

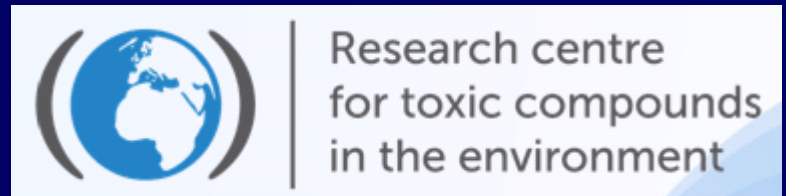
Cyanobacteria and their toxins: ecological and health risks

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www.recetox.muni.cz

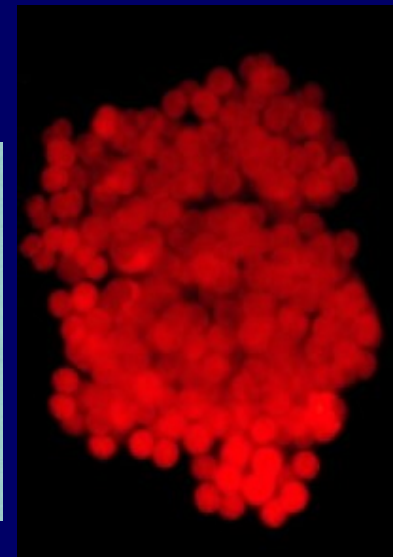
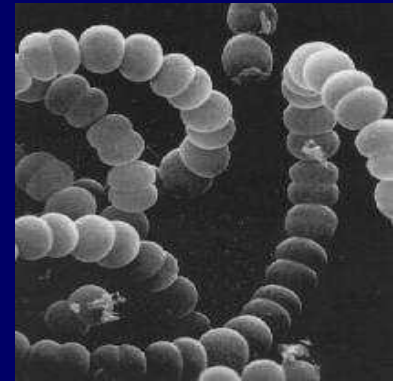
www.cyanobacteria.net



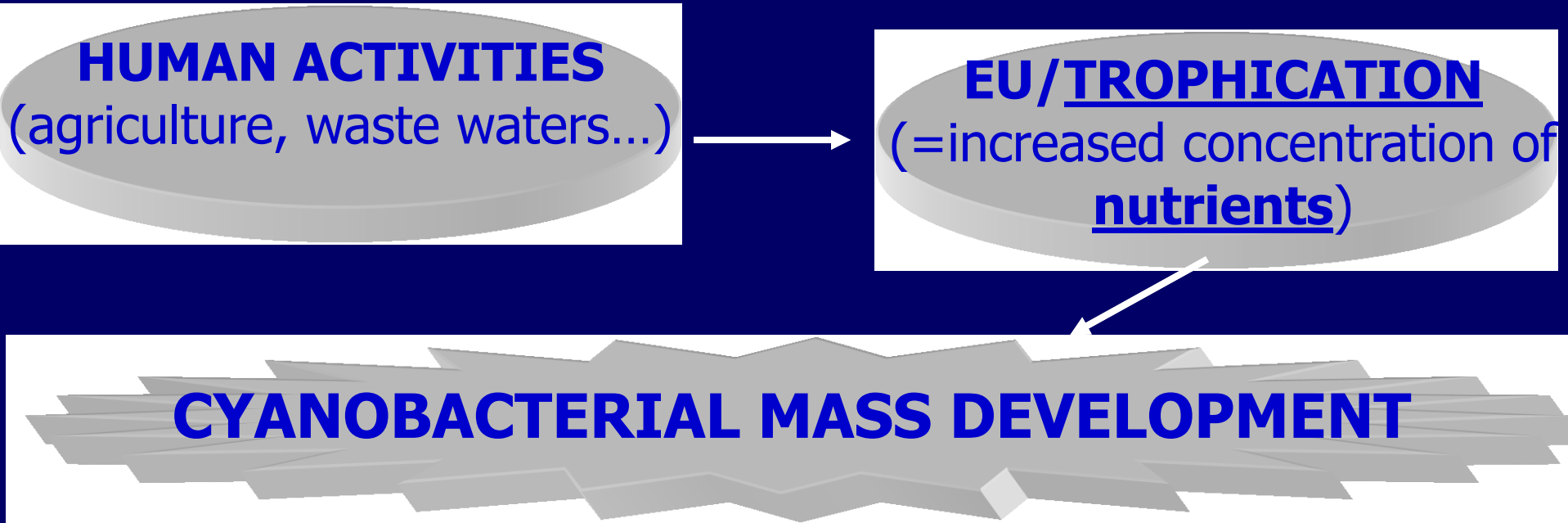
Blue green algae

(CYANOBACTERIA, CYANOPHYTA)

- photosynthetic **prokaryota**
 - live at **various biotops**
(**water**, soil, ice, rocks, lichens ...)
- cca 3×10^9 years old
- formation of the oxygen atmosphere



Cyanobacteria - current problem



Cyanobacterial water blooms – global problem



Upper Saranac River, USA



Bedetti Lake, Argentina



Neuse River, USA



Baltic sea, Europe



Nové Mlýny, Czech Rep.



Yellow sea, China



Lake Mokoan, Australia



South Africa

Talking about „risks“ of cyanobacteria

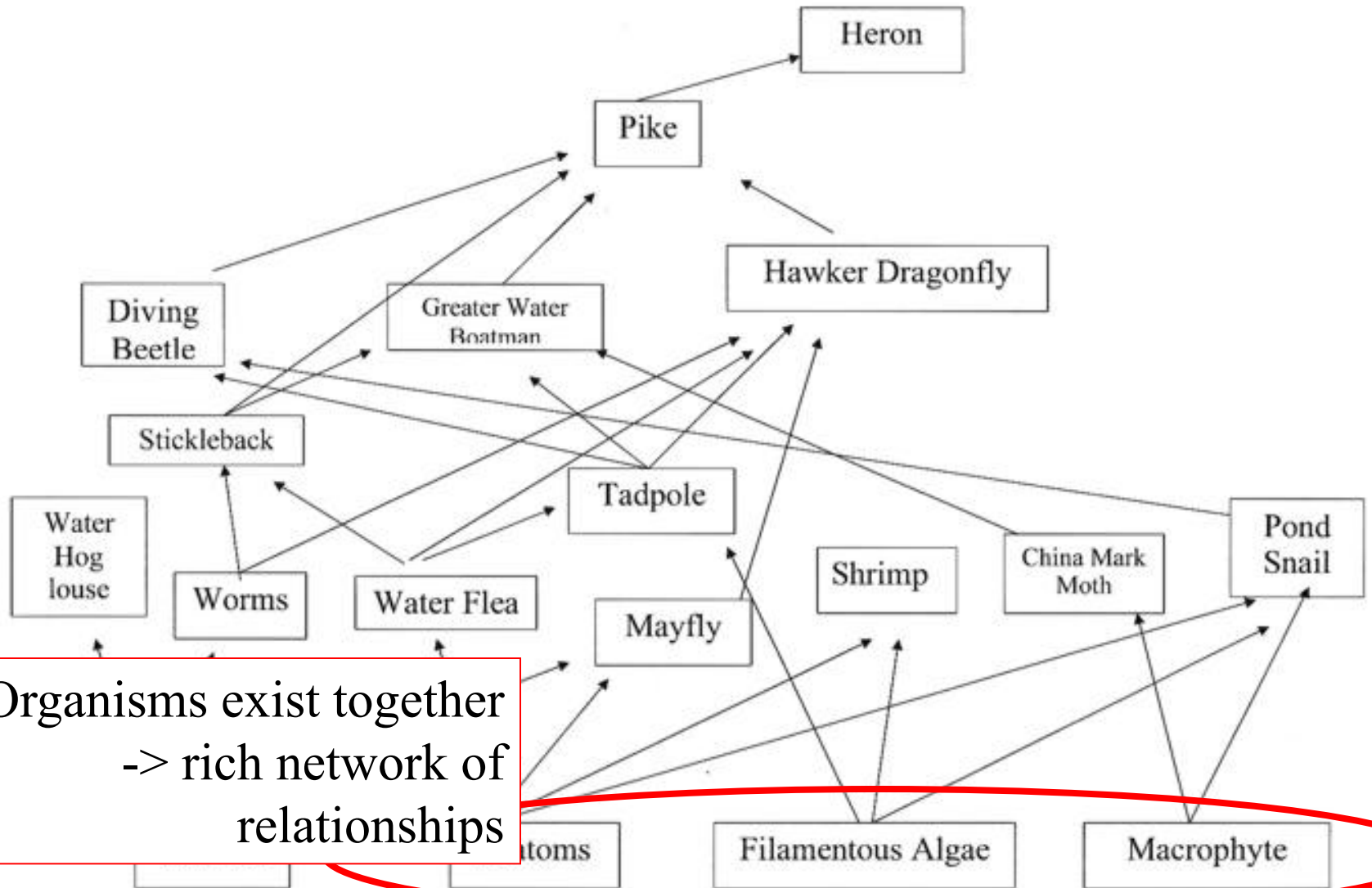
- **RISK = probability of the occurrence of HAZARDOUS event**
- „Hazardous events“ resulting from eu/trophication of the environment
 - **Primary** damage to structure and functioning of ecosystems
 - **Secondary** signs -> ecotoxicity and toxicity

Ecological „stability“

- **Stable and functioning ecosystem**
 - Complex and complicated structure (diversity)
 - Many links (food networks) among organisms = ecosystem functioning
 - *Including „ecosystem services“ to humans: supplies, regulations, cultural / aesthetic, supporting*

Complex ecosystem

Generalised Food Web of a Pond

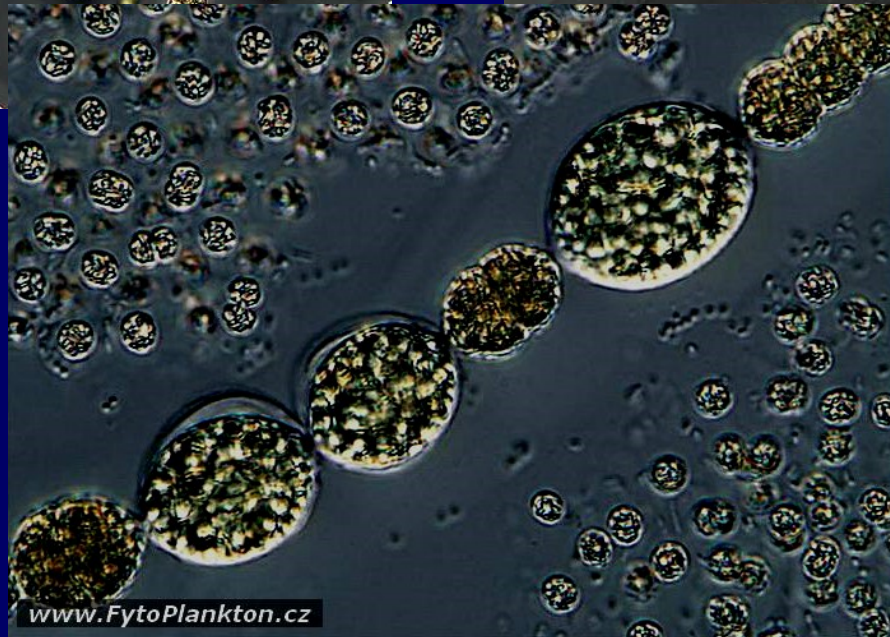
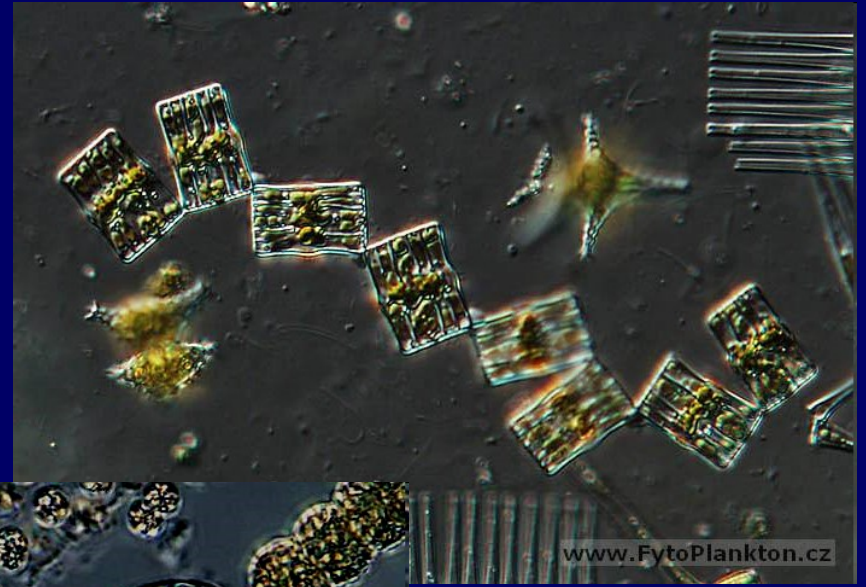


Organisms exist together
-> rich network of
relationships

Ecological risk 1: Loss of phytoplankton biodiversity

- Anthropogenic changes in the environment (more nutrients - P,N)
 - > advantage for „some“ phytoplankton organisms
- Complex communities replaced with „monoculture“ (often *Microcystis aeruginosa*, *Planktothrix sp.*)
- „Monocultures“ **have secondary effects**
 - > changes in hydrochemistry (higher pH, transparency)
 - > further indirect impacts on other organisms

Ecological risk 1: Loss of phytoplankton biodiversity

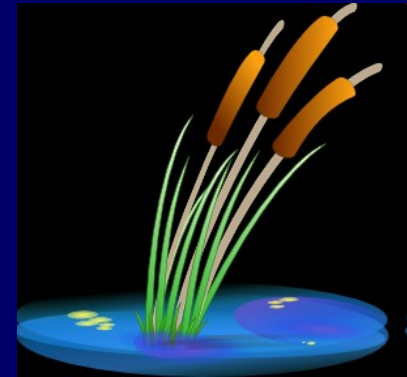


Ecological risk 1: Loss of phytoplankton biodiversity



Ecological risk 2: Further ecosystem changes

- **Phytoplankton -> changes in the whole network**
 - Reported examples ...
 - Changes in the **consumers communities**
zooplankton -> fish -> ...
 - **Makrophyte disappearance** (reed)
(shading -> no germination ...)
 - > **macrophytes**
= substrate for other organisms ...
- **New „expansive“ species**
 - cyanobacterium *Cylindrospermopsis raciborskii* (?)
- **Water blooms** = substrate for „associated bacteria“



Ecological risk 3: Ecosystem catastrophes

- Sudden disappearance of the producers „monoculture“
(*rapid environmental changes, „infections“ by viruses/phages*) -> **Ecosystem collapse**
- Seasonal changes
 - Cyanobacterial biomass lysis
 - > bacterial decay -> loss of O₂
 - > **anaerobic conditions - collapse**
 - Deaths of aquatic organisms (fish ...)
 - Pathogens (anaerobic Clostridium botulinum)

Ecological risk 4: Cyanobacterial toxins

- **Cyanobacteria** - evolutionary old and important organisms (atmospheric oxygen)
- **G- bacteria** (10 mil. Cells / mL)
 - G- : cell walls contain lipopolysaccharides (LPS, *similar to E. coli, Salmonella sp...*)
- **Water blooms**
 - several complex problems (see previous slides...)
 - just one of the problems = **toxin production**

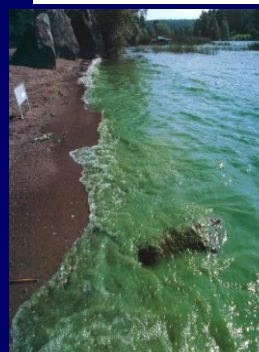
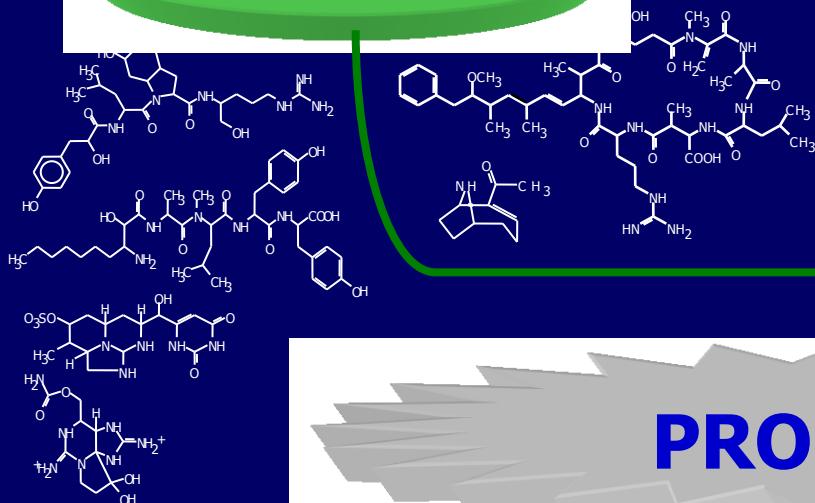
Cyanobacteria



(Eu)trophication

Water blooms

Cyanotoxins



PROBLEM

Categorization of cyanotoxins

1. According to the chemical structure

- cyclic and linear peptides
- alkaloids
- lipopolysaccharides

2. According to biological activity

mechanisms of toxicity

- hepatotoxicity, neurotoxicity, cytotoxicity, irritating, immunotoxicity, genotoxicity ...

TOXIN	STRUCTURE	STRUCTURE VARIATION	LD50* ($\mu\text{g.kg}^{-1}$)	TOXICITY
Microcystin	cyclic heptapeptide	>60	50-1200	hepatotoxicity, tumor promotion, induction of oxidative stress
Nodularin	cyclic pentapeptide	7	50-2000	hepatotoxicity, tumor promotion
Anatoxin	alkaloide	2	200-250	neurotoxicity
Anatoxin-a(S)	methylphospho-ester N-hydroxy-guanine	1	20	neurotoxicity
Saxitoxin	carbamat alkaloid	19	10	neurotoxicity
Cylindrospermopsin	guanidin alkaloid	2	200**	cytotoxicity, target organs: liver and kidney
Aplysiatoxin		2		dermatotoxicity, tumor promotion
Lyngbyatoxin	modified cyclic dipeptide	1		dermatotoxicity, tumor promotion
Lipopolysaccharide				irritate effect

Cyanobacteria

Toxins produced

Anabaena

Anatoxins, Microcystins, Saxitoxins, LPS's

Anabaenopsis

Microcystins, LPS's

Anacystis

LPS's

Aphanizomenon

Saxitoxins, Cylindrospermopsins, LPS's

Cylindrospermopsis

Cylindrospermopsins, Saxitoxins, LPS's

Hapalosiphon

Microcystins, LPS's

Lyngbia

Aplysiatoxins, Lyngbiatoxin-a, LPS's

Microcystis

Microcystins, LPS's

Nodularia

Nodularin, LPS's

Nostoc

Microcystins, LPS's

Phormidium (Oscillatoria)

Anatoxin, LPS's

Planktothrix (Oscillatoria)

Anatoxins, Aplysiatoxins, Microcystins, Saxitoxins, LPS's

Schizothrix

Aplysiatoxins, LPS's

Trichodesmium

yet to be identified

Umezakia

Cylindrospermopsin, LPS's

THE COMPARISON OF TOXICITY OF THE NATURAL TOXINS

(i.p. injection, acute rat test, **LD50 in $\mu\text{g}/\text{kg}$**)

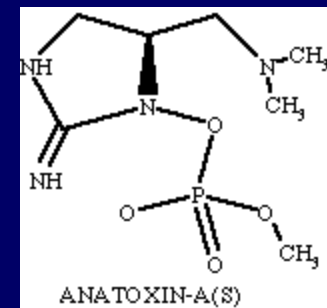
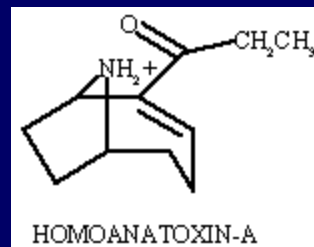
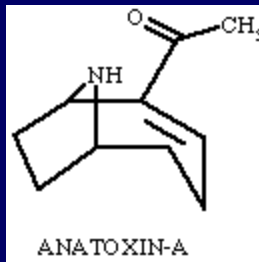
Bacteria-cyanobacteria- animals- fungi- plants

Amatoxin	<i>Amanita phalloides</i>	fungus	500
Muscarin	<i>Amanita muscaria</i>	fungus	1100
Aphanotoxin	<i>Aphanizomenon flos-aquae</i>	cyano	10
Anatoxin -A	<i>Anabaena flos-aquae</i>	cyano	20
microcystin LR	<i>Microcystis aeruginosa</i>	cyano	43
nodularin	<i>Nodularia spumigena</i>	cyano	50
botulin	<i>Clostridium botulinum</i>	bacteria	0,00003
tetan	<i>Clostridium tetani</i>	bacteria	0,0001
kobra	<i>Naja naja</i>	snake	20
kurare	<i>Chondrodendron tomentosum</i>	plant	500
strychnine	<i>Strychnos nux-vomica</i>	plant	2 000



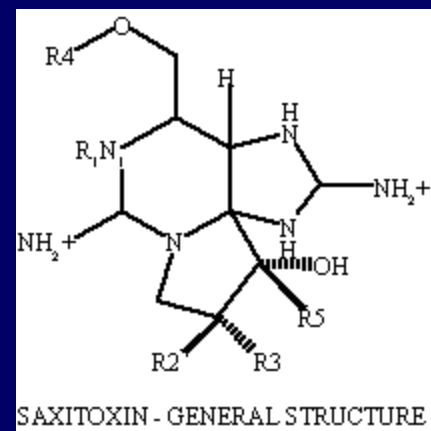
Anatoxin-A, Anatoxin-A(S)

- **neurotoxic** alkaloids
- produced by a number of cyanobacterial genera including *Anabaena*, *Oscillatoria* and *Aphanizomenon*.
- LD50s from 20 $\mu\text{g kg}^{-1}$ (by weight, I.P. mouse) making them **more toxic than microcystins.**

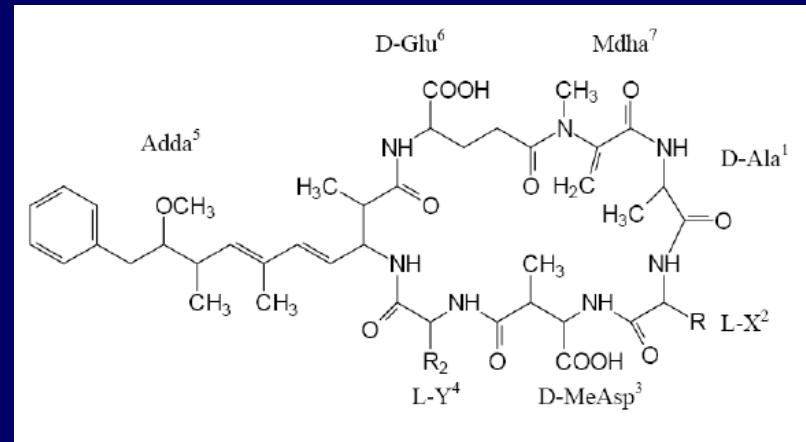


SAXITOXINS

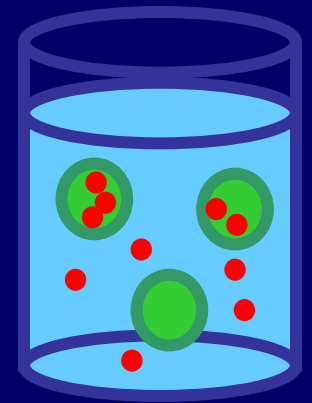
- **neurotoxic alkaloids**
- also known as PSP's - paralytic shellfish poisons - due to their accumulation in seafood
- Produced by marine dinoflagellates and cyanobacteria (*but also in others such as Aphanizomenon sp.*)
- **Number of STX variants exist**



MICROCYSTINS

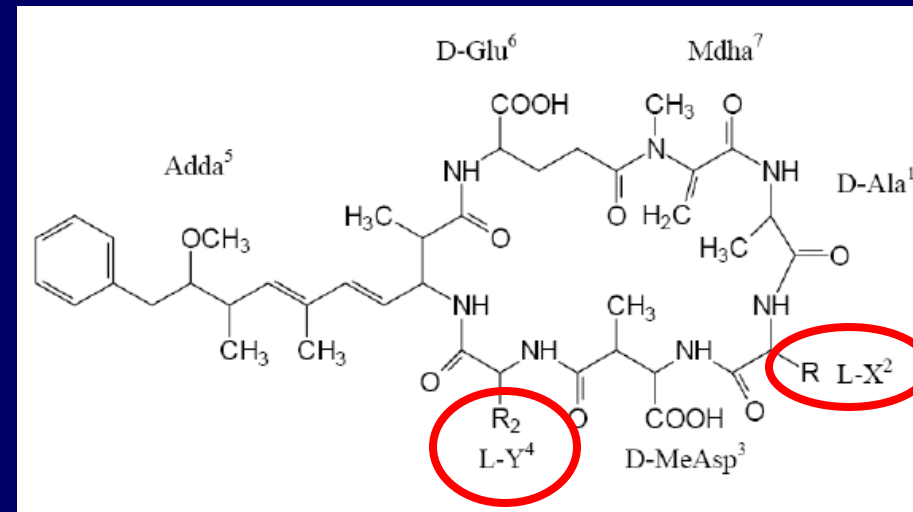


- **The most studied and most important**
- Produced and present inside cells:
 - **Intracellular:**
 - up to 10 mg/g d.w. of biomass
 - 1% dw -> tons / reservoir
 - **Extracellular** (dissolved): up to 10 ug/L
- Stable in water column, bioaccumulative (?)



MICROCYSTINS

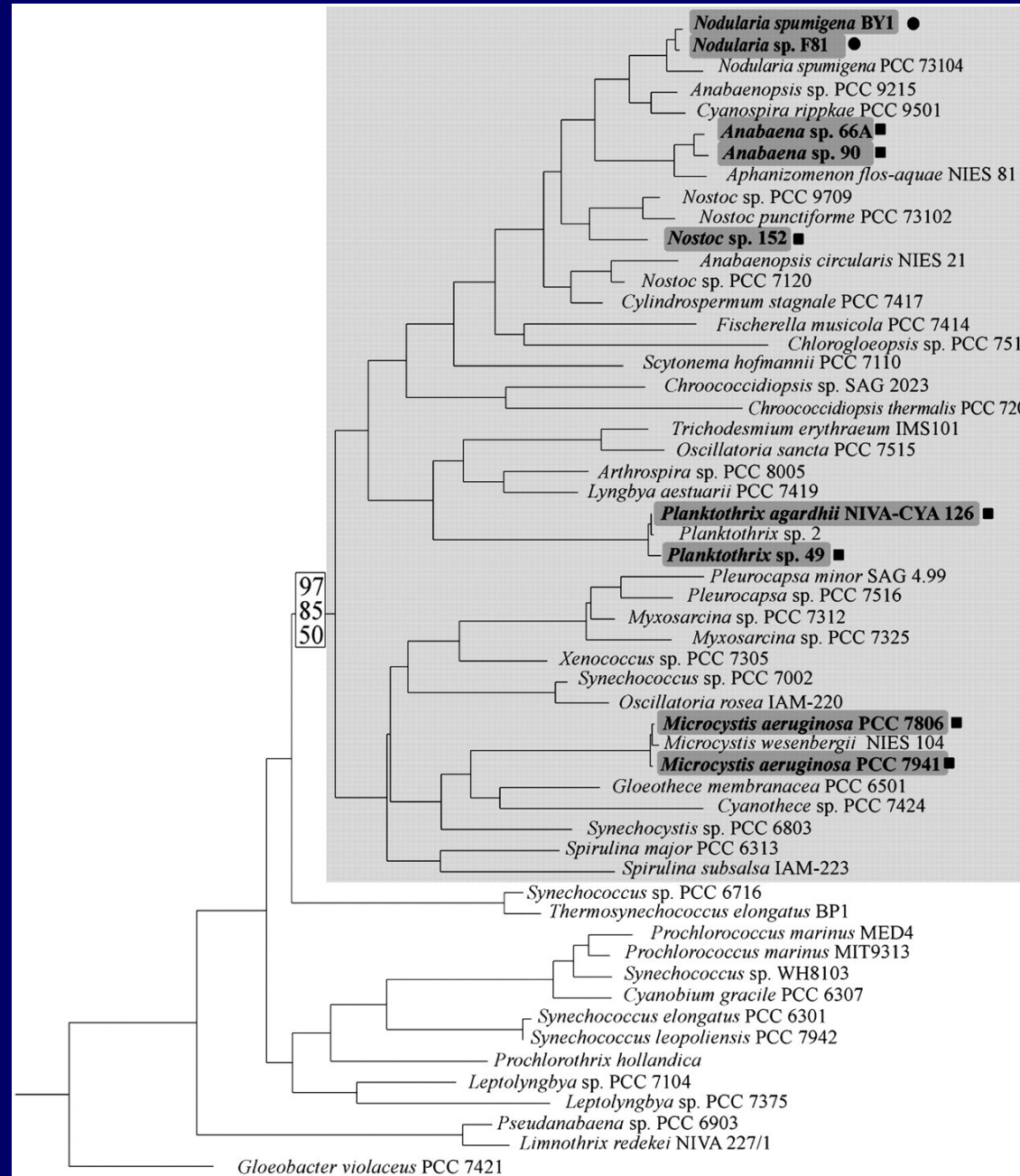
- Inhibit regulatory **protein phosphatases**
 - > tumor promoter
 - > hepatotoxic



- **70 variants**: MC-LR only considered by WHO
 - chronic TDI: 0.04 ug/kg b.w./day
 - drinking water guideline recommendation: 1 ug/L
- **Highly toxic to mammals and humans**
- Ecotoxicology ? Natural function ?

Microcystin synthesis

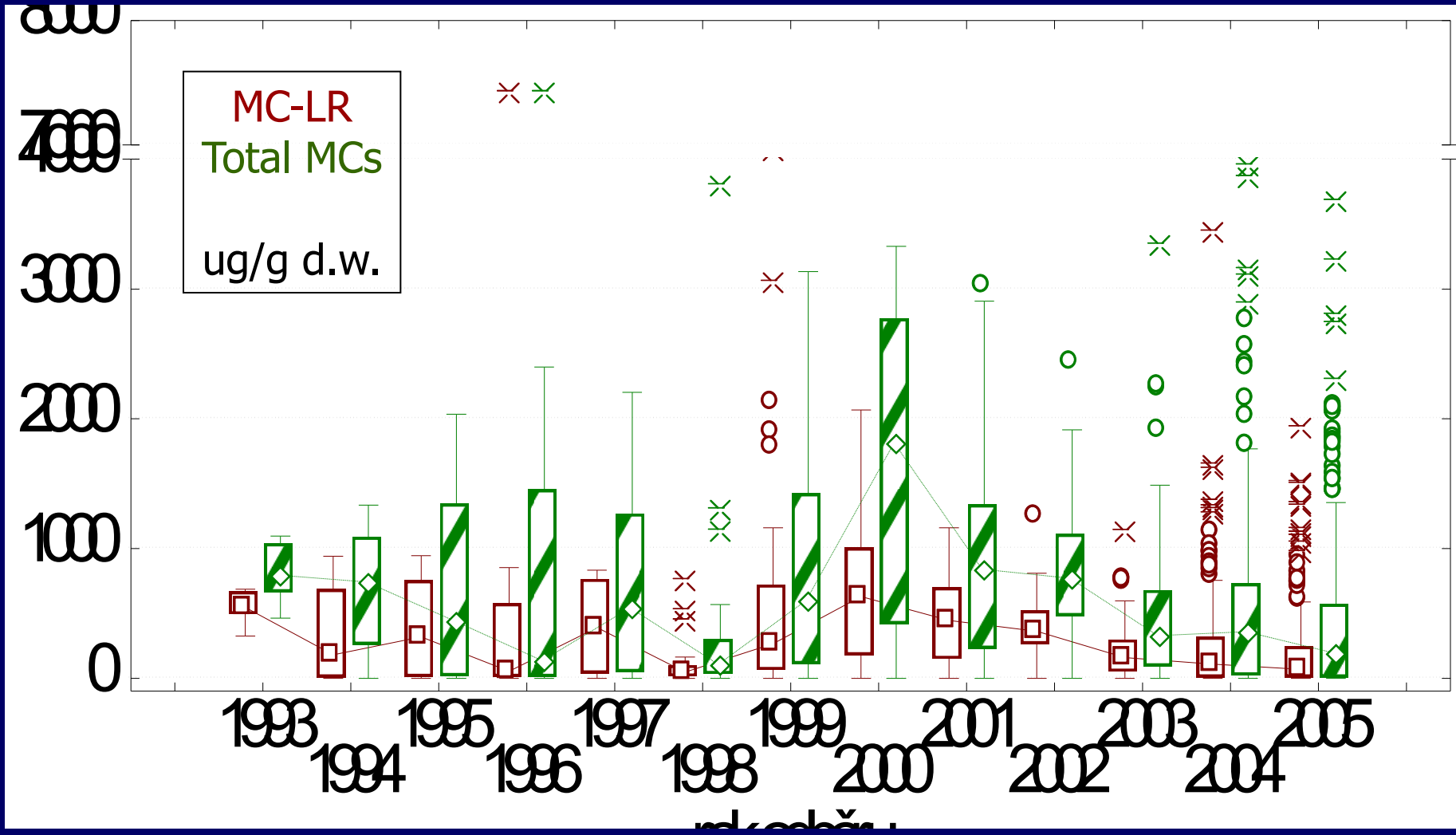
- Non-ribosomal polyketide synthetases
- Evolutionary old genes
 - *Why remained?*
- Horizontal gene transfer



0.1 substitutions/site

Microcystins in the Czech Rep.

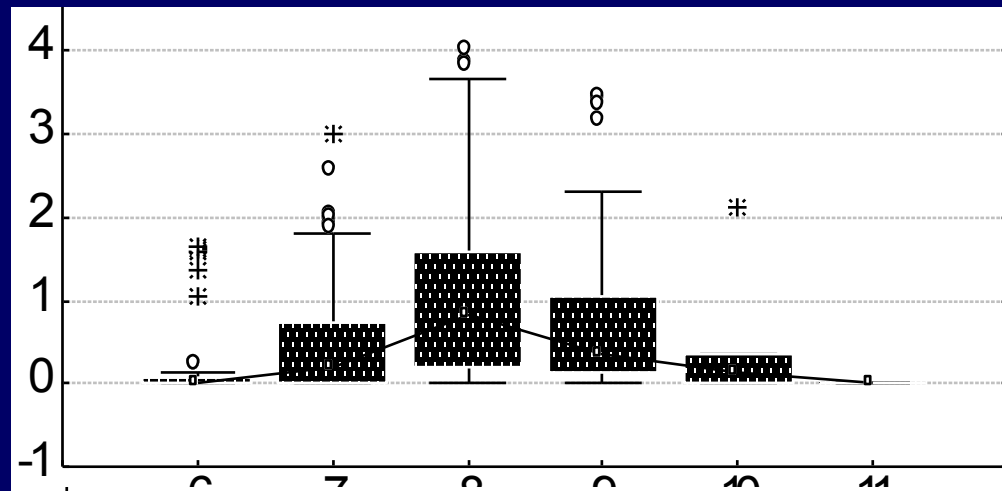
(Water bloom biomass concentrations
... up to several mg/g dry weight)



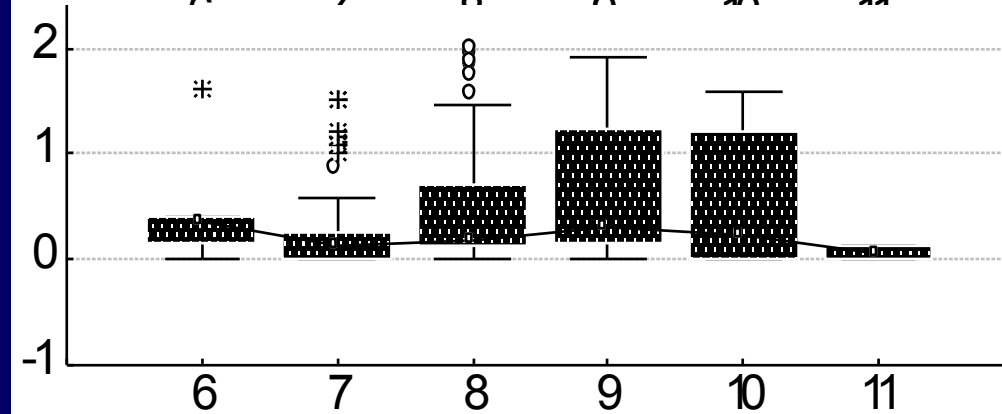
Seasonal variability

- **dissolved** microcystins in the C.R.
(water concentrations)

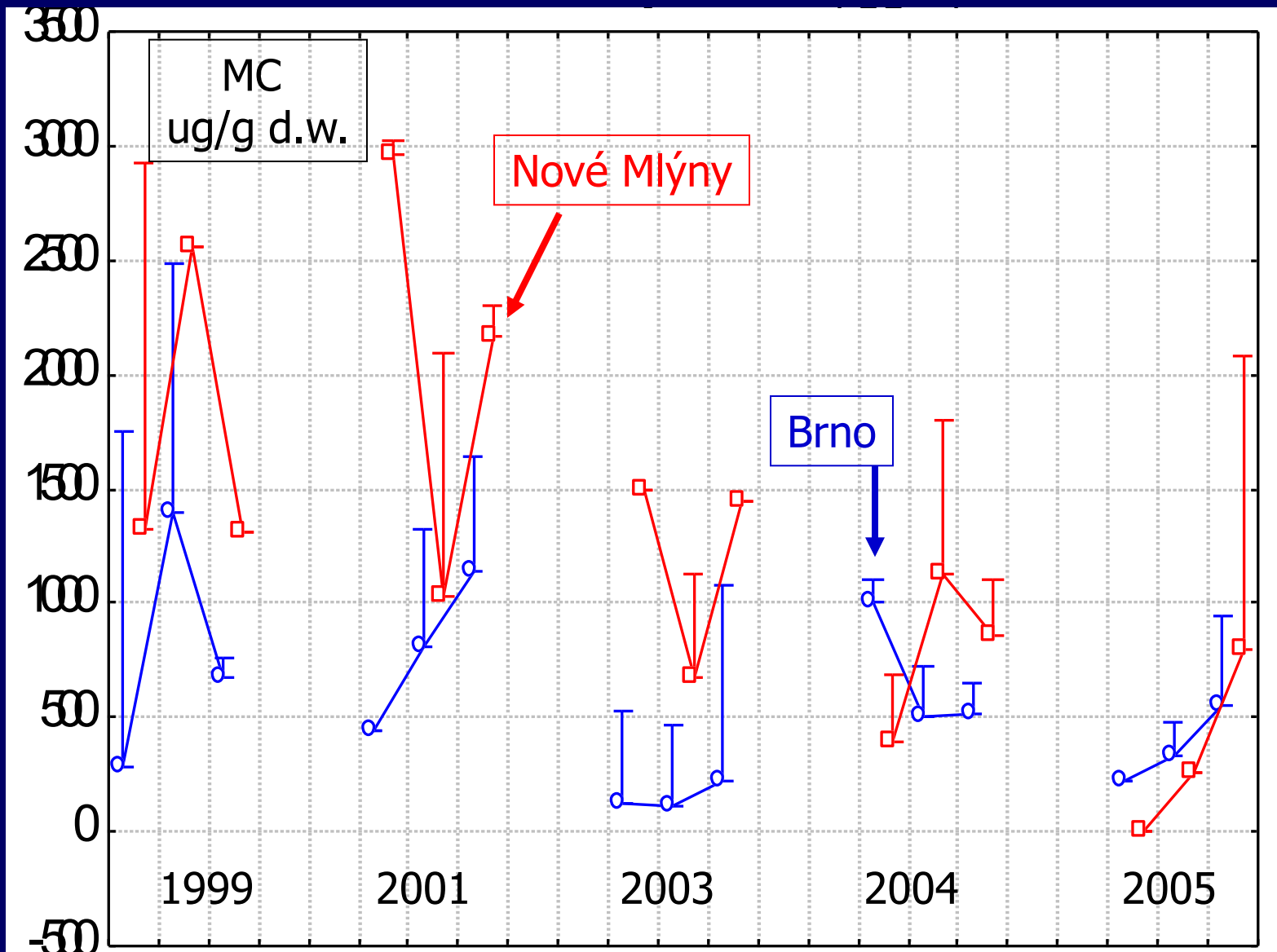
2004



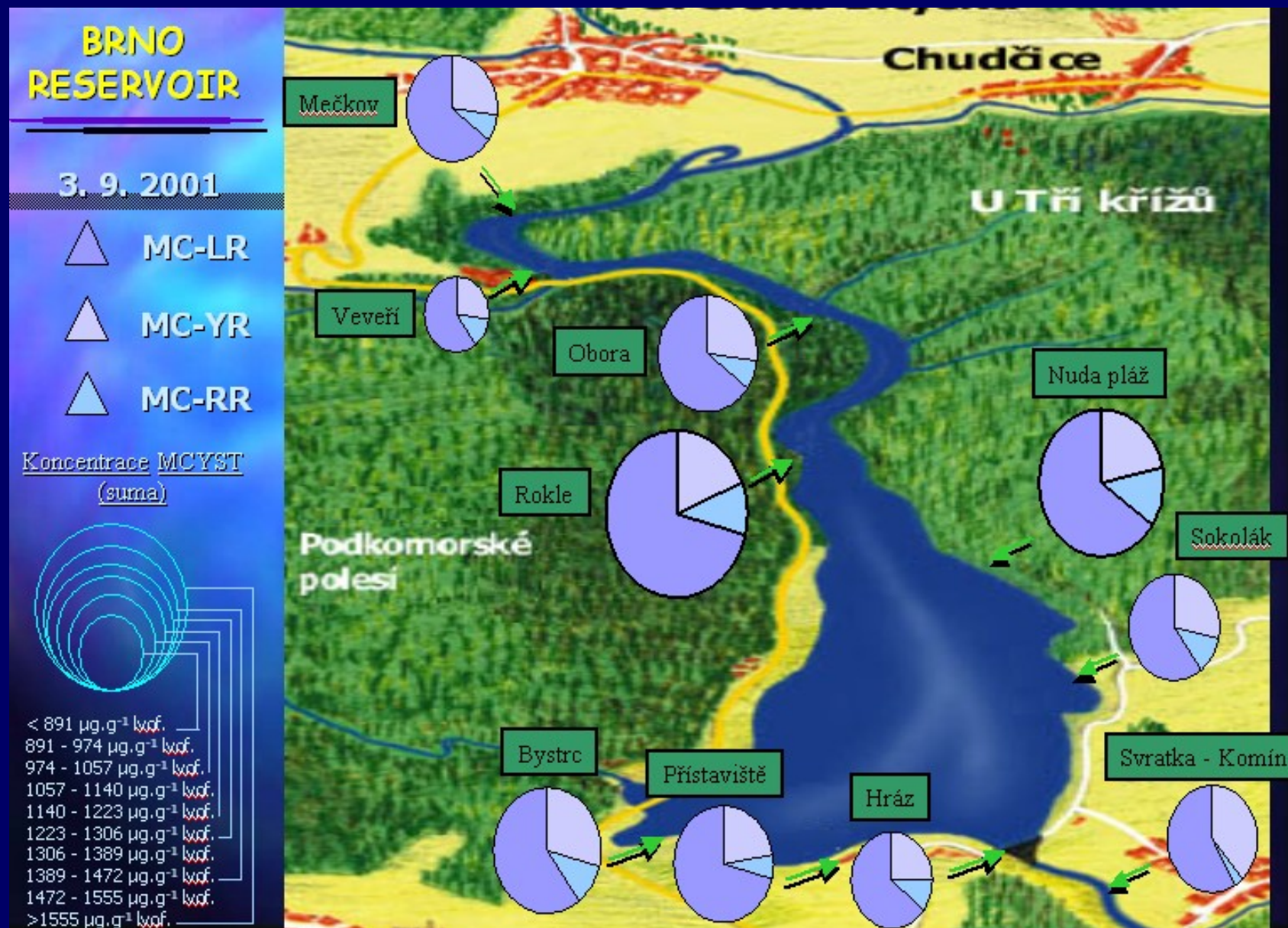
2005



Reservoir seasonal data



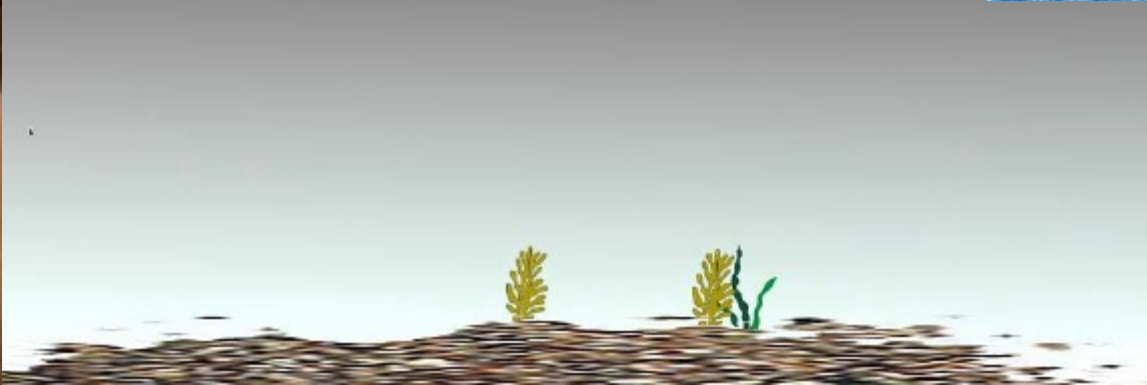
Reservoir spatial variability



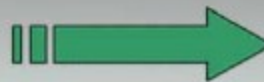
Microcystins

HUMAN HEALTH RISKS

EXPOSURE ROUTES

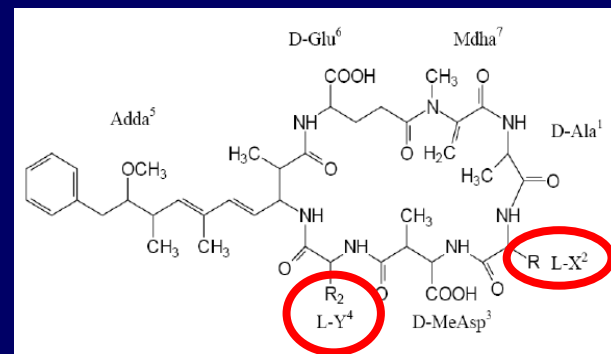


EXPOSURE ROUTES



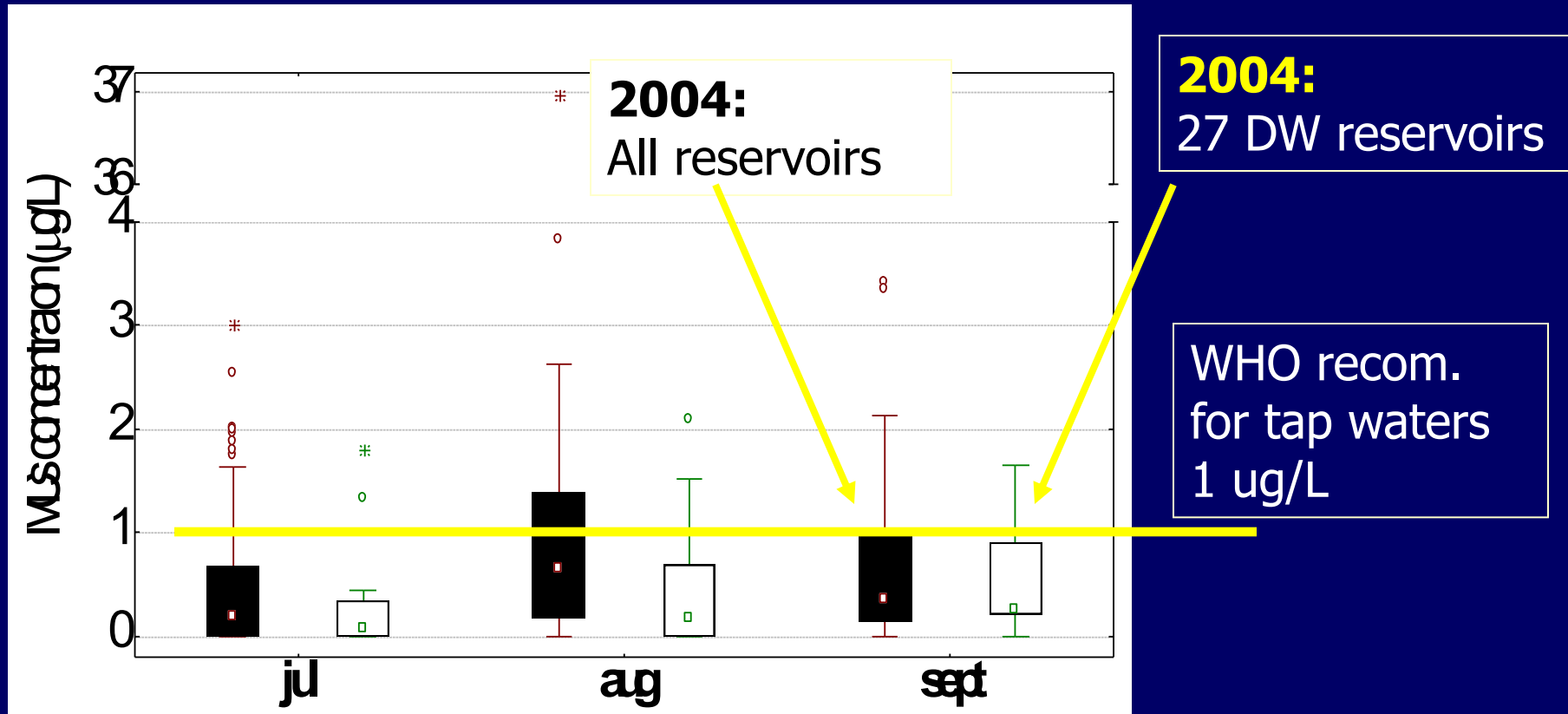
MICROCYSTINS

... brief reminder ...



- **70 structural variants:**
MC-LR only (about 30-50% of MCs) considered by WHO
- Human chronic TDI: **0.04 ug/kg b.w. daily**
 - drinking water guideline recommendation: **1 ug/L**
(usually accepted in national laws worldwide, incl. Czech Rep.)
- **High toxicity** - safety risks: **manipulation regulated**
United Nations - Bacteriological and Toxin Weapons Convention
Czech Rep. - Law no. 281/2002 Sb. and 474/2002 Sb.

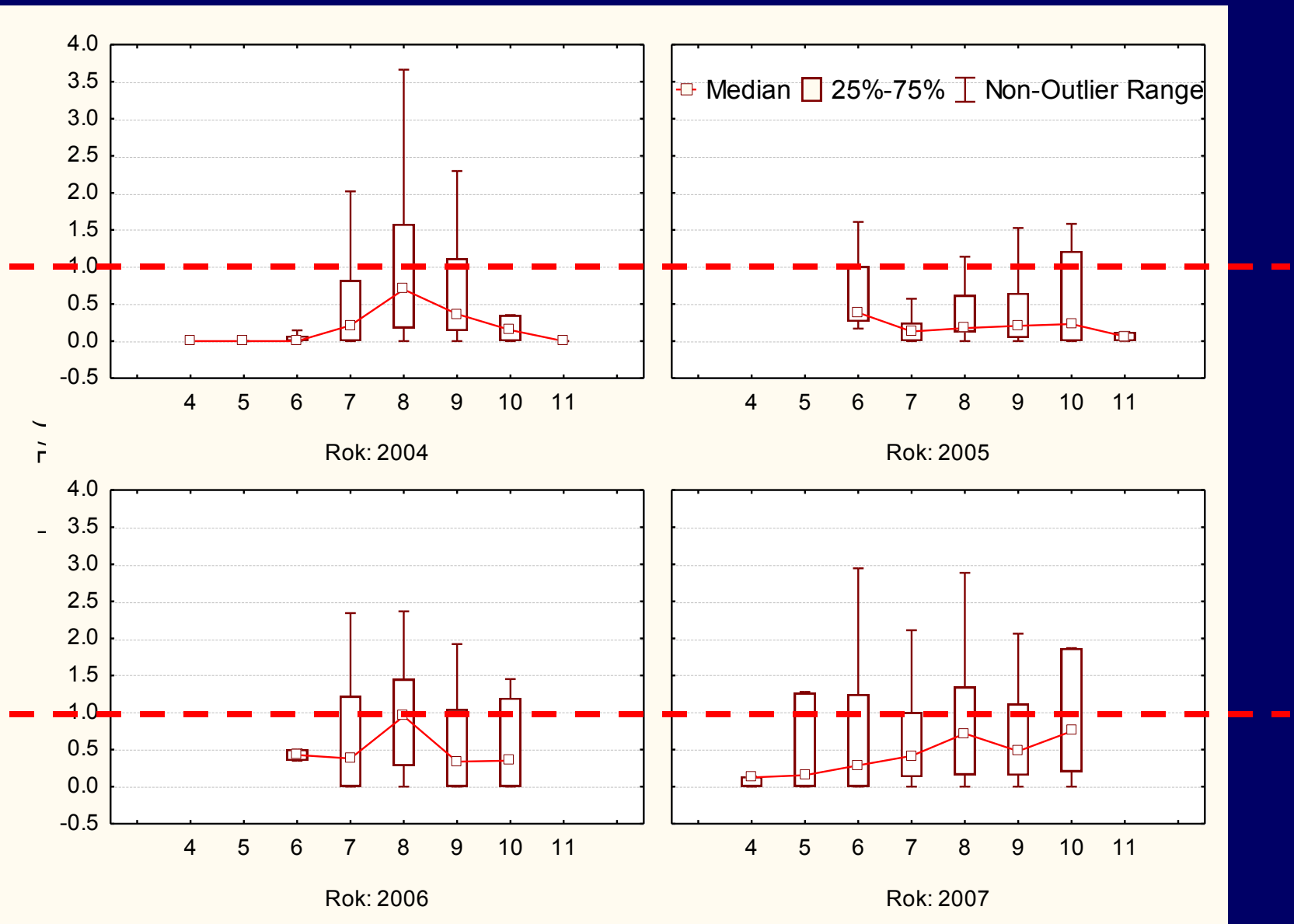
MCs in drinking water reservoirs



- **Tap waters up to 8 µg/L (1999)**

Bláha & Maršálek (2003) Arch Hydrobiol

MCs in drinking water reservoirs



"TOP" MCs **in waters** (Czech Rep. 2004-7)

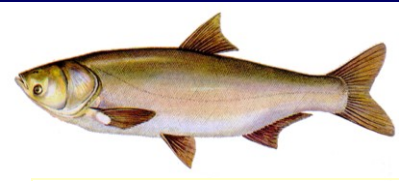
Lokalita	Datum odběru	MC [ug/L]
Velké Žernoseky (pískovna)	1.8.2004	37.0
Nechranice	31.7.2004	19.0
Dubice, Česká Lípa	8.9.2004	15.1
Prostřední, Lednice	6.9.2005	18.7
Lučina	19.7.2005	17.3
České údolí VN	8.8.2005	9.3
Plumlov	15.8.2006	24.8
Dalešice	14.7.2006	16.3
Hracholusky	21.8.2006	16.3
Nechranice	26.7.2007	29.8
Skalka	22.8.2007	19.9
Novoveský	2.10.2007	16.3

Risks of MCs in drinking water supplies

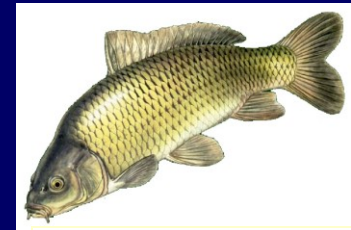
concentration of dissolved MC	20% daily intake from sources of drink.w.		100% daily intake from sources of drink.w.	
	child (25kg)	adult (70kg)	child (25kg)	adult (70kg)
	dose MC($\mu\text{g.kg}^{-1}$ live wt. day $^{-1}$)	dose MC($\mu\text{g.kg}^{-1}$ live wt. day $^{-1}$)	dose MC($\mu\text{g.kg}^{-1}$ live wt. day $^{-1}$)	dose MC($\mu\text{g.kg}^{-1}$ live wt. day $^{-1}$)
	HI	HI	HI	HI
median 0.205 $\mu\text{g/L}$	0.0015 0.038	0.0005 0.014	0.0075 0.189	0.0027 0.067
extreme 17.27 $\mu\text{g/L}$	0.1272 3.180	0.0454 1.136	0.6359 15.898	0.2271 5.678

- SIGNIFICANT HEALTH RISKS EXIST !
- To minimize risk
 - Adopt appropriate technologies and treatments
 - Establish routine monitoring of MCs during the season

Accumulation of MCs in fish



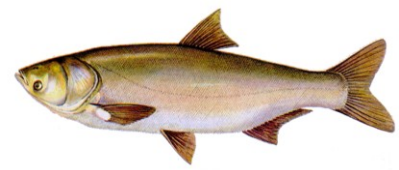
Silver carp



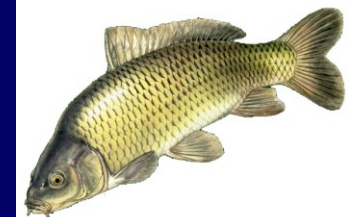
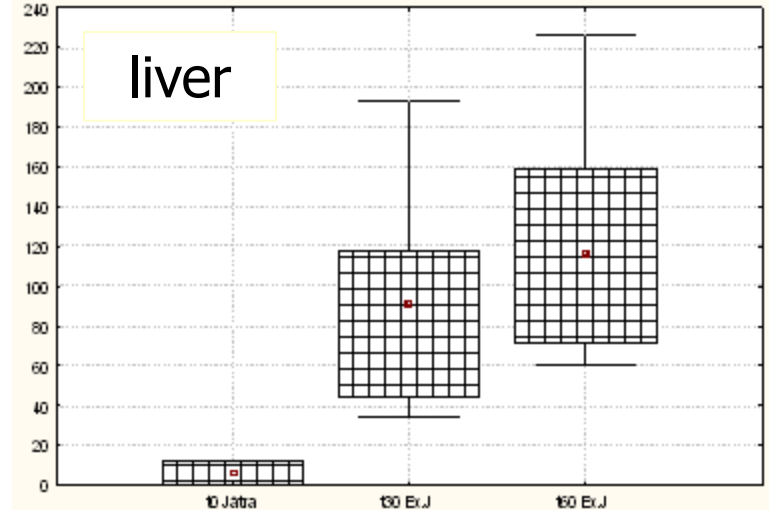
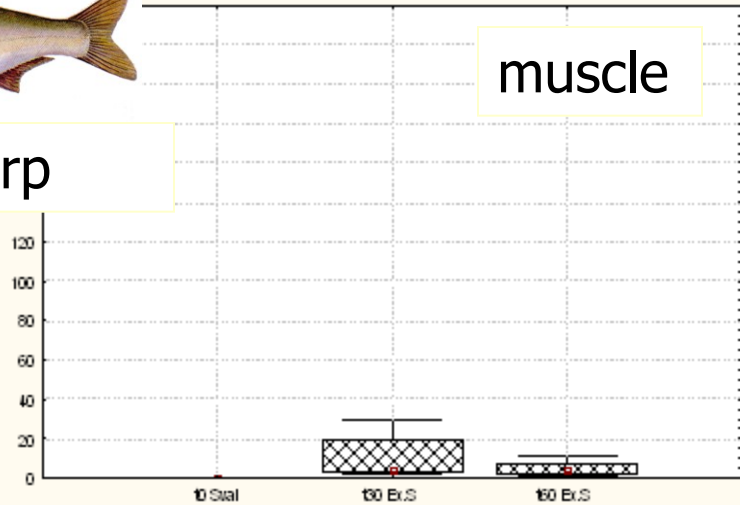
Common carp



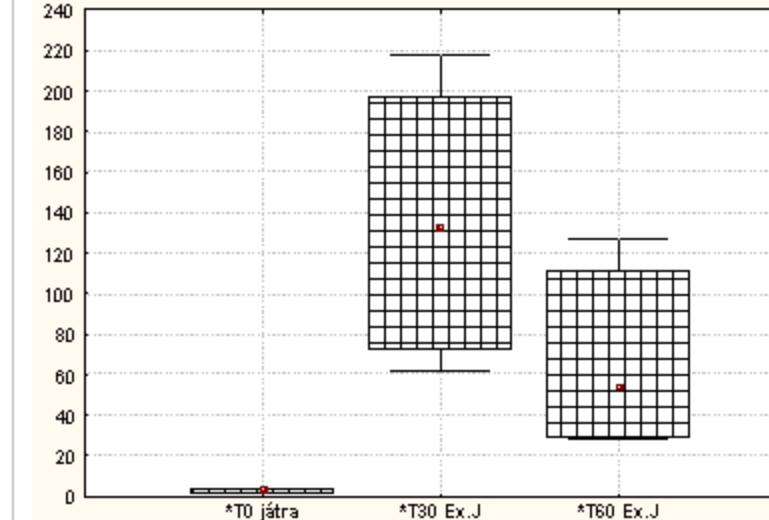
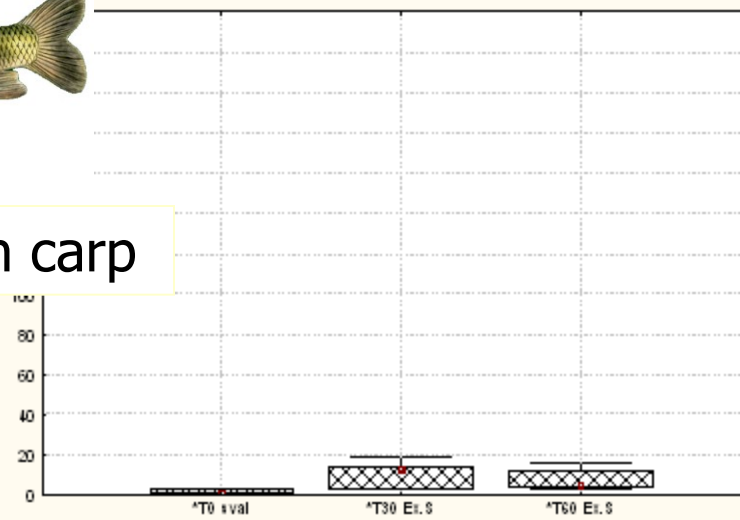
Accumulation of MCs in fish



Silver carp



Common carp



Control

30 d

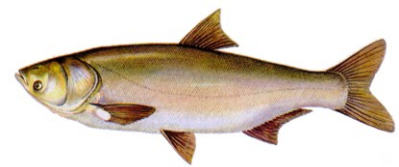
60 d

Control

30 d

60 d

Risk of MCs in edible fish



Silver carp



Common carp

	Max. conc. (dose)	Max. HI	Average conc. (dose)	Average HI
SC: liver	226 ng/g 68 ug	28	106 ng/g 32 ug	13.2
muscle	29 8.8	3.7	8.4 2.5	1.1
CC: liver	217 65	27	132 39	16.5
muscle	18.8 5.6	2.4	8.5 2.6	1.1

*100% of food from the contaminated source
avg. person: 60kg, food - 300g*

TDI: 0.04 ug/kg/day

MCs in fish [ng/g f.w.] (Czech Republic reservoirs, 2008)

	Liver		Muscle
	Average	Maximum	
Pike perch	15.6	22.7	0
Amur	2.02	6.1	0
Carp	0.57	1.8	0
Catfish	0	0	0
Silver salmon	4.14	9.5	0

- Exposure to MCs from fish

Less (if any) significant health risks

RECREATIONAL EXPOSURE

- **Contact dermatitis**

non-specific (!!!!)

responsible agents

(? MCs, LPS?)



Lipopolysaccharides ?

- **Pyrogenicity of LPS**

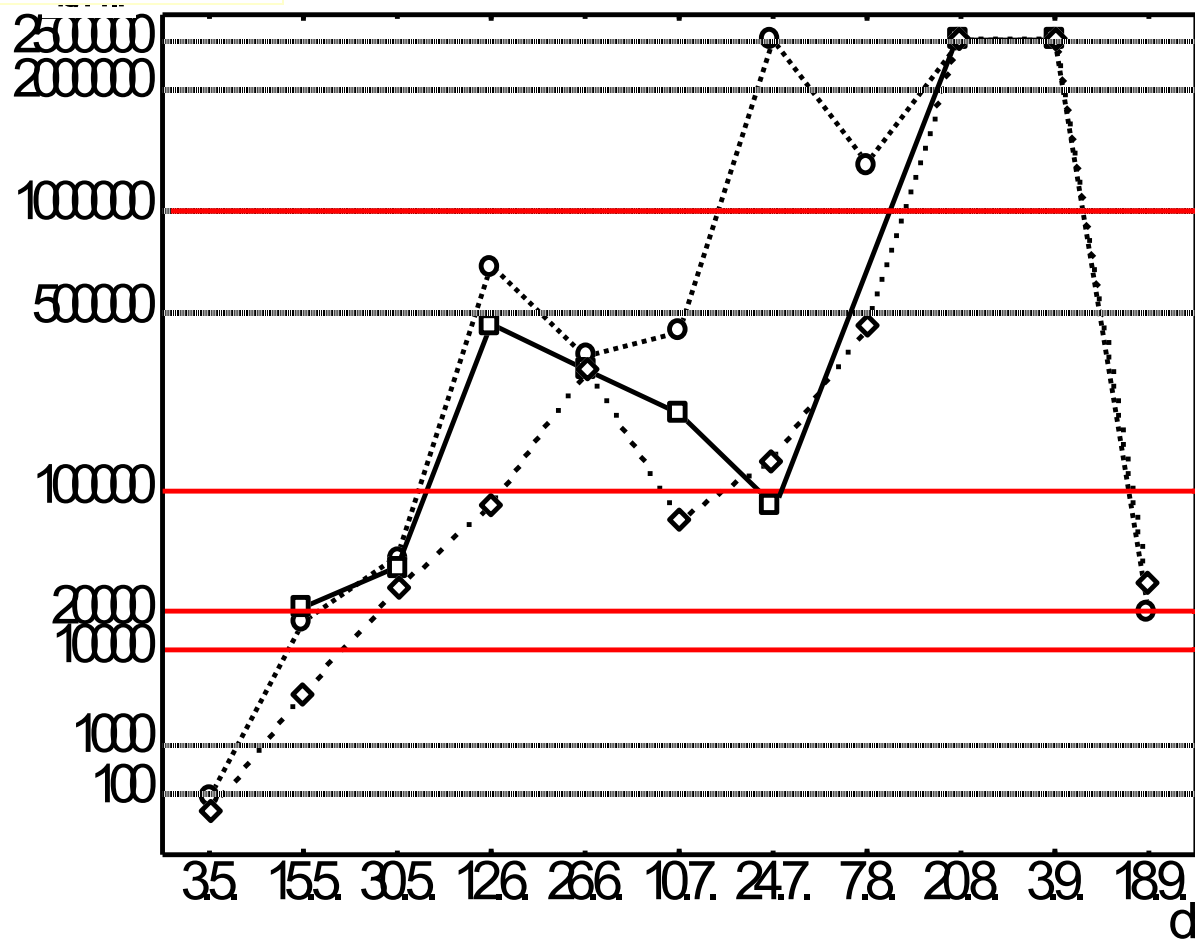
significant in water blooms
(less in lab cultures)

Sample	Endotoxin activity	
	(EU mg ⁻¹ d.w.)	(EU mg ⁻¹ LPS)
Green alga		
<i>P. subcapitata</i>	0	0
Cyanobacterial culture		
<i>P. agardhii</i>	301	35 456
<i>A. flos-aquae</i>	426	38 399
<i>M. aeruginosa</i>	257	36 809
<i>T. variabilis</i>	2 518	270 848
Water bloom		
<i>Planktothrix sp.</i>	61	46 959
<i>Aphanizomenon sp.</i>	7 895	918 118
<i>M. aeruginosa</i>	799	199 895
<i>Microcystis sp.</i>	989	449 576
<i>Anabaena sp.</i>	277	48 699
Heterotrophic bacteria		
<i>E. coli</i>	14 692	1 347 959
<i>K. intermedia</i>	1 702	239 770
<i>P. putida</i>	11 392	1 294 592
<i>P. fluorescens</i>	55	6 669

Bernardová et al.
2008 J Appl Toxicol

Toxic cyanobacteria in recreational reservoirs (WHO approach - „preliminary caution“)

Cells / mL



High risks

Swim. not recommended

Risk for sensitive

Warning

- o -

- □ -

- ◇ -

datum

RECREATIONAL EXPOSURE

- **Contact dermatitis**

*non-specific (!!!!)
responsible agents
(? MCs, LPS?)*



- **Toxins enter the body**

(MCs risk assessment possible)



Risks of MCs: recreational exposure (US EPA R.A.methodology)

biomass-bound MC	7 days per year (chronic exposure)				1 day acute exposure			
	Guidance level 2 100 000 cells/mL		Guidance level 3 2 000 000 cells/ml		Guidance level 2 100 000 cells/mL		Guidance level 3 2 000 000 cells/ml	
	child (25kg/80ml.h ⁻¹)	adult (70kg/50ml.h ⁻¹)	child (25kg/80ml.h ⁻¹)	adult (70kg/50ml.h ⁻¹)	child (25kg/80ml.h ⁻¹)	adult (70kg/50ml.h ⁻¹)	child (25kg/80ml.h ⁻¹)	adult (70kg/50ml.h ⁻¹)
	MC dose ($\mu\text{g.kg}^{-1}\text{bw. day}^{-1}$) HI	MC dose ($\mu\text{g.kg}^{-1}\text{bw. day}^{-1}$) HI	MC dose ($\mu\text{g.kg}^{-1}\text{bw. day}^{-1}$) HI	MC dose ($\mu\text{g.kg}^{-1}\text{bw. day}^{-1}$) HI	MC dose ($\mu\text{g.kg}^{-1}\text{bw. day}^{-1}$) HI	MC dose ($\mu\text{g.kg}^{-1}\text{bw. day}^{-1}$) HI	MC dose ($\mu\text{g.kg}^{-1}\text{bw. day}^{-1}$) HI	MC dose ($\mu\text{g.kg}^{-1}\text{bw. day}^{-1}$) HI
median concentration 348 $\mu\text{g/g dw}$	0.00019 0.005	0.00004 0.001	0.00389 0.097	0.00087 0.022	0.01013 0.253	0.00226 0.057	0.20268 5.067	0.04524 1.1310
extreme concentration 3945 $\mu\text{g/g dw}$	0.00220 0.055	0.00049 0.012	0.04406 1.102	0.00984 0.246	0.11488 2.872	0.02564 0.641	2.29757 57.439	0.51285 12.823

- Recreation exposure
-> significant risks of MCs

Summary I - MCs and the health risks

- MCs present in 80-90% of reservoirs
- High MCs concentrations
- **All exposure routes pose significant health risks** under certain scenarios
 - ! Recreation, Drinking water
 - (MCs accumulated in fish - less important)*

Cyanobacterial EKOtoxicity ?

- Isolated microcystins - many toxicological studies
- HOWEVER: **Water blooms are more than microcystins**
 - complex mixtures of many compounds (toxins, lipopolysaccharides, non-toxic components...)
 - ? accumulated toxicants (metals, POPs ???)

Many studies:

tested complex water blooms BUT interpreted as „MCs“

Ecotoxicity of WATER BLOOMS to **bacterioplankton**

- highly relevant question (MCs are evolutionary old ... as well as bacteria)
- only few studies - in general **low toxicity** observed



Ecotoxicity of WATER BLOOMS to **algae (phytoplankton)**

- Algae = competitors to cyanobacteria
 - limited data
 - **weak direct toxicity** only at high (nonrelevant) concentrations
 - some studies indicate allelopathy between cyanobacteria & algae (*inhibition of growth, specific effects on dormant stages*)



Ecotoxicity of WATER BLOOMS to **zooplankton**

- invertebrates - **lower sensitivity** than vertebrates
- variable sensitivity of different (even closely related) invertebrate species
- one of the first hypotheses: „MCs are against predators“ (not confirmed - several contras...)

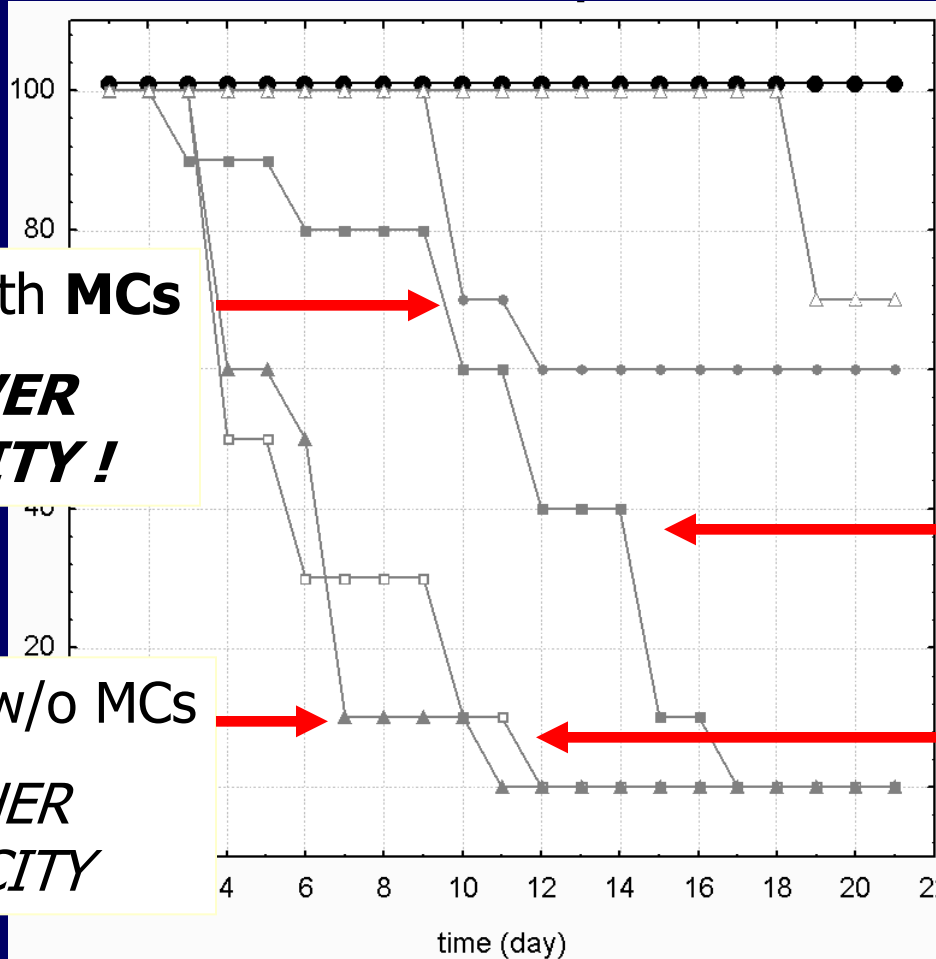
*BUT: zooplankton prefers nontoxic strains during feeding
(? -> indirect effects on development of toxic blooms ?)*



Ecotoxicity of cyanobacteria



Reproduction



Fraction with **MCs**

! LOWER TOXICITY !

Fraction w/o MCs

HIGHER TOXICITY

Controls

Nontoxic biomass (spinach)

Complex water bloom

Extract

- control
- BIOM.
- AQ. EXTRACT
- ▲ C18 PERMEATE
- ◆ C18 ELUATE
- △ SPINACH

Ecotoxicity of WATER BLOOMS to **fish and amphibians**

- Many studies ... toxin accumulations
 - + several effects observed (histology, biochemistry...)

**! Indirect effects (pH changes, oxygen content)
more important in toxicology !**



Ecotoxicity of WATER BLOOMS to **birds**

- deaths documented (with toxins in bird tissues)
- limited number of controlled experiments
 - low direct toxicity to model birds

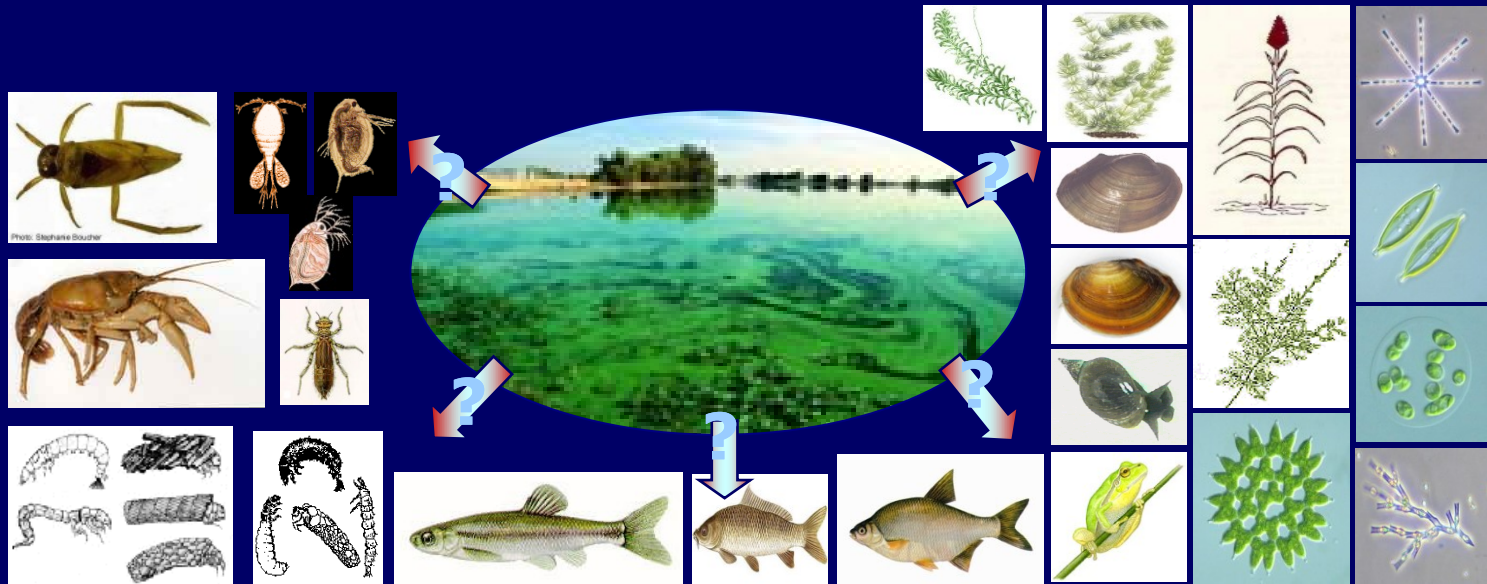
**! Water blooms stimulate effects of other agents
(lead toxicity, immunosuppressions)**



Summary II - Ecotoxicological risks

- **Only MCs studied** (*... results disputable ...*)
- **In general: Lower importance of „known“ isolated toxins (such as MCs)**

! Complex bloom effects are more important !



... emerging toxins

Cylindrospermopsin (CYN)

	MC	CYN
LD50 (acute oral toxicity)	6000 µg/kg	5000µg/kg
NOAEL	40 µg/kg/den	30 µg/kg/den
TDI	0.04 µg/kg	0.03 µg/kg
Limit pro pitnou vodu	1 µg/L*	1 µg/L * * 15 µg/L * * *

- discovered in tropics (Australia, Florida, New Zealand ...)
- now reported from Europe ... including C.R.

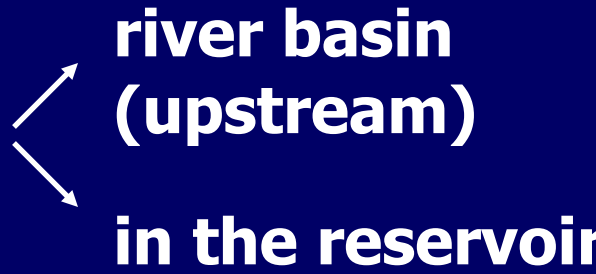
Risks of both MCs and CYN are comparable
(CYN not regulated, concentrations unknown...)

Cylindrospermopsis in the C.R.

<u>nádrž / odběr</u>	<u>tax. složení vodního květu</u>	CYN (μg/L) ELISA
Dubice		
2007-08-27	<u>Aphanizomenon flos-aquae var. klebahnii</u> 5%, Limnothrix redekei 70%, Planktothrix sp. 5%, Microcystis sp. 15%, Anabaena lemmermannii	3.135±0.003
Máchovo jezero		
2007-07-30	<u>Aphanizomenon gracile</u> 10%, <u>Aphanizomenon sp.</u> (10%), Microcystis sp. 30%, Aphanocapsa sp. 10%, Oscillatoriales 20%, Aphanothece sp., Anabaena sp.	0.470±0.032
Svět		
2007-07-25	<u>Aphanizomenon flos-aquae var. klebahnii</u> 5%, Anabaena flos-aquae 40%, Anabaena planctonica 50%, <u>Cylindrospermopsis raciborskii</u>	0.061±0.010

Bláhová et al.
2008 Toxicon

How to manage toxic blooms?

- Limit **nutrient sources** 
 - river basin (upstream)
 - in the reservoir
- **Cyanocides** (chemical, natural - e.g. Humic acids)
- **Flocculants** Al(OH)_3 ...
- **Biological control** (... planktophagous fish)
- **Others** (mechanical removal, ultrasonic ...)

How to manage toxic blooms?

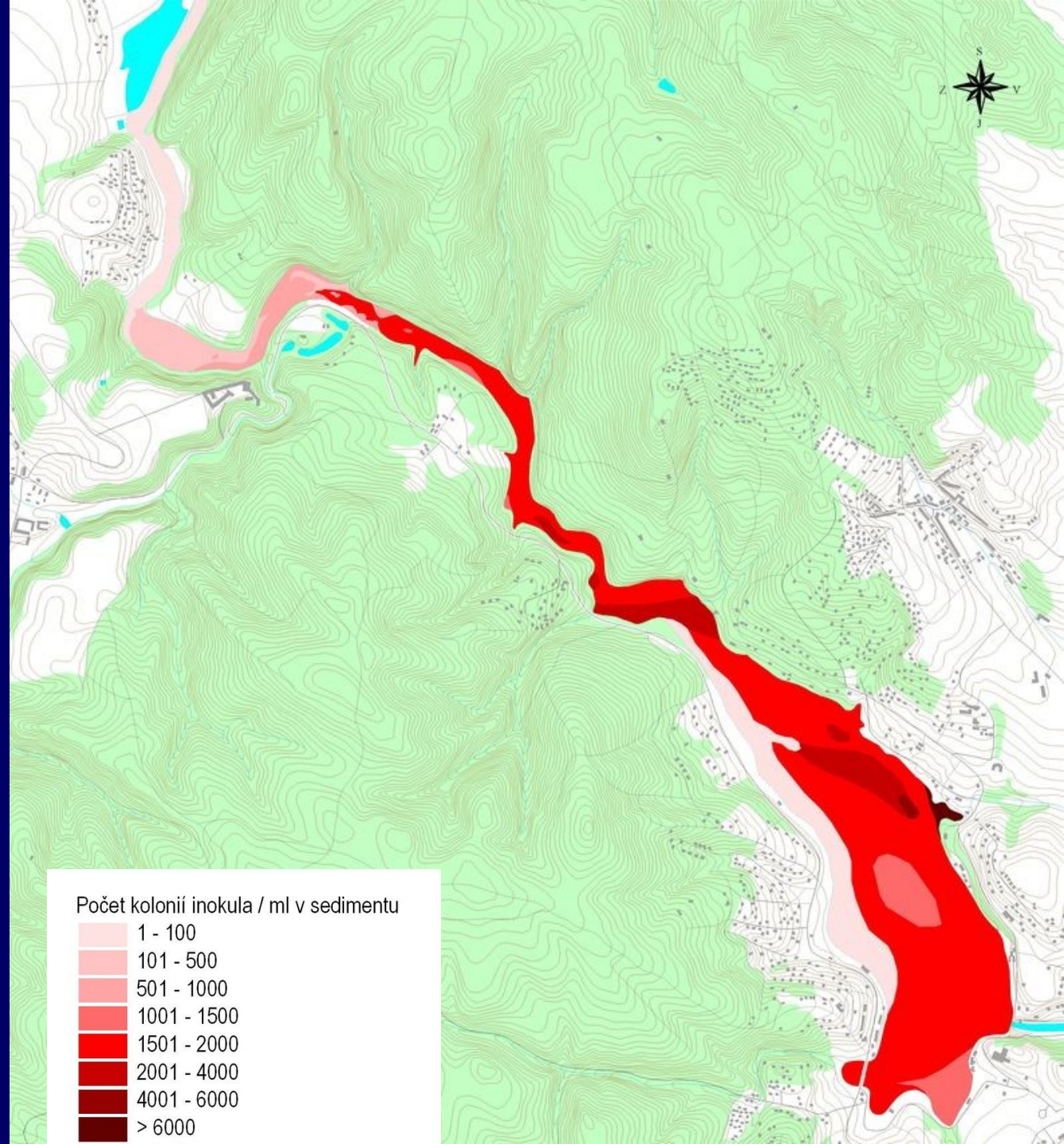
No ideal and universal approach exists

- combinations of methods
- locality-specific approach

Example

Brno reservoir

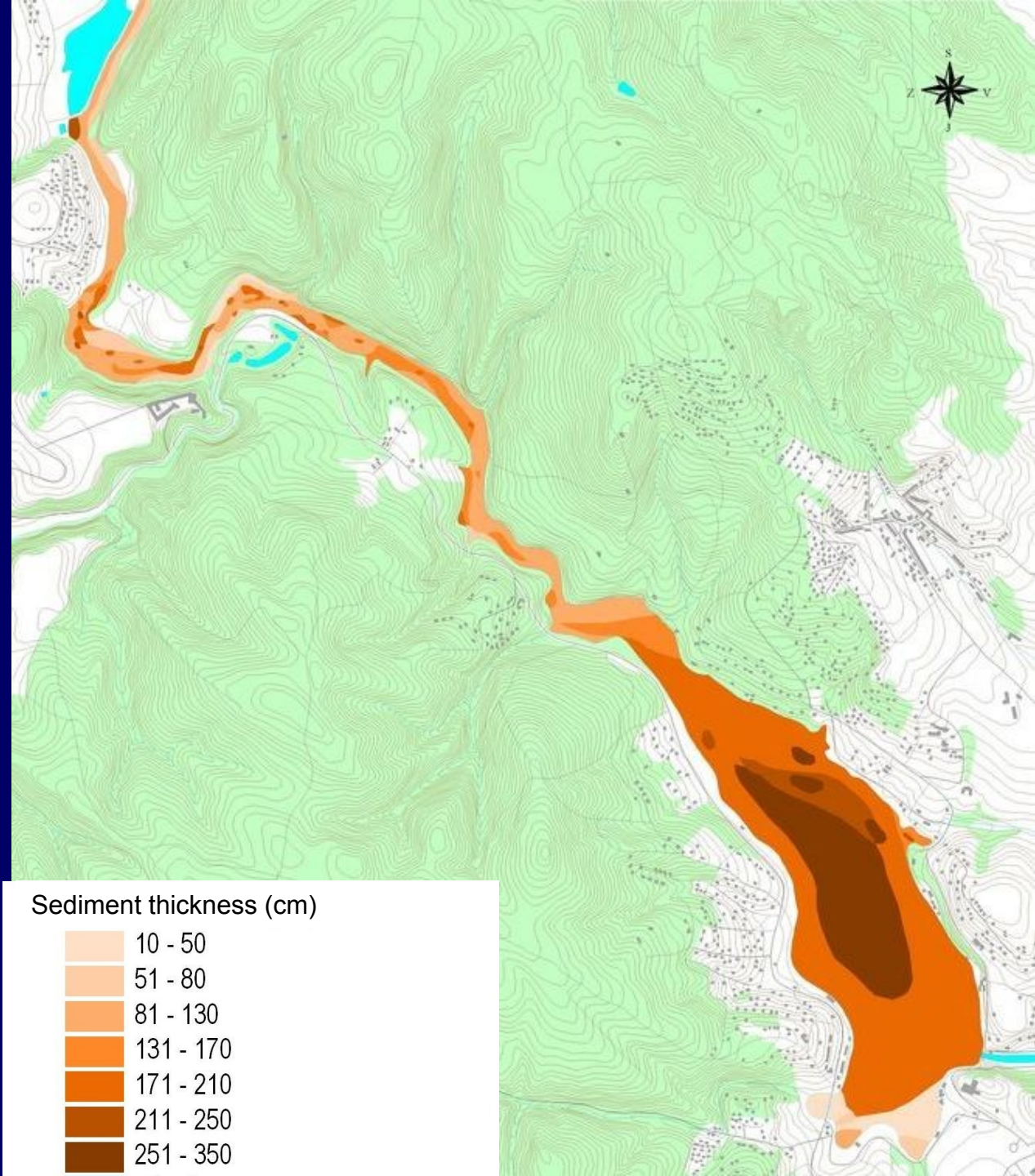
sources of
cyanobacteria
(colonies
in sediment)



Sources of nutrients

... in the
reservoir

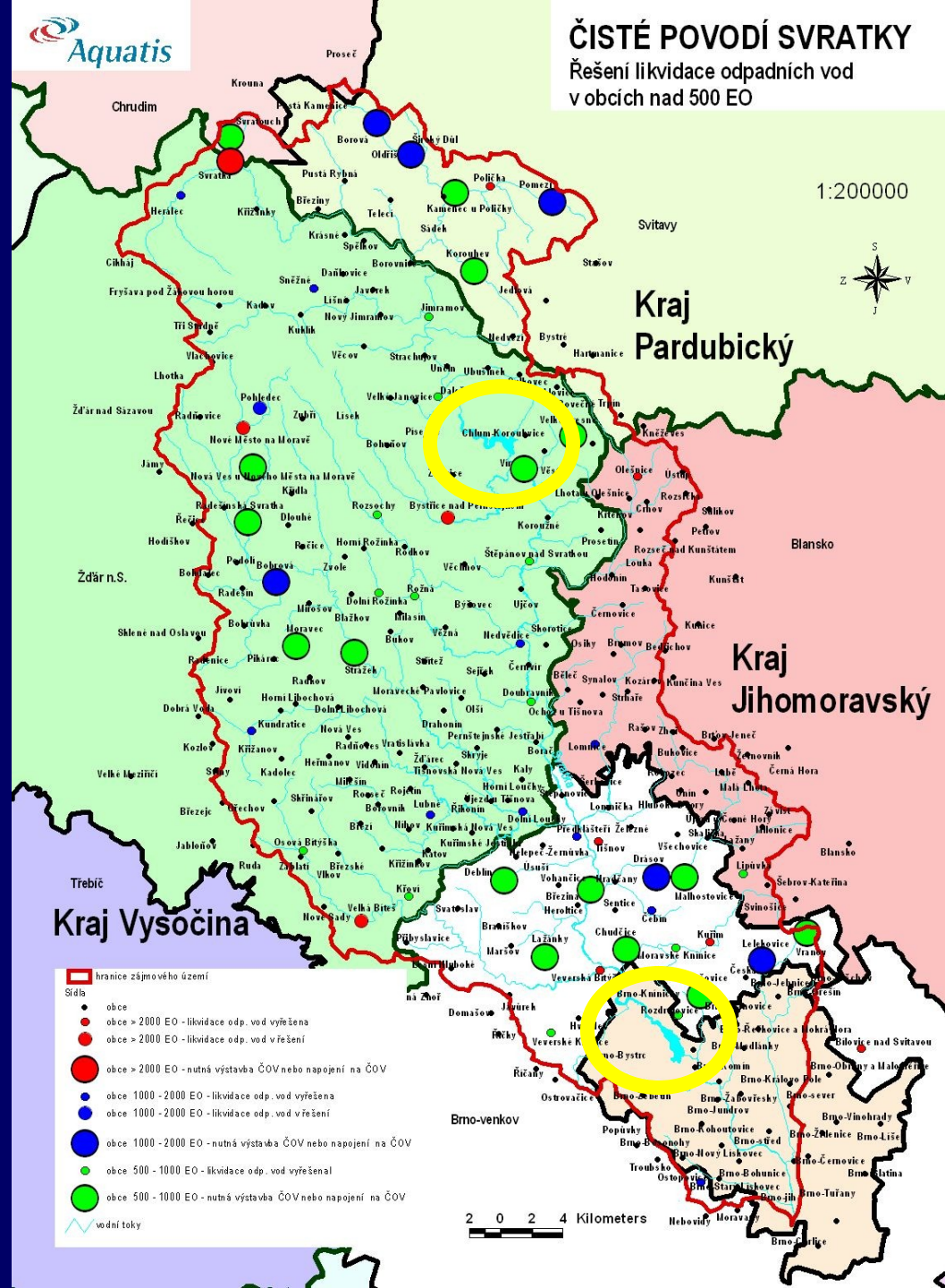
*(sediments
up to 3 m
thickness)*



Sources of nutrients

... upstream

- several small towns & villages (no WWTPs)



CONCLUSIONS

- Eutrophication causes complex risks with complicated management

1) Ecological risks

- Loss of diversity ... followed by losses of functioning
- Secondary changes in the environment
 - hydrochemistry (pH, O₂)
 - loss on natural habitats (makrophytes...)
 - new conditions (associated bacteria - pathogenic ?)
- Susceptibility to catastrophes
- Direct ecotoxicity of individual (known) cyanotoxins seems to be less important

CONCLUSIONS

2) HEALTH RISKS OF CYANOTOXINS

- Lower importance - known toxins (MC) in food chains (*fish*)
- MC in drinking water - higher costs needed for management and control
- Important risk - recreation !

- New and less explored risks
 - new toxins (and their mixtures) - LPS, CYN ...
 - water blooms as „sorbents“ of other toxins (metals, POPs)