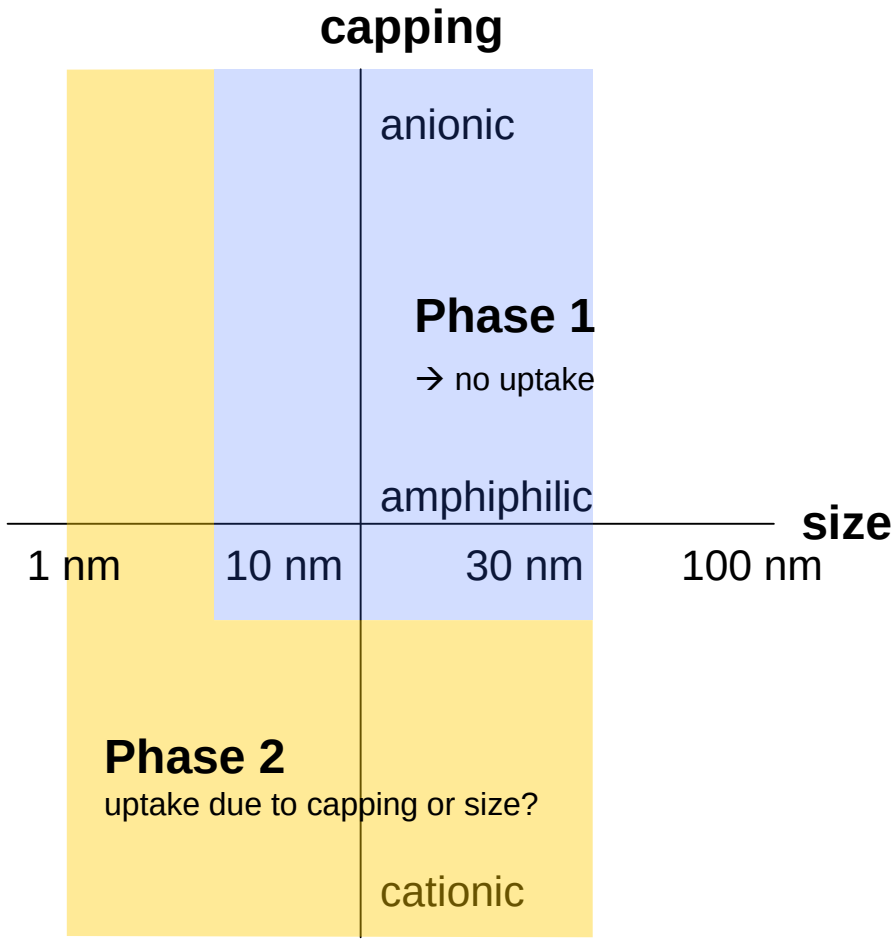
5 nm, Citric

5 nm
SH(CH2)10COOH



Synchotron X-Ray fluorescence analysis of a daphnia





Characterising risk: an example

Fullerenes

100 mg/l

Daphnids – mortality (Zhu et al., 2006; Oberdorster et al., 2006)

10

Bacteria – respiration (Fortner et al., 2005)

Daphnids – molting and reproduction (Oberdorster et al., 2006)

1.0

Fish - biomarkers (Oberdorster et al., 2006)

Bacteria - growth (Fortner et al., 2005)

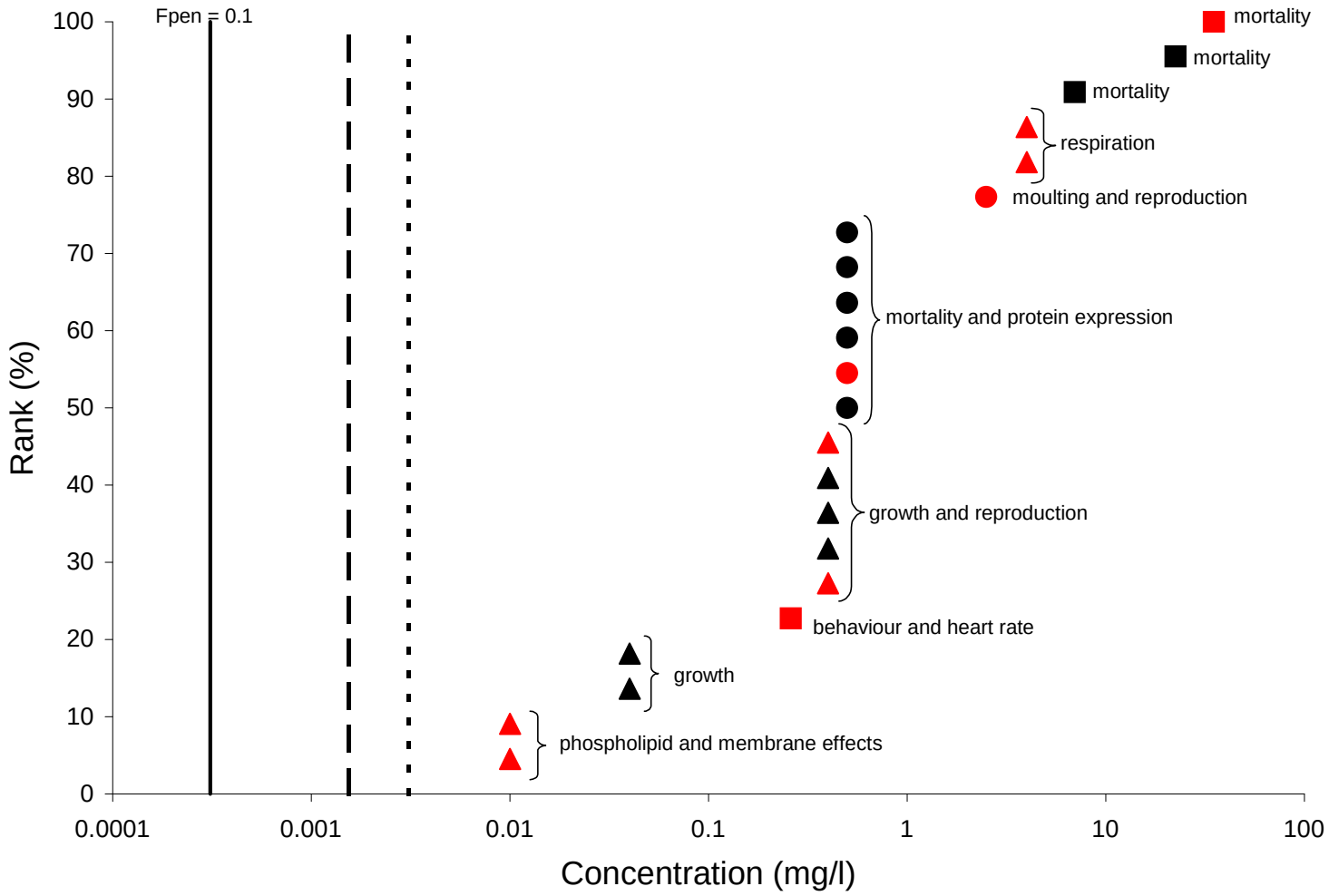
Daphnids – hopping, heart rate, appendage movement (Lovern et al., 2007)

0.1

Bacteria - phospholipids & membrane phase behaviour (Fang et al., 2007)

0.01 mg/l

Fullerenes


Fpen = 0.1
Rank (%)
100
90
80
70
60
50
40
30
20
10
0
0.0001
0.001
0.01
0.1
1
10
100
Concentration (mg/l)
mortality
mortality
mortality
respiration
moulting and reproduction
mortality and protein expression
growth and reproduction
behaviour and heart rate
growth
phospholipid and membrane effects

Closing comments

- ERA required for a range of product types
- Tiered approach is typical
- General ERA paradigm appropriate for ENPs
- Lower tier assessment is possible
- Long way off having high tier approaches
- ERAs for traditional chemicals make many assumptions – complexity is often glossed over

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