Ippen Lecture, Kuala Lumpur, 2017

Cellular Automata in ecohydraulics modeling:

principles, scales and applications

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1935

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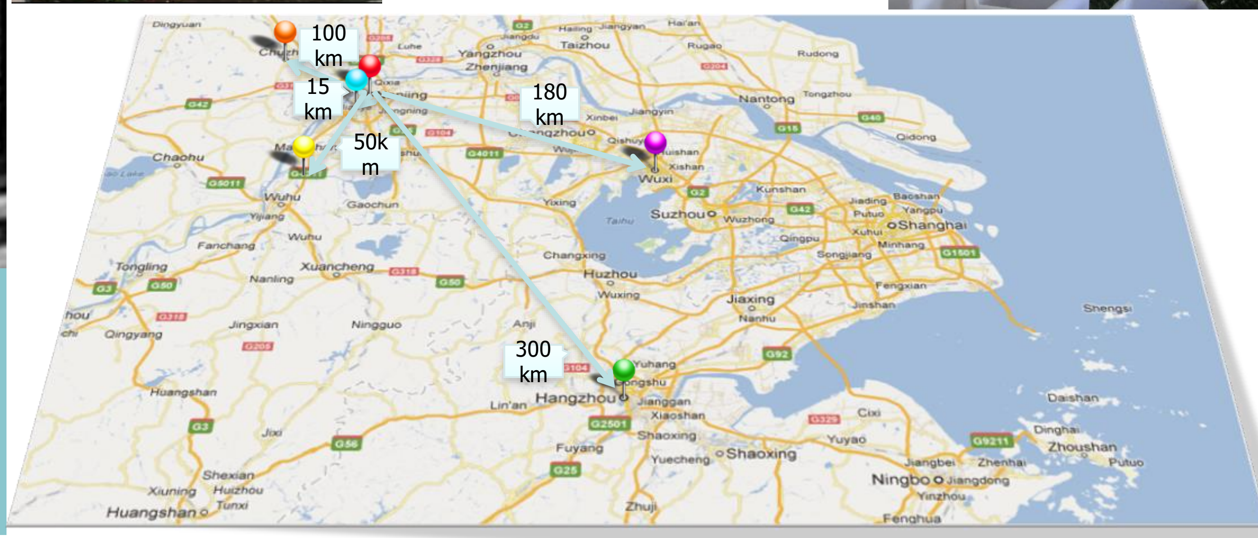
PhD Program

- •River Hydraulics
- •Port, coast and offshore.
- •Water resources
- •Hydro-power engineering
- •Hydraulic structures

NHRI



2009

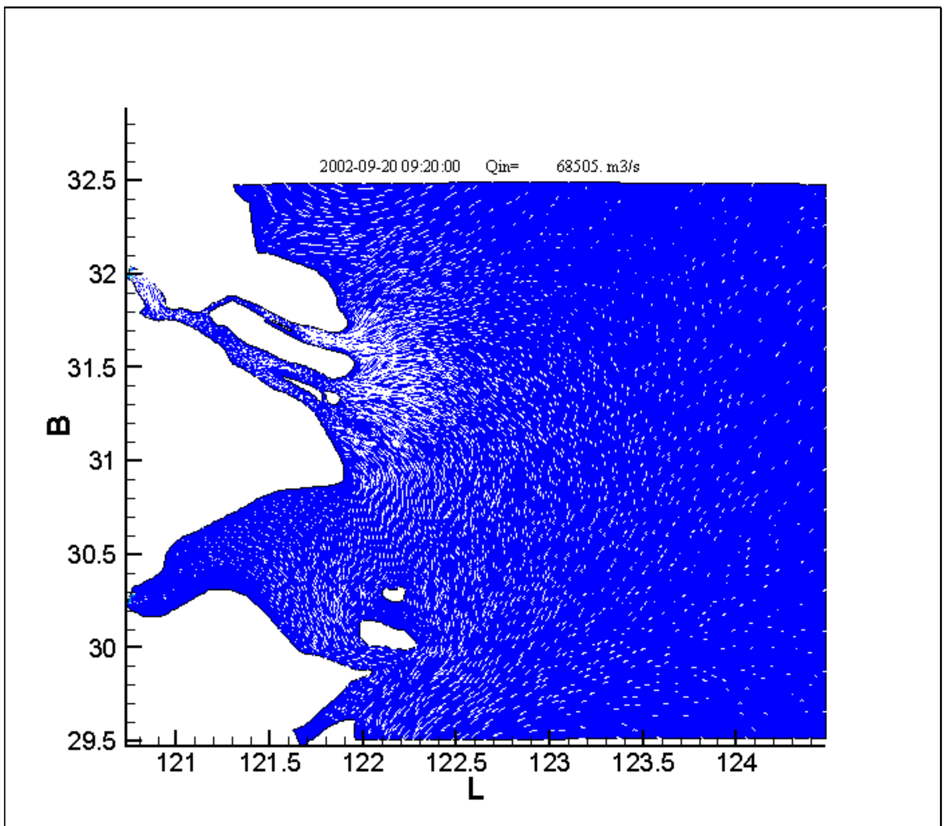
Nanjing Hydraulic Research Institute, MWR, MOT, NEA

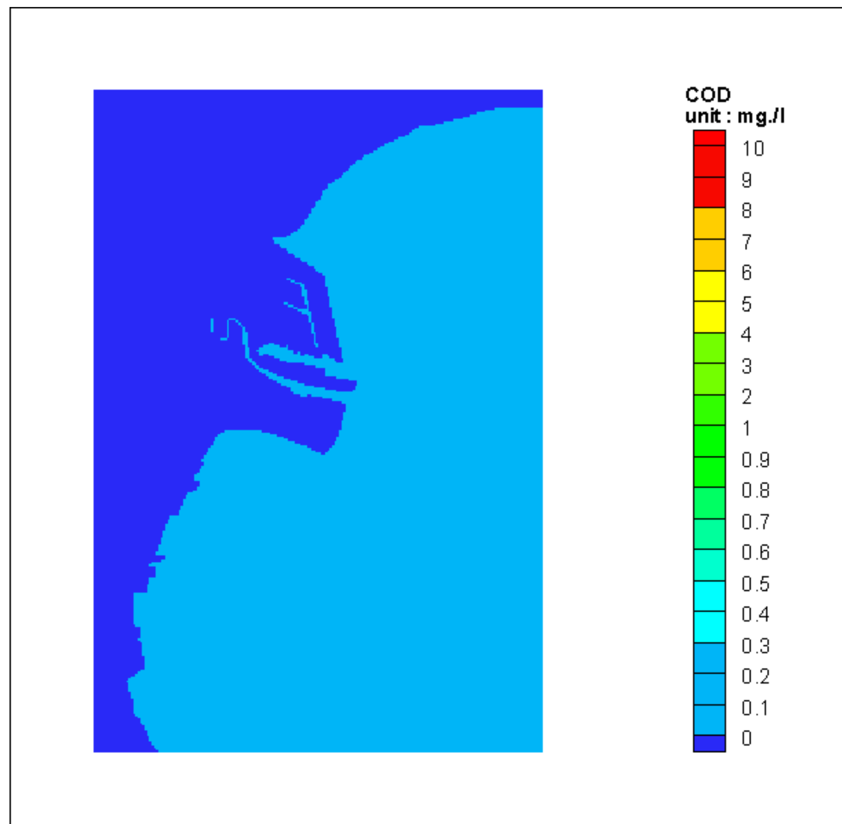
1. Principles in continuous world

❑ Continuity and homogeneity in hydrodynamics

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V} \bullet \nabla)\vec{V} = \vec{F} - \frac{1}{\rho}\nabla P + \upsilon \nabla^2 \vec{V} \qquad \nabla \bullet \vec{V} = 0$$

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} + w\frac{\partial c}{\partial y} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} + D_z \frac{\partial^2 c}{\partial z^2} + S + f_R(c,t)$$





1. Principles in discontinuous world

❑ Peso-continuity and homogeneity in eco-dynamics

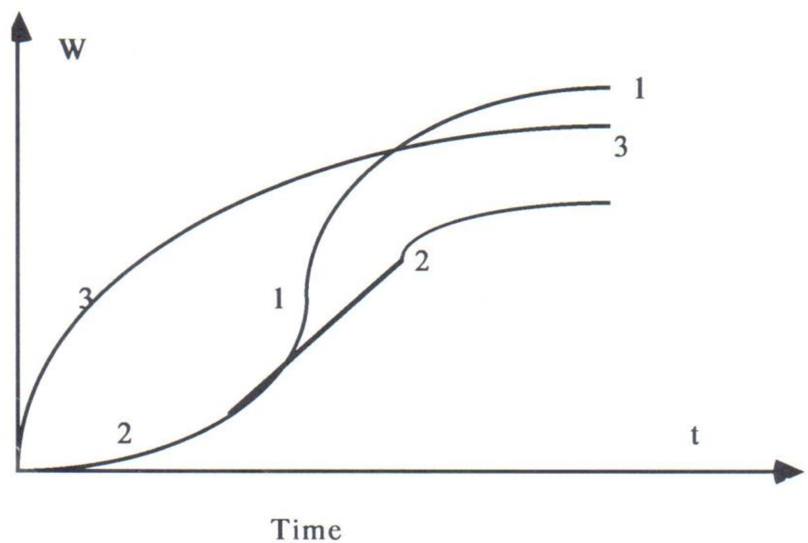
$$r(t) = r_{\max} \frac{C}{K_s + C}$$ Michaelis-Menten

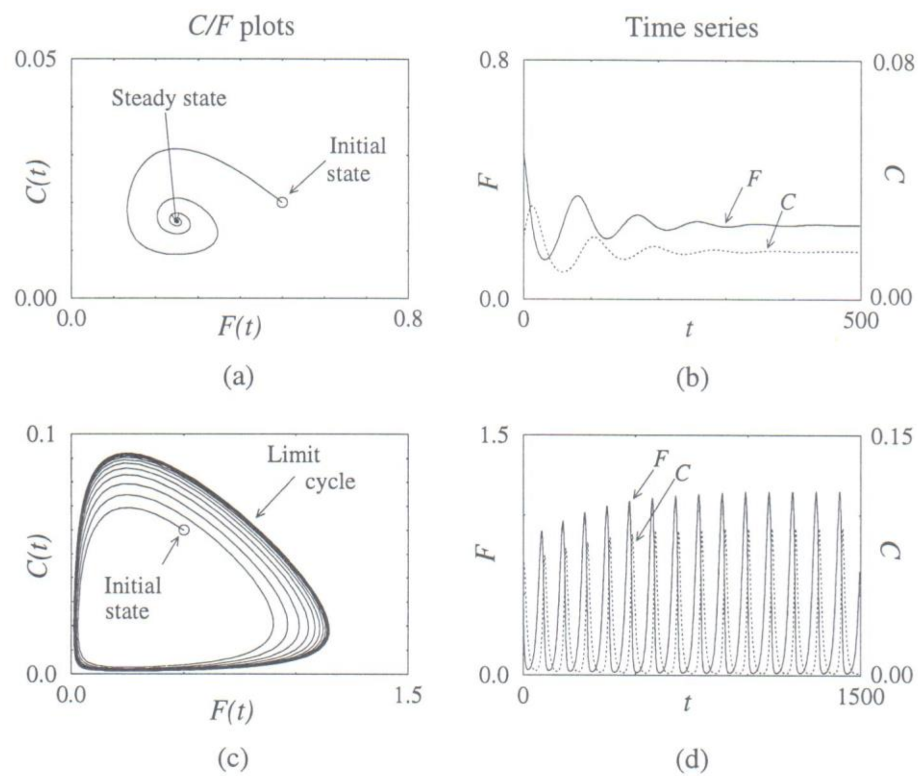
$$\frac{dN}{dt} = rN(1 - \frac{N}{K})$$ Logistic growth

$$\frac{dN}{dt} = rN - \alpha NP$$

$$\frac{dP}{dt} = -cP + \beta NP$$

Lotka-Volterra



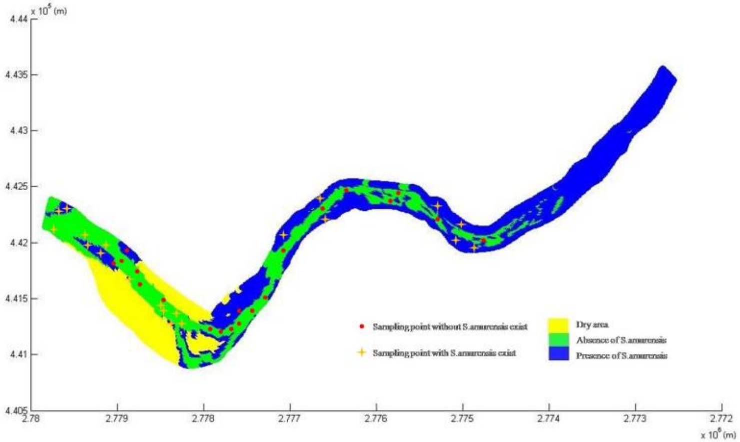


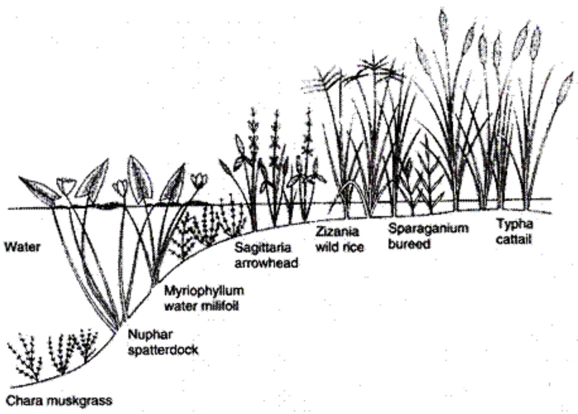
S.E. Jorgensen, Fund. of Ecol. Mod., 1994

W.S. Gurney & R. Nisbet, Ecol. Dyna., 1998

1. Principles in discontinuous world

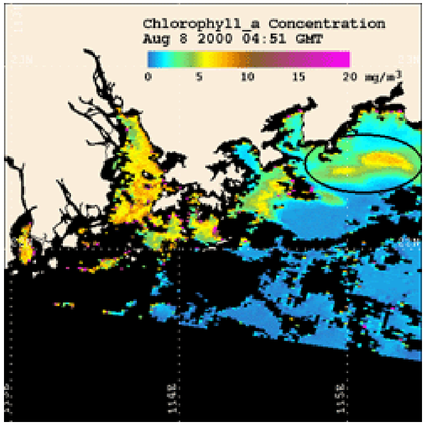
❑ **Facts of aquatic eco-dynamics:** discontinuity & heterogeneity

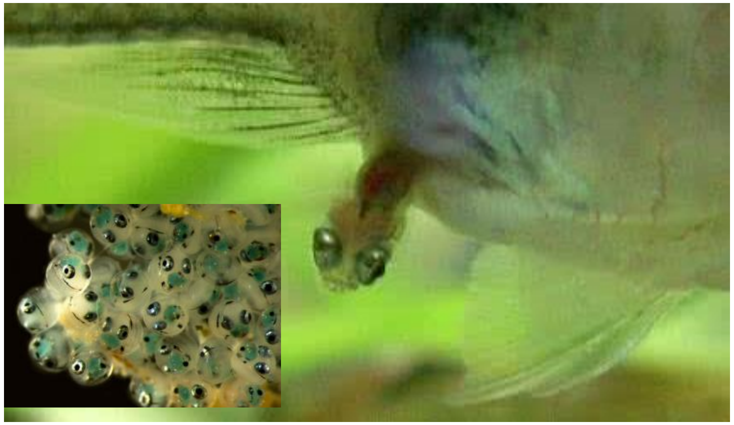




Discrete state: presence/absence

Local vs. global interactions





Spatial heterogeneity

Discontinuous reproduction

Discontinuous predation

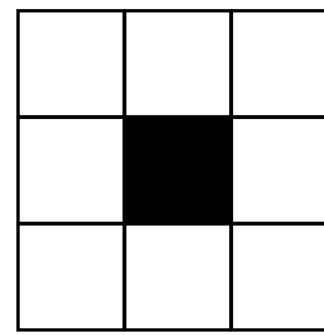
1. Principles in discontinuous world

- **Challenges** in linking fluid dynamics & eco-dynamics
  - ✧ Discrete state
  - ✧ Individual difference
  - ✧ Local interactions



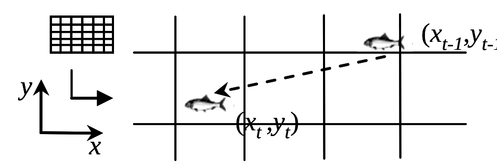
- **Innovative solution** to eco-hydraulics modelling

Cellular automata: discrete in time and space, reproduce complex spatial-temporal dynamic patterns by some simple local interaction rules between cells.



$$a_{i,j}^{t+1} = f(a_{i-1,j-1}^{t}, a_{i-1,j}^{t}, a_{i-1,j+1}^{t}, a_{i,j-1}^{t}, a_{i,j}^{t}, a_{i,j+1}^{t}, a_{i+1,j-1}^{t}, a_{i+1,j}^{t}, a_{i+1,j+1}^{t})$$

Individual based: describe individual properties & behaviours, interactions between individuals, individual & environments.



1. Principles in discontinuous world

❑ Cellular Automata

① A mathematical system, discrete in space and time

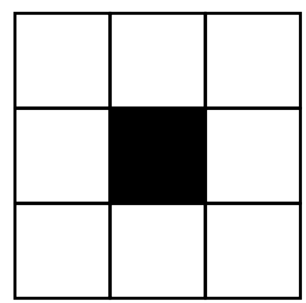
② Consist of a regular lattice of cells (automaton)

③ Each cell has finite possible states

④ Cell state updates according to local interactions

⑤ Global complex patterns emerge through evolutions

$$a_i^{t+1} = f(a_{i-1}^t, a_i^t, a_{i+1}^t)$$



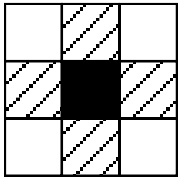
$$a_{i,j}^{t+1} = f(a_{i-1,j-1}^t, a_{i-1,j}^t, a_{i-1,j+1}^t, a_{i,j-1}^t, a_{i,j}^t, a_{i,j+1}^t, a_{i+1,j-1}^t, a_{i+1,j}^t, a_{i+1,j+1}^t)$$

✧ Local behaviours ✧ Spatially explicit ✧ Patchy phenomena

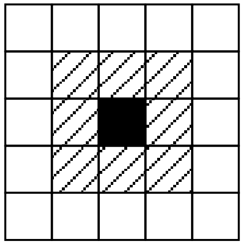
1. Principles in discontinuous world

❑ Cellular Automata: neighbor scheme

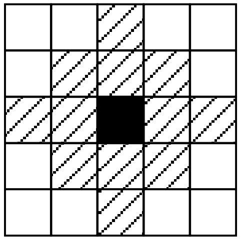
1D Moore



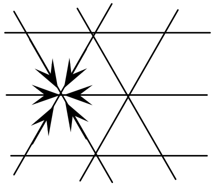
Von Neumann



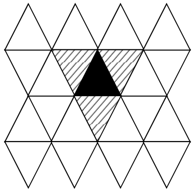
2D Moore



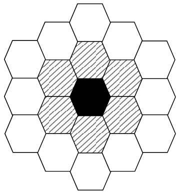
Extended Moore



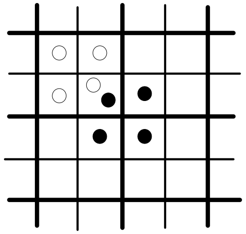
Lattice gas



Triangular



Hexagon



Margolus

1. Principles in discontinuous world

❑ Cellular Automata: initial condition

- ✧ In close automata, initial condition is not sensitive due to memoryless
- ✧ In open automata, external governing factor are incorporated, initial condition must be correctly set

❑ Cellular Automata: boundary conditions

- ✧ In modelling practice, CA must be finite and have boundaries

b	*a*				*b*	*a*

Period boundary

0	*a*				*b*	*0*

Fixed boundary

a	*a*				*b*	*b*

Adiabatic boundary

c	*a*	*c*		*d*	*b*	*d*

Reflection boundary

1. Principles in discontinuous world

❑ Cellular Automata: evolution rules

$$a_{i,j}^{t+1} = f(a_{i-1,j-1}^{t}, a_{i-1,j}^{t}, a_{i-1,j+1}^{t}, a_{i,j-1}^{t}, a_{i,j}^{t}, a_{i,j+1}^{t}, a_{i+1,j-1}^{t}, a_{i+1,j}^{t}, a_{i+1,j+1}^{t})$$

- *f*: evolution rules define cell updating

Stochastic | Deterministic | Hybrid

- Usually totalistic or outer totalistic rule are used

$$C = \sum_{n} f(n) k^{n}$$

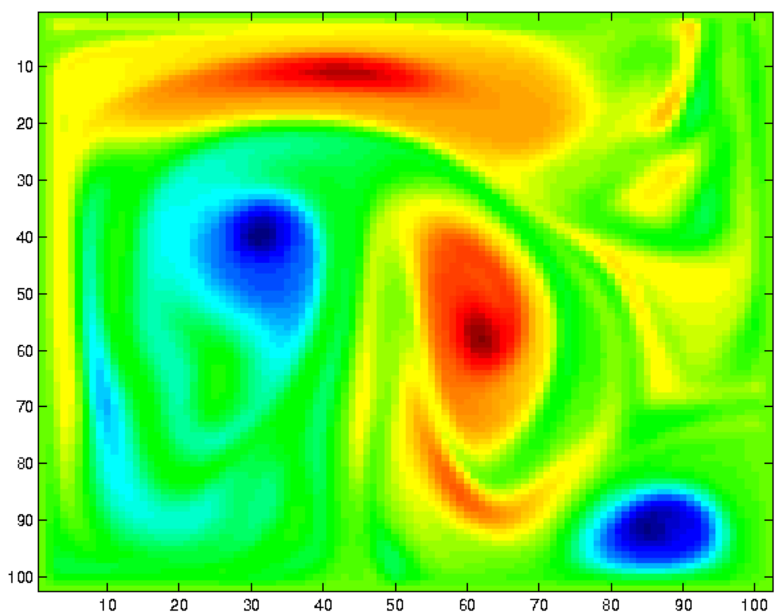
$$\tilde{C} = \sum_{n} \tilde{f}[a,n] k^{kn+a}$$

(Von Neumann, 1949)

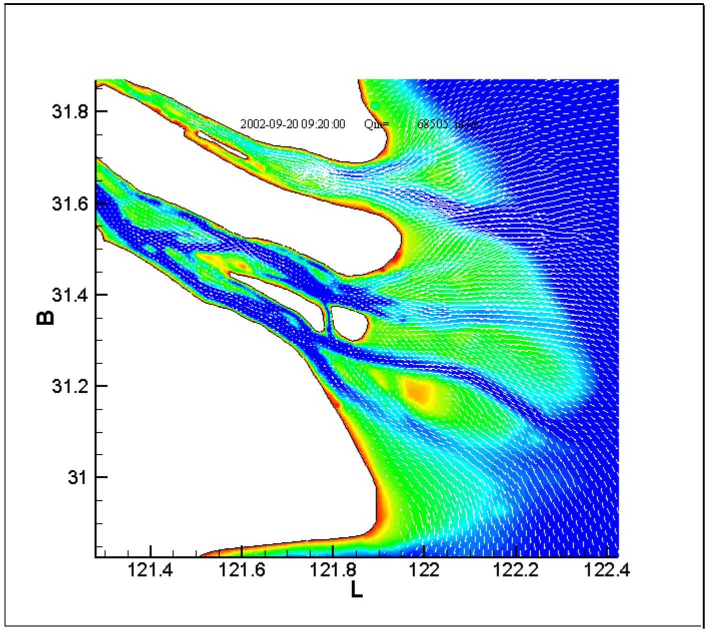
2. Scales in eco-hydraulic model

❑ Scales in hydrodynamic model

- ✧ Direct numerical simulation (DNS): □x = □/2, □ Kolmogorov length scale
- ✧ Large eddy simulation (LES): □x > □/2
- ✧ Reynolds averaged N-S simulation (RANS): engineering scale $C_r = \frac{u\Delta t}{\Delta x}$

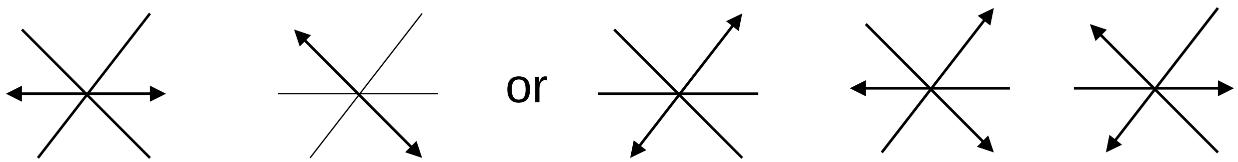


(from *Firmijn Zijl, 2002, TUD*)



2. Scales in eco-hydraulic model

❑ Scales in lattice gas model



(two particles) (three particles)

$$n_i(x+\lambda c_i, t+\tau) = n_i(x,t) + \Delta_i[n(x,t)]$$

$$c_i = (\cos \pi i/3, \sin \pi i/3) \quad u_i = \lambda c_i/\tau \quad \rho(x,t) = \sum_{i=1}^{6} N_i(x,t)$$

$$\sum_i n_i(x+\lambda c_i, t+\tau) = \sum_i n_i(x,t)$$

$$\sum_i u_i n_i(x+\lambda c_i, t+\tau) = \sum_i u_i n_i(x,t)$$

$$\partial_t(u) + (u\nabla)u = -\frac{1}{\rho g(\rho)}\nabla p + \nu\nabla^2 u \qquad \nu = \frac{1}{g(\rho)}\left(\frac{1}{2\rho(1-\frac{\rho}{6})^3} - \frac{1}{8}\right)$$

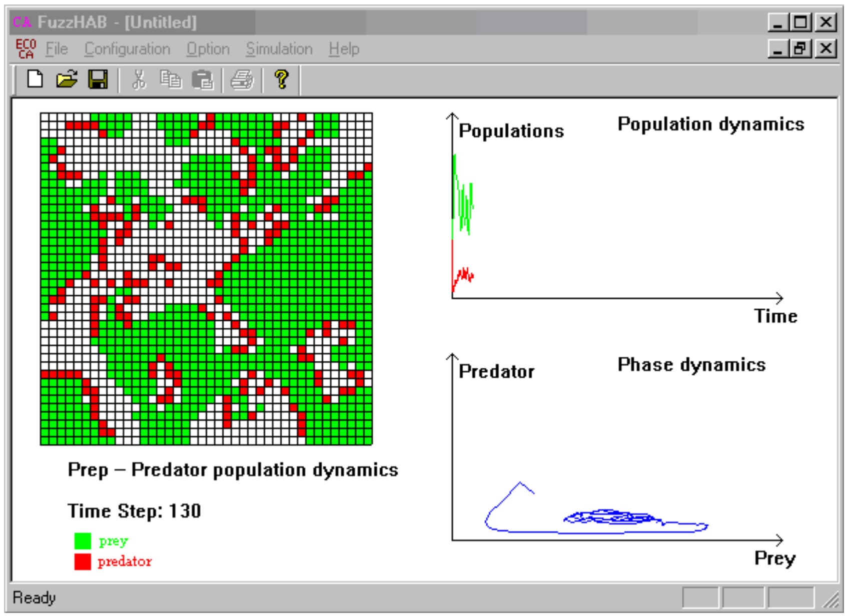
(Wolfram, 1984)

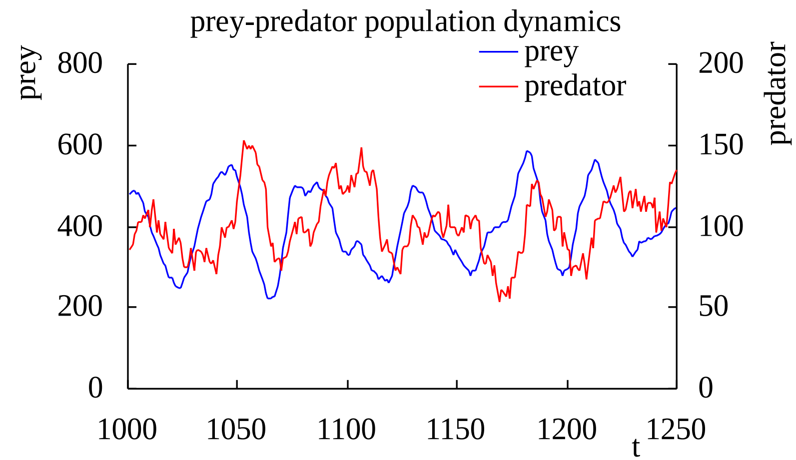
✧ unit Δt, unit Δx, Boolean state, high gradient

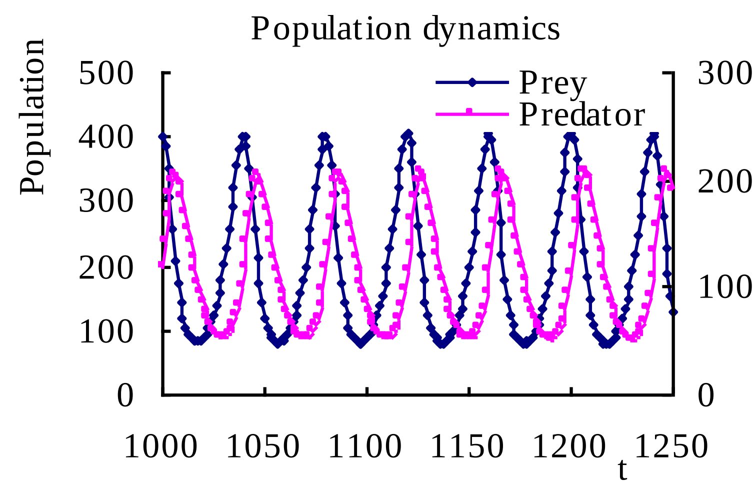
Wolfram, 1984, Nature, 311: 419-424; Wolf-Gladrow, 2000, LNM

2. Scales in eco-hydraulic model

❑ Scales in two species dynamic model







✧ Δt: mean predation time interval

✧ Δx: maximum searching radius

Qu et al, 2008, *Eco Inf*, 3: 252-258 (citations: 58)

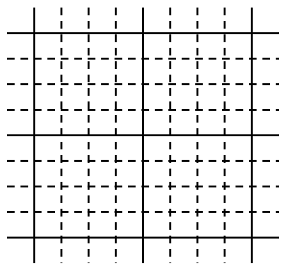
Chen and Mynett., 2003,*SIMPRA*, 11: 609-625

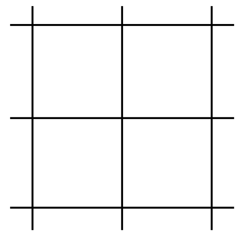
$$\frac{dN}{dt} = rN - \alpha NP \qquad \frac{dP}{dt} = -cP + \beta NP$$

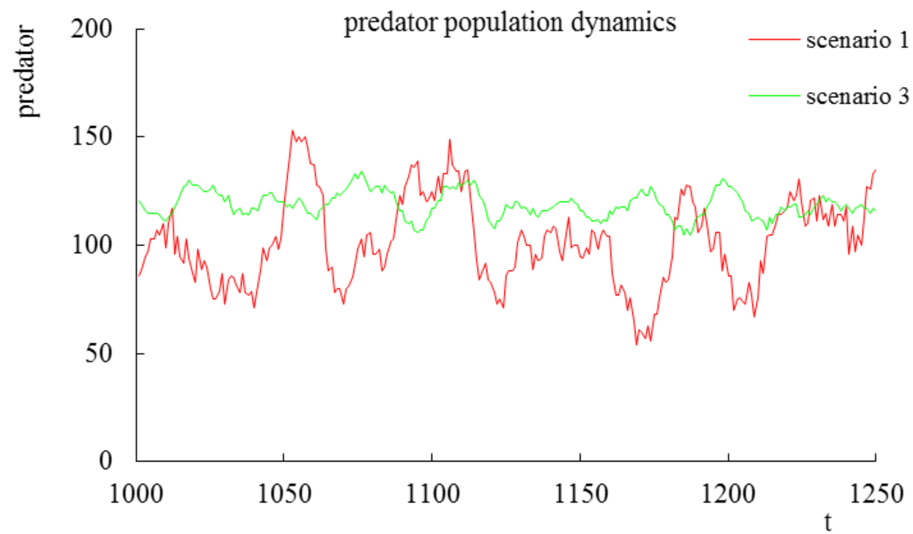
No Δx!!

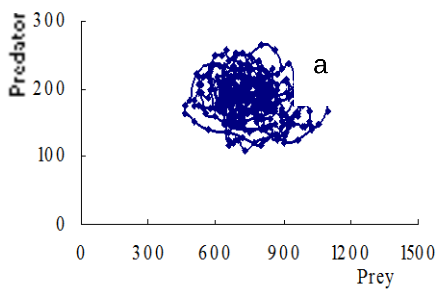
2. Scales in eco-hydraulic model

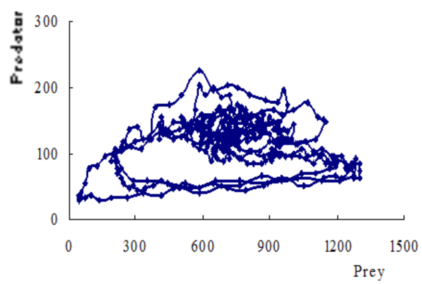
❑ Scales in two species dynamic model











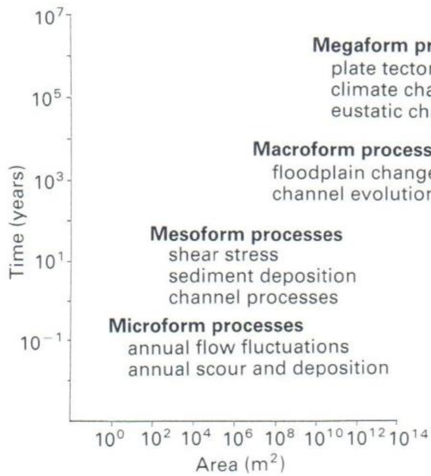
	Scenario 1		Scenario 2	
	Mean	Stdv.	Mean	Stdv.
Prey	397	89	382	24
Predator	106	23	118	6

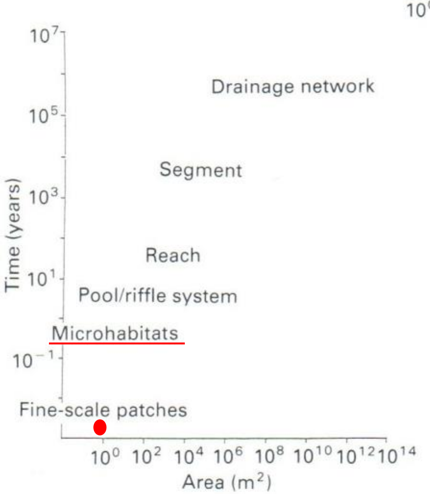
- ✧ CA reveals the embedded structure stability
- ✧ Improper spatial scale (Δx) creates artefact patterns

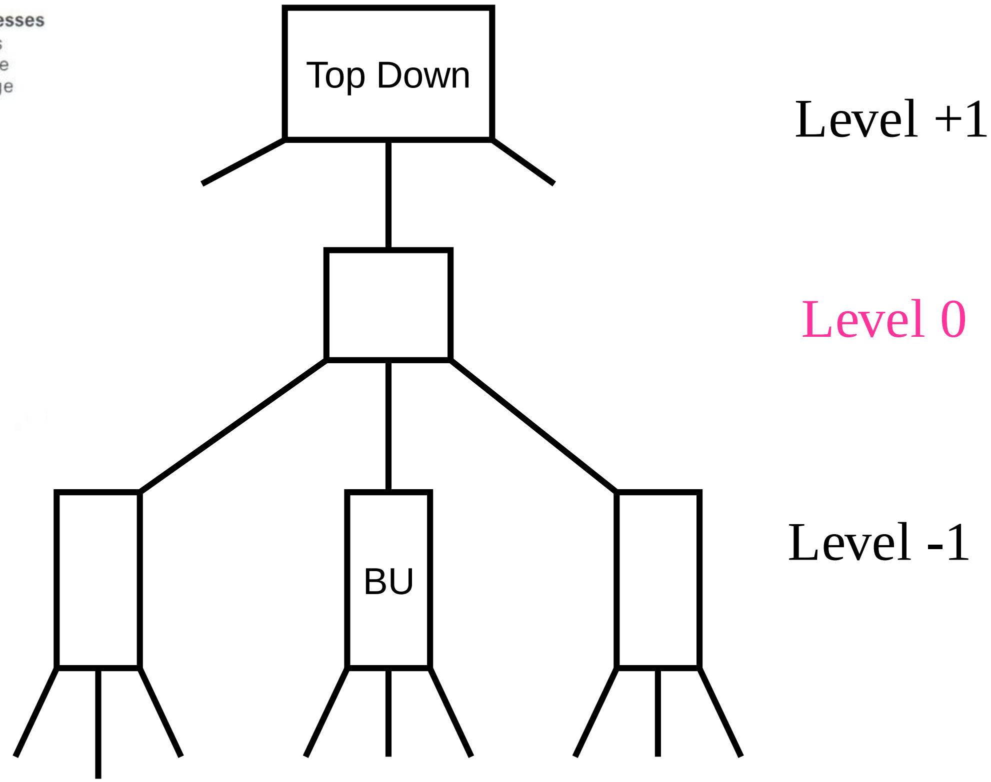
Chen and Mynett., 2003, *SIMPRA*, 11: 609-625

2. Scales in eco-hydraulic model

❑ Hierarchic scales in aquatic ecosystem







P.S. Giller, et al., 1994, Aquatic ecology   *J. Wu & David J.L.,* Eco Mod, 153: 7-26

2. Scales in eco-hydraulic model

❑ Scales identification and coupling

- Spatial scale analysis (Gussian field)

$$\rho_{x,\, x+\Delta x} = \rho_0 + (1-\rho_0) e^{-(\Delta x / L)^2}$$

$\rho_{x,\, x+\Delta x}$: correlation between two spatial cells

L: characteristic scale of studied system level

- Spatial scale analysis (Wavelet analysis)

$$\omega(\eta, x) = \frac{1}{a}\int_{-\infty}^{+\infty} f(x) g(x - \frac{\xi}{\eta}) dx \qquad \omega(\eta) = \int_{-\infty}^{+\infty} \omega^2(\eta, x) dx$$

η : scale factor;

ξ: the point around which the Wavelet is centred.

✧ Cell size $\Delta x \le L/2$, Δt is determined according to Δx.

2. Scales in eco-hydraulic model

❑ Scales identification and coupling

- High frequency components: Upscaling

Simple averaging: $$\overline{A(t)} = \frac{1}{N}\sum_{i=1}^{N} A$$

Weighted averaging: $$\overline{A(t)} = \int_{\varepsilon} A(E')p(t,E')dE'$$

Power averaging: $$\overline{A(t)} = [\frac{1}{N}\sum_{i=1}^{N} A_i^p]^{\frac{1}{p}}$$

- Low frequency components: Downscaling

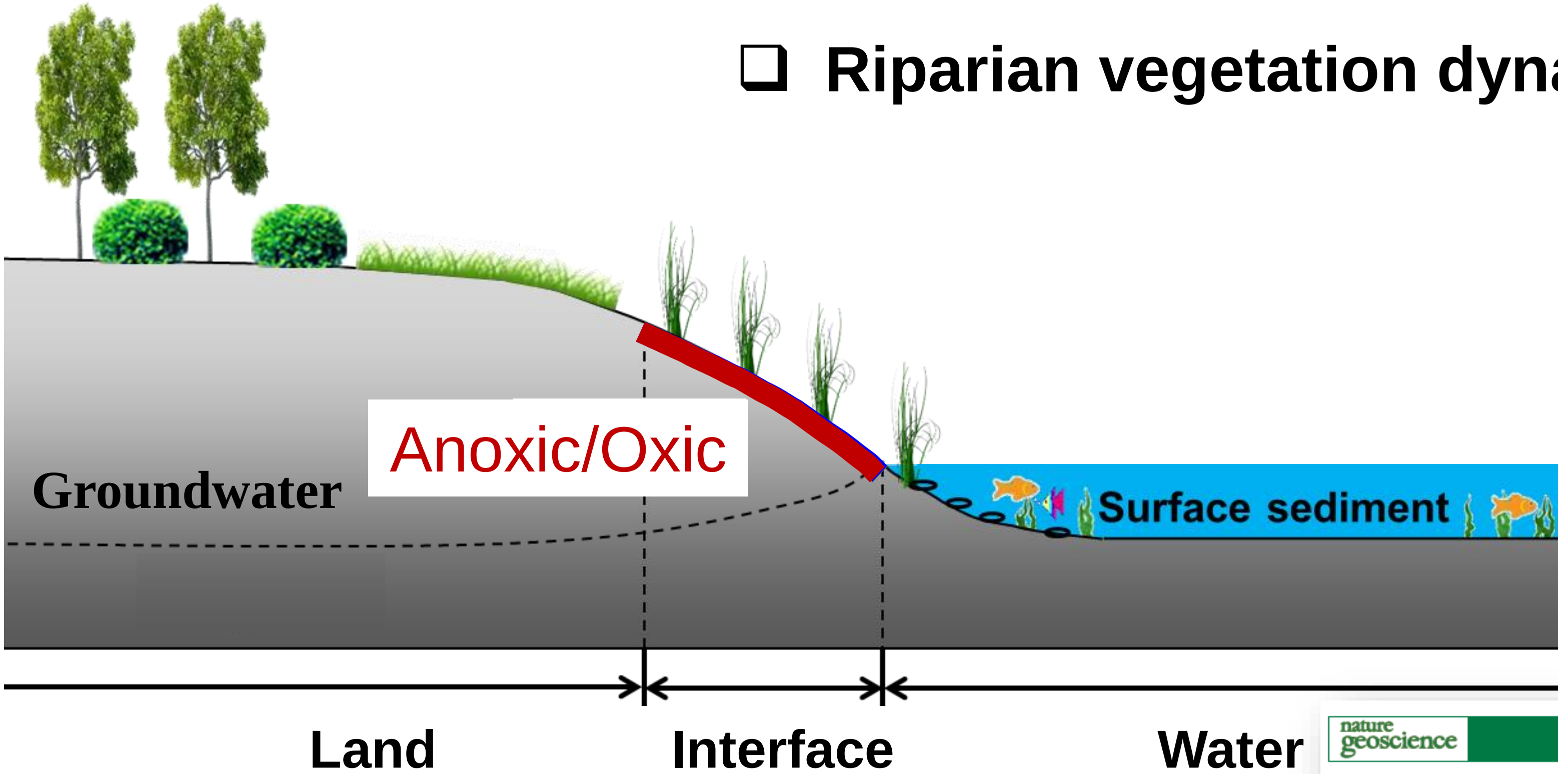
Use up level components as constraint to the dynamics of the studied level

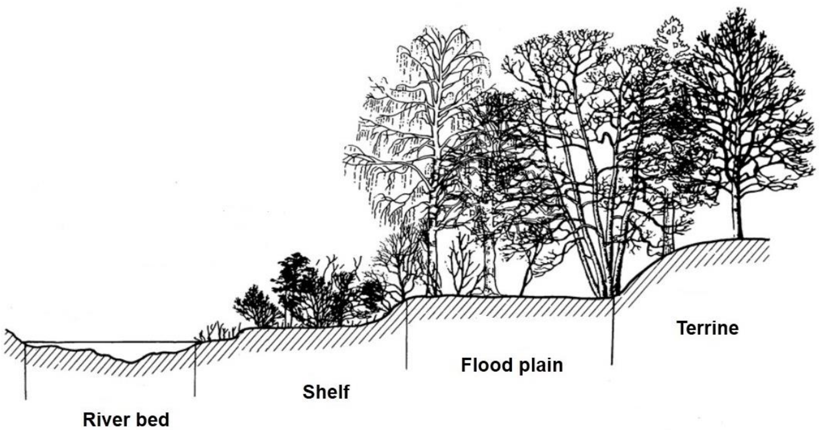
$$a_{i,j}^{t+1} = f(Neb,\ For \,|\, B)$$

Chen et al., 2006, *JHI*,8(3): 297-316; Chen et al., 2006, *Eco Mod*, 199(1): 73-82

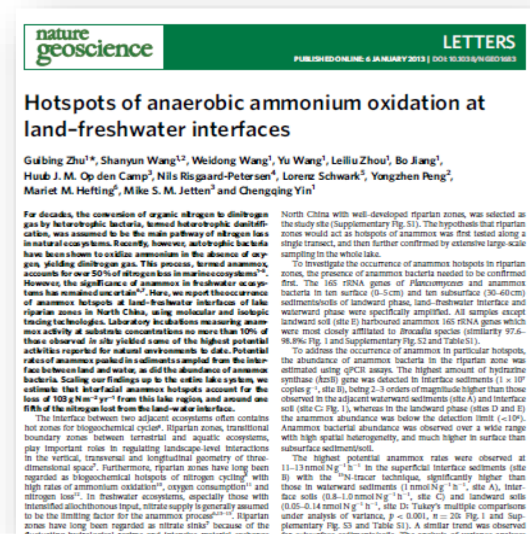
3. Applications in ecohydraulics

❑ Riparian vegetation dynamics





Zhu, et al.,
Nature Geoscience,
2011, 981-987



nature geoscience LETTERS
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Hotspots of anaerobic ammonium oxidation at land–freshwater interfaces

Guibing Zhu[1]*, Shanyun Wang[1,2], Weidong Wang[1], Yu Wang[1], Leiliu Zhou[1], Bo Jiang[1], Huub J. M. Op den Camp[3], Nils Risgaard-Petersen[4], Lorenz Schwark[5], Yongzhen Peng[2], Mariet M. Hefting[6], Mike S. M. Jetten[3] and Chengqing Yin[1]

For decades, the conversion of organic nitrogen to dinitrogen gas by heterotrophic bacteria, termed heterotrophic denitrification, was assumed to be the main pathway of nitrogen loss in natural ecosystems. Recently, however, autotrophic bacteria have been shown to oxidize ammonium in the absence of oxygen, yielding dinitrogen gas. This process, termed anammox, accounts for over 50% of nitrogen loss in marine ecosystems[1–5]. However, the significance of anammox in freshwater ecosystems has remained uncertain[6,7]. Here, we report the occurrence of anammox hotspots at land–freshwater interfaces of lake riparian zones in North China, using molecular and isotopic tracing technologies. Laboratory incubations measuring anammox activity at substrate concentrations no more than 10% of those observed *in situ* yielded some of the highest potential activities reported for natural environments to date. Potential rates of anammox peaked in sediments sampled from the interface between land and water, as did the abundance of anammox bacteria. Scaling our findings up to the entire lake system, we estimate that interfacial anammox hotspots account for the loss of 103 g N m^{-2} yr^{-1} from this lake region, and around one fifth of the nitrogen lost from the land–water interface.

The interface between two adjacent ecosystems often contains hot zones for biogeochemical cycles[8]. Riparian zones, transitional boundary zones between terrestrial and aquatic ecosystems, play important roles in regulating landscape-level interactions in the vertical, transversal and longitudinal geometry of three-dimensional space[7]. Furthermore, riparian zones have long been regarded as biogeochemical hotspots of nitrogen cycling[9] with high rates of ammonium oxidation[10], oxygen consumption[11] and nitrogen loss[12]. In freshwater ecosystems, especially those with intensified allochthonous input, nitrate supply is generally assumed to be the limiting factor for the anammox process[6,13–15]. Riparian zones have long been regarded as nitrate sinks[7] because of the

North China with well-developed riparian zones, was selected as the study site (Supplementary Fig. S1). The hypothesis that riparian zones would act as hotspots of anammox was first tested along a single transect, and then further confirmed by extensive large-scale sampling in the whole lake.

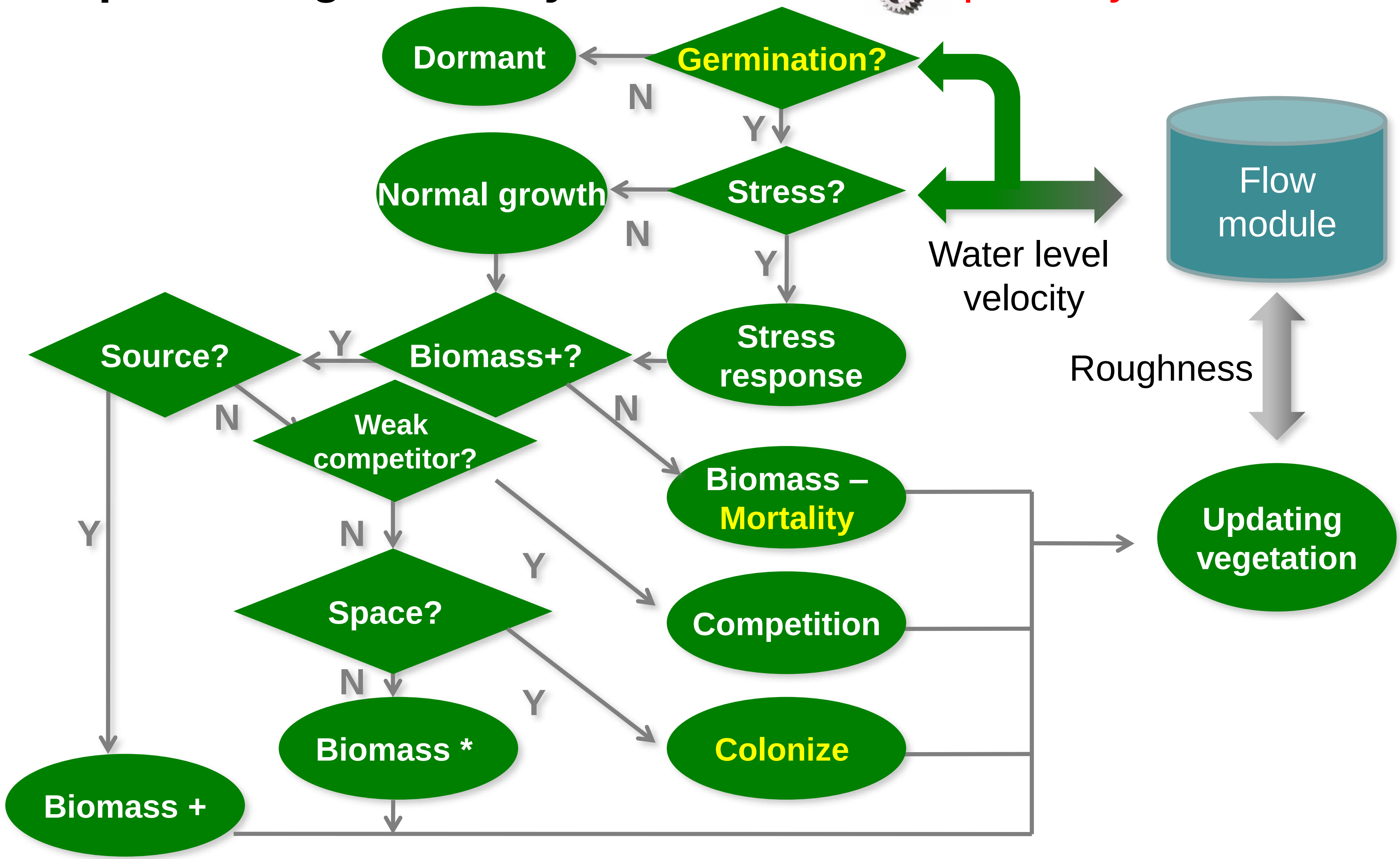
To investigate the occurrence of anammox hotspots in riparian zones, the presence of anammox bacteria needed to be confirmed first. The 16S rRNA genes of *Planctomycetes* and anammox bacteria in ten surface (0–5 cm) and ten subsurface (30–60 cm) sediments/soils of landward phase, land–freshwater interface and waterward phase were specifically amplified. All samples except landward soil (site E) harboured anammox 16S rRNA genes which were most closely affiliated to *Brocadia* species (similarity 97.6–98.8%; Fig. 1 and Supplementary Fig. S2 and Table S1).

To address the occurrence of anammox in particular hotspots, the abundance of anammox bacteria in the riparian zone was estimated using qPCR assays. The highest amount of hydrazine synthase (*hzsB*) gene was detected in interface sediments (1×10^7 copies g^{-1}, site B), being 2–3 orders of magnitude higher than those observed in the adjacent waterward sediments (site A) and interface soil (site C; Fig. 1), whereas in the landward phase (sites D and E) the anammox abundance was below the detection limit ($<10^4$). Anammox bacterial abundance was observed over a wide range with high spatial heterogeneity, and much higher in surface than subsurface sediment/soil.

The highest potential anammox rates were observed at 11–13 nmol N g^{-1} h^{-1} in the superficial interface sediments (site B) with the ^{15}N-tracer technique, significantly higher than those in waterward sediments (1 nmol N g^{-1} h^{-1}, site A), interface soils (0.8–1.0 nmol N g^{-1} h^{-1}, site C) and landward soils (0.05–0.14 nmol N g^{-1} h^{-1}, site D; Tukey's multiple comparisons under analysis of variance, $p < 0.001$, $n = 20$; Fig. 1 and Supplementary Fig. S3 and Table S1). A similar trend was observed

3. Applications in ecohydraulics

❑ **Riparian vegetation dynamics:** flow plant dynamics



3. Applications in ecohydraulics

❑ Riparian vegetation dynamics – flow stress

$$Y(t+\Delta t)=\begin{cases} lag\cdot bY(t)\left[1-Y(t)/K\right]\Delta t+Y(t) & \text{Light stress} \\ (1-loss)\cdot Y(t) & \text{Middle stress} \\ (1-loss)\cdot Y(t)\cdot\dfrac{abs\left[sign(\Delta r)\right]+sign(\Delta r)}{2} & \text{Strong stress} \end{cases}$$

Growth rate is < current growth rate

Biomass loss

Biomass loss & certain mortality

Ye F., et al., 2010, *Eco. Info.*, 5: 108-114

Liu R., et al., 2014,*Scientific Report*, 4: 5507

3. Applications in ecohydraulics

❑ Riparian vegetation dynamics – species competition

$$\Delta B_{weak} = -\Delta B_{strong} \cdot \frac{C_{strong}}{C_{weak}}$$

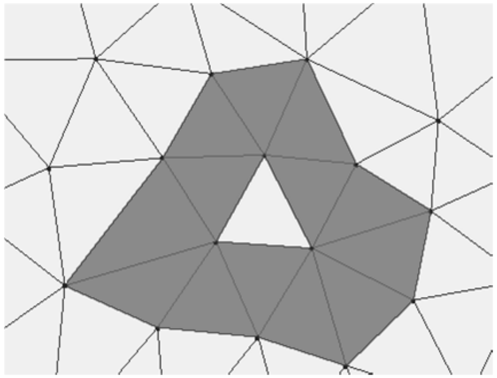
ΔB_{weak} = biomass change of weak competing species

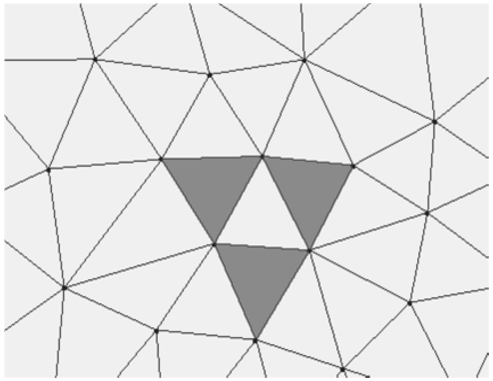
C_{weak} = source consumption rate of weak species

ΔB_{strong} = biomass change of weak competing species

C_{strong} = source consumption rate of strong species

❑ Riparian vegetation dynamics – species colonization





Each species has a maximum colonization extend, depending on species physiology and filed survey results

3. Applications in ecohydraulics

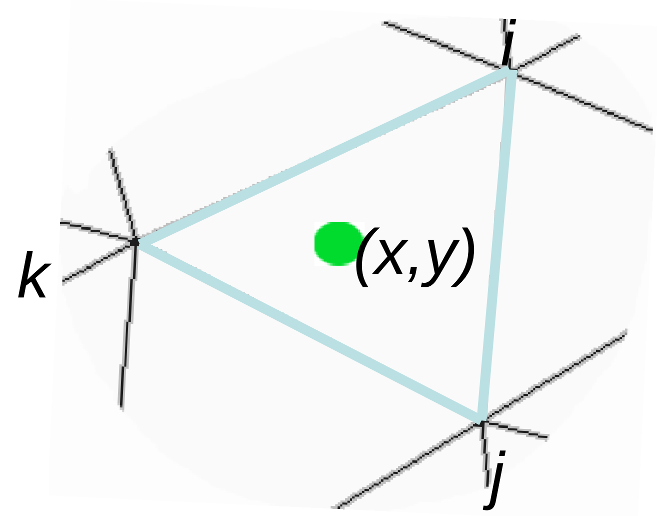
❑ Flow → Vegetation interaction

- To each CA cell, define…

$$L_i = \frac{1}{2\Delta}\left(a_i + b_i x + c_i y\right)$$

$$L_j = \frac{1}{2\Delta}\left(a_j + b_j x + c_j y\right)$$

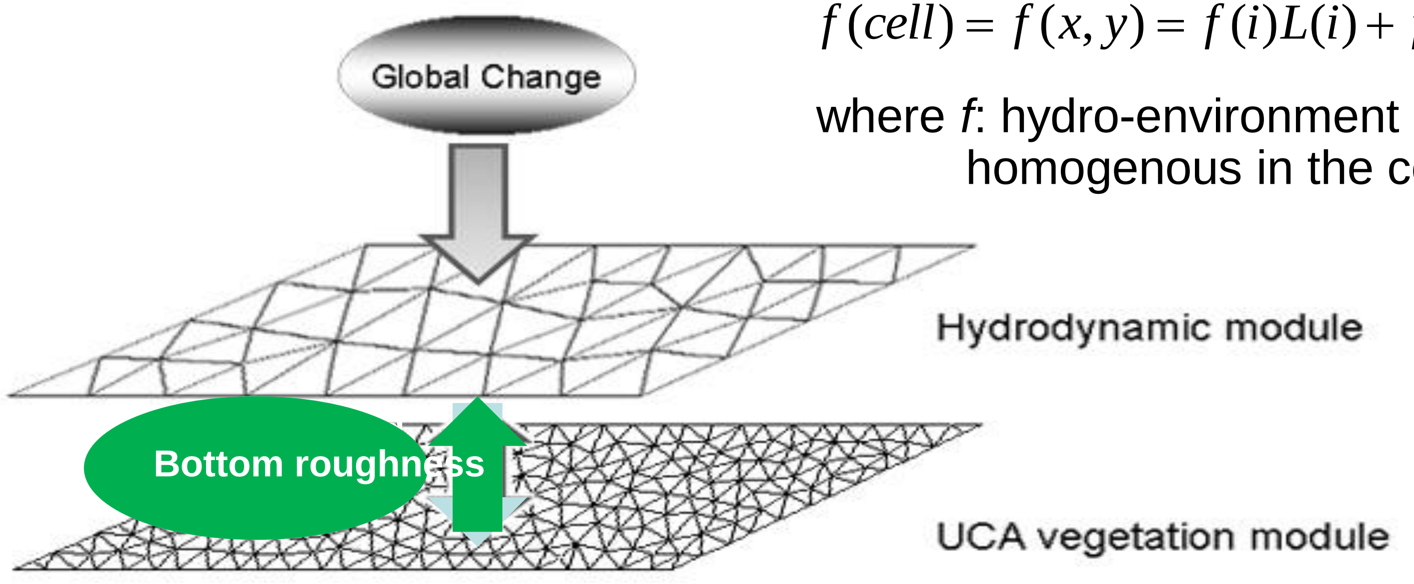
$$L_m = \frac{1}{2\Delta}\left(a_m + b_m x + c_m y\right)$$



- To each CA cell, the hydro-environ effect

$$f(cell) = f(x,y) = f(i)L(i) + f(j)L(j) + f(k)L(k)$$

where *f*: hydro-environment factor, and assuming homogenous in the cell

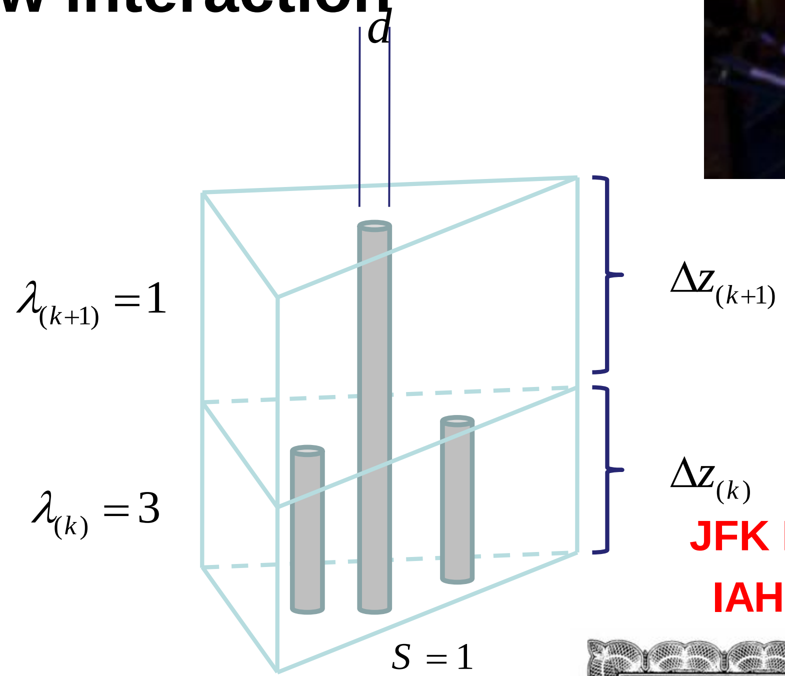


3. Applications in ecohydraulics

❑ Vegetation → Flow interaction

- Method 1

$$C_d = \frac{g(n_b + n_{plant})^2}{R^{1/3}}$$



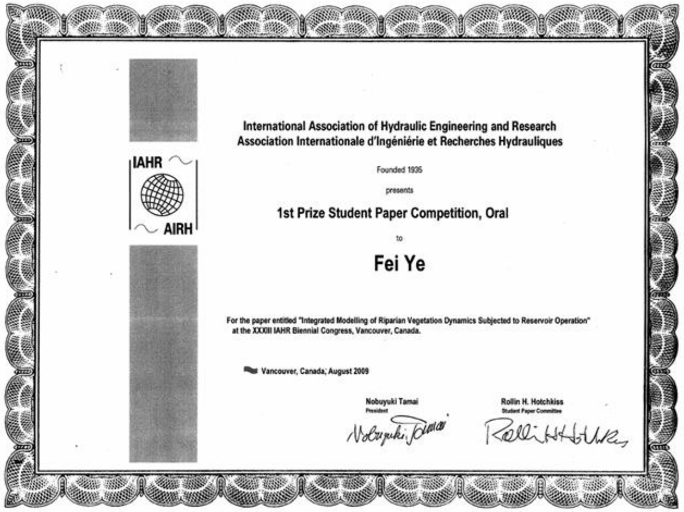
- Method 2

$$F_D = \frac{1}{2} C'_d \lambda \rho U^2$$

- Method 3

$$F_D = \frac{1}{2} C'_d \rho U^2$$

JFK Best Student Paper, IAHR 2009, Vancouver



IAHR
AIRH

International Association of Hydraulic Engineering and Research
Association Internationale d'Ingéniérie et Recherches Hydrauliques

Founded 1935

presents

1st Prize Student Paper Competition, Oral

to

Fei Ye

For the paper entitled "Integrated Modelling of Riparian Vegetation Dynamics Subjected to Reservoir Operation" at the XXXIII IAHR Biennial Congress, Vancouver, Canada.

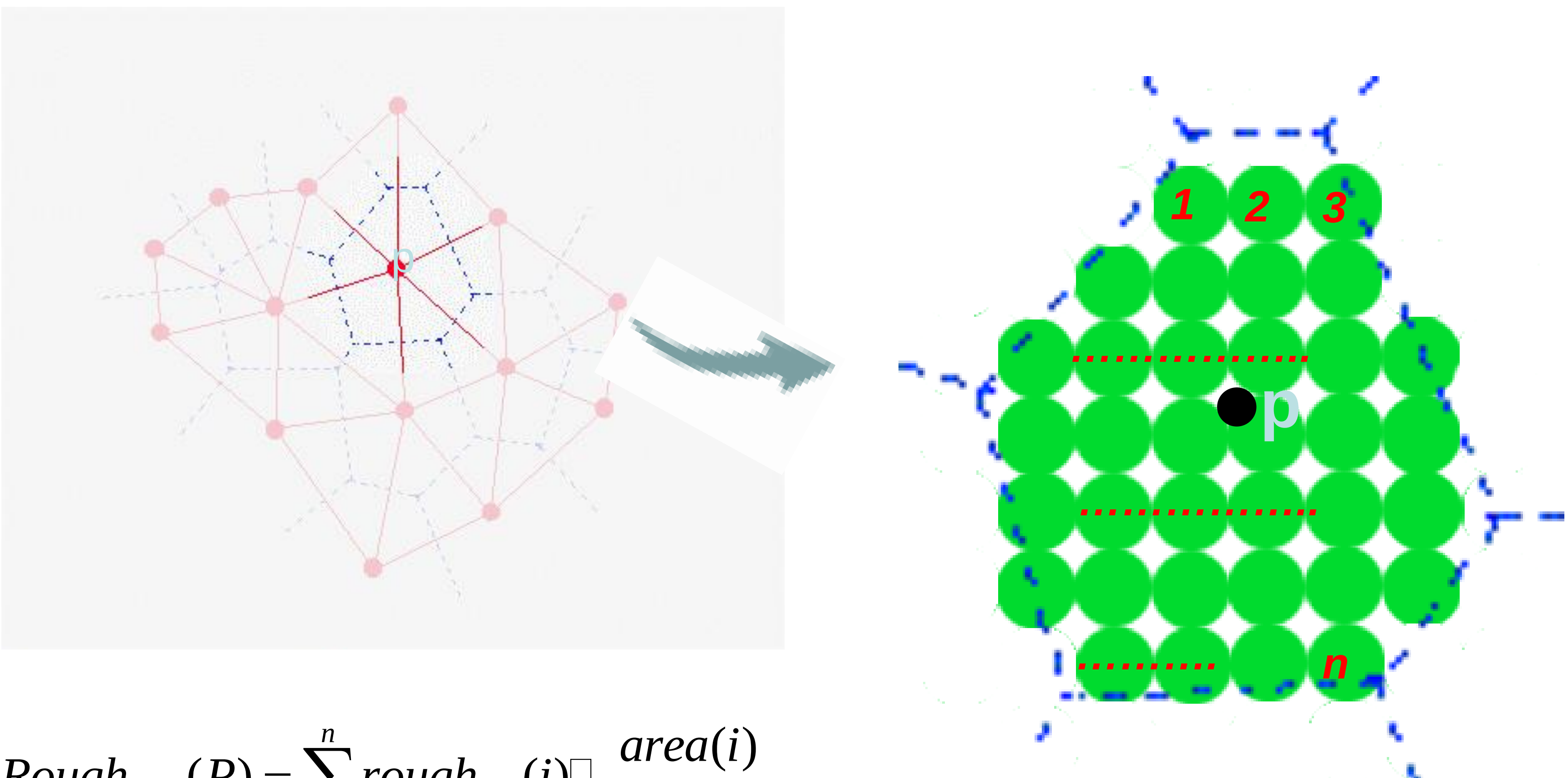
Vancouver, Canada; August 2009

Nobuyuki Tamai
President

Rollin H. Hotchkiss
Student Paper Committee

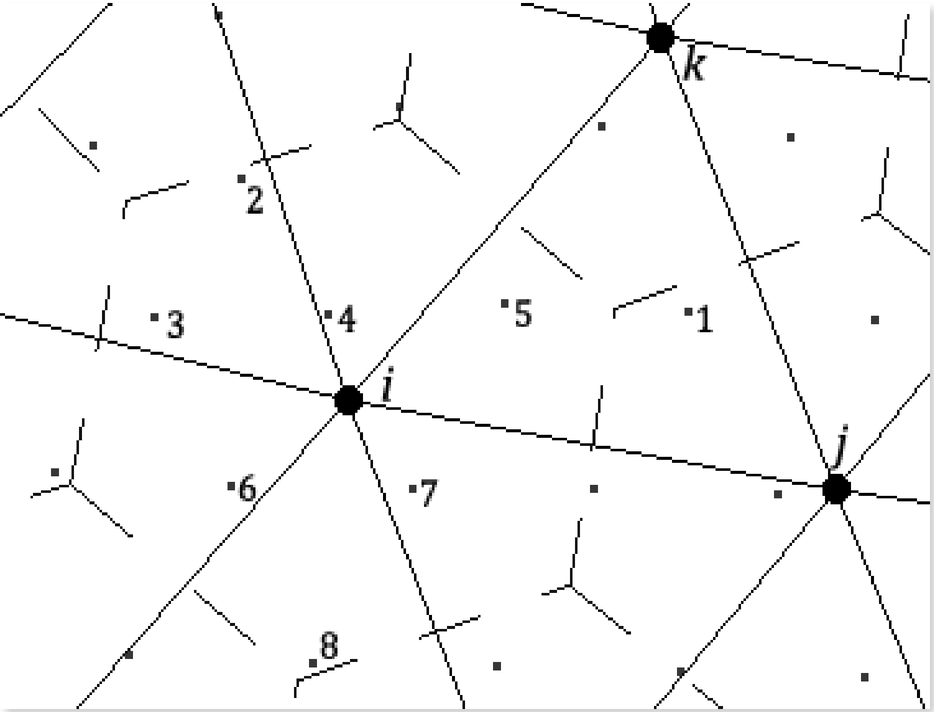
3. Applications in ecohydraulics

❑ Vegetation → Flow interaction



$$Rough_{node}(P) = \sum_{i=1}^{n} rough_{cell}(i) \cdot \frac{area(i)}{\sum_{i=1}^{n} area(i)}$$

3. Applications in ecohydraulics



——— Flow edge

- - - - Tientsin polygon

● Flow node

• Plant node

Flow→Plant

$$f_{plant}(1) = f_{plant}(x_c, y_c) = f_{hydro}(i)L_i + f_{hydro}(j)L_j + f_{hydro}(k)L_k$$

$$\begin{cases} L_i(x,y) = \dfrac{(x_j y_k - x_k y_j) + (y_j - y_k)x + (x_k - x_j)y}{2\Delta_{ijk}} \\ L_j(x,y) = \dfrac{(x_k y_i - x_i y_k) + (y_k - y_i)x + (x_i - x_k)y}{2\Delta_{ijk}} \\ L_k(x,y) = \dfrac{(x_i y_j - x_j y_i) + (y_i - y_j)x + (x_j - x_i)y}{2\Delta_{ijk}} \end{cases}$$

Plant →Flow

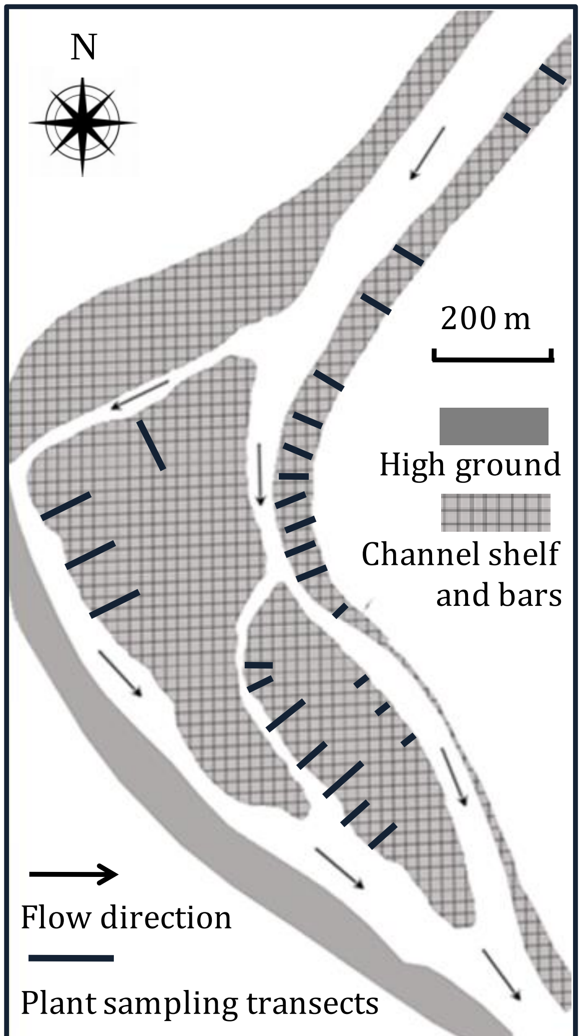
$$f_{hydro}(i) = \sum_{n=2}^{8} f_{plant}(n)w(n)$$

$$w(n) = \Delta_n / \Delta_{ijk}$$

Ye F., et al., 2013, *Ecohydrology*, 6(4): 567-585

3. Applications in ecohydraulics

❑ Riparian vegetation dynamics – study area



Location

Middle reach of Lijiang River: 25° 06′ N, 110° 25′ E

Flow condition

2009.01~2010.12：20~3720m^3

Vegetation survey

Several transects were surveyed, each transect have 5 squares in S shape：

Rumex Maritimus: Near water, averagely 3/m^2, relatively tall.

Leonurus Heterophyllus: near the bank, away from the water. averagely 1/m^2

Polygonum Hydropiper: In between, averagely 32/m^2~35/m^2

3. Applications in ecohydraulics

❑ Riparian vegetation dynamics – modeled species

R. Maritimus

Rumex maritimus

P. Hydropiper

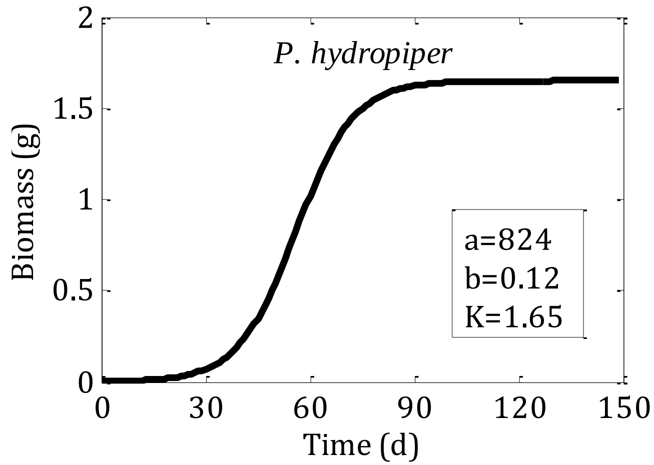
Polygonum hydropiper

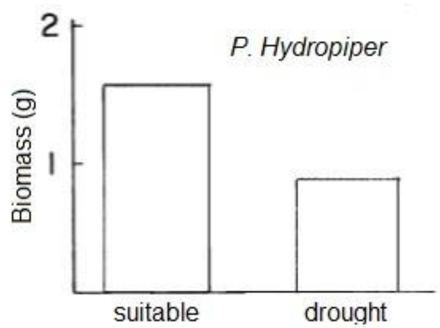
L. Heterophyllus

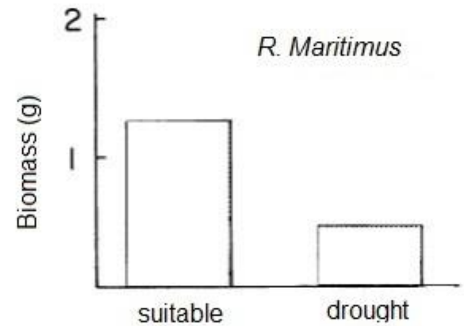
Leonurus heterophyllus

3. Applications in ecohydraulics

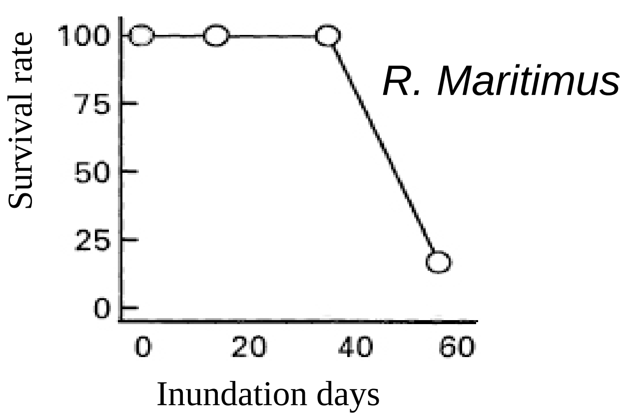
❑ Riparian vegetation dynamics – flow stress

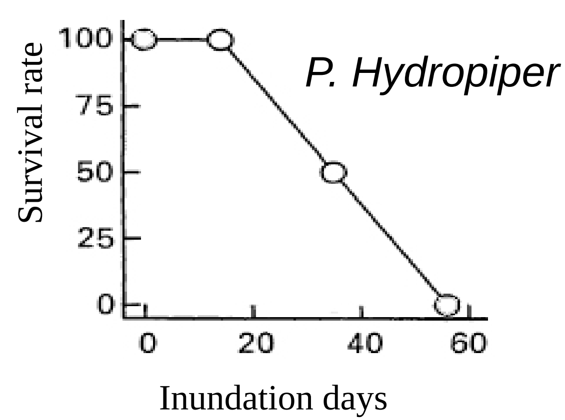






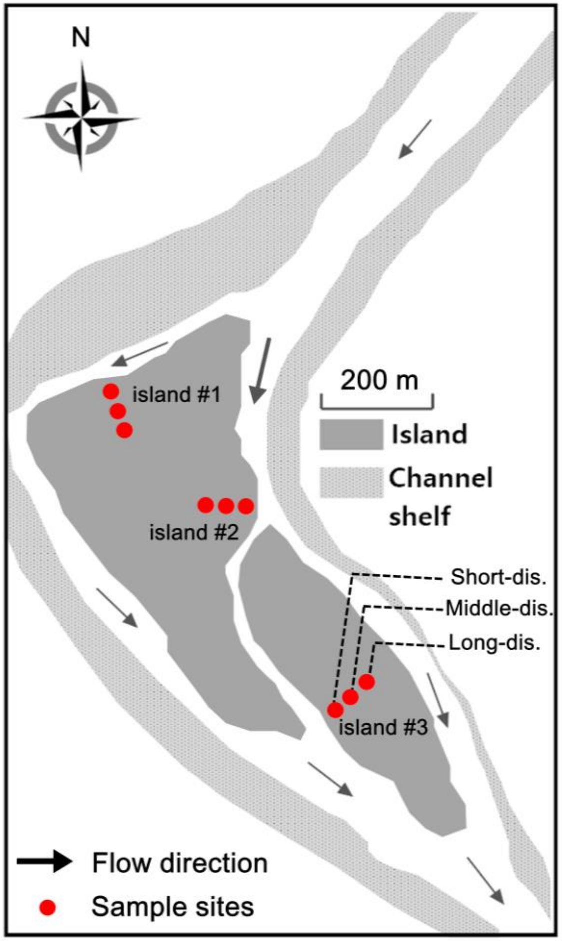
Transform to discrete form: $Y(t+\Delta t) = bY(t)\left[1 - Y(t)/K\right]\Delta t + Y(t)$





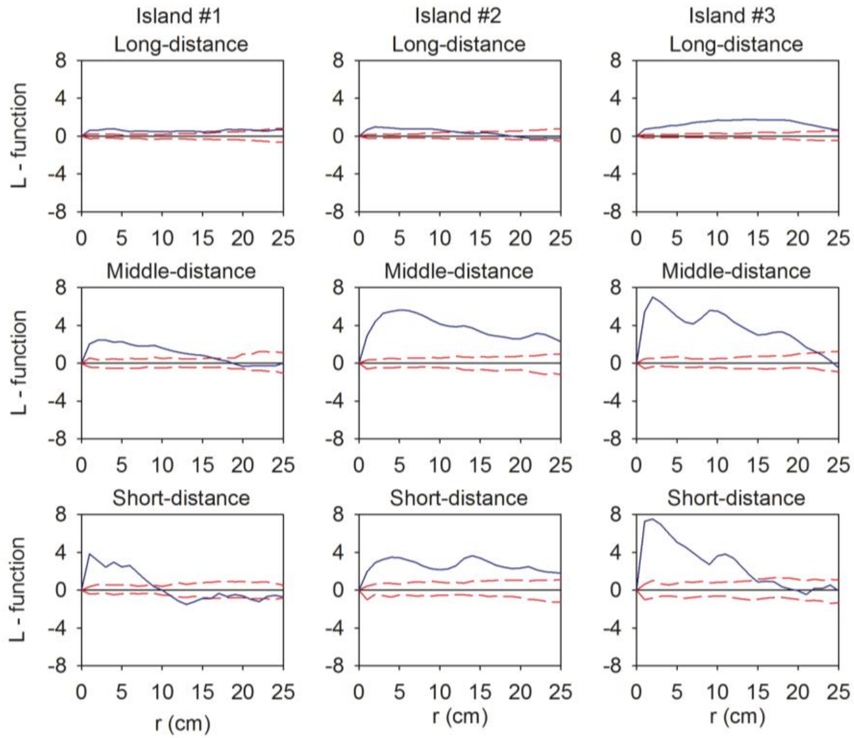
3. Applications in ecohydraulics

❑ Riparian vegetation dynamics – the scales



- Ripley L function

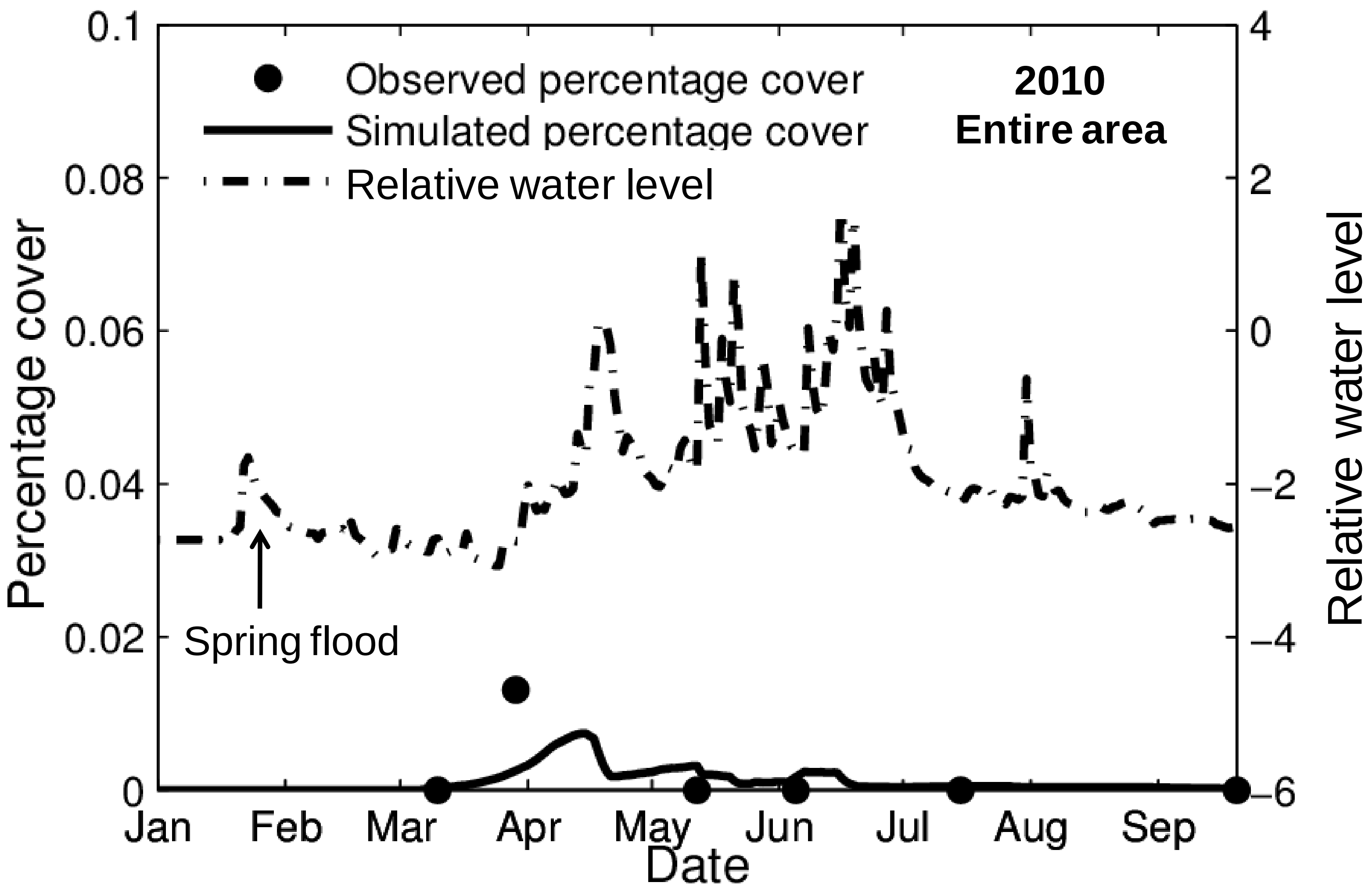
$$L(r) = \sqrt{\frac{K(r)}{\pi}} - r \qquad K(r) = \frac{A}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{I_r(d_{ij})}{w_{ij}}$$



Δx = *r*/2, Δt = 9 hours

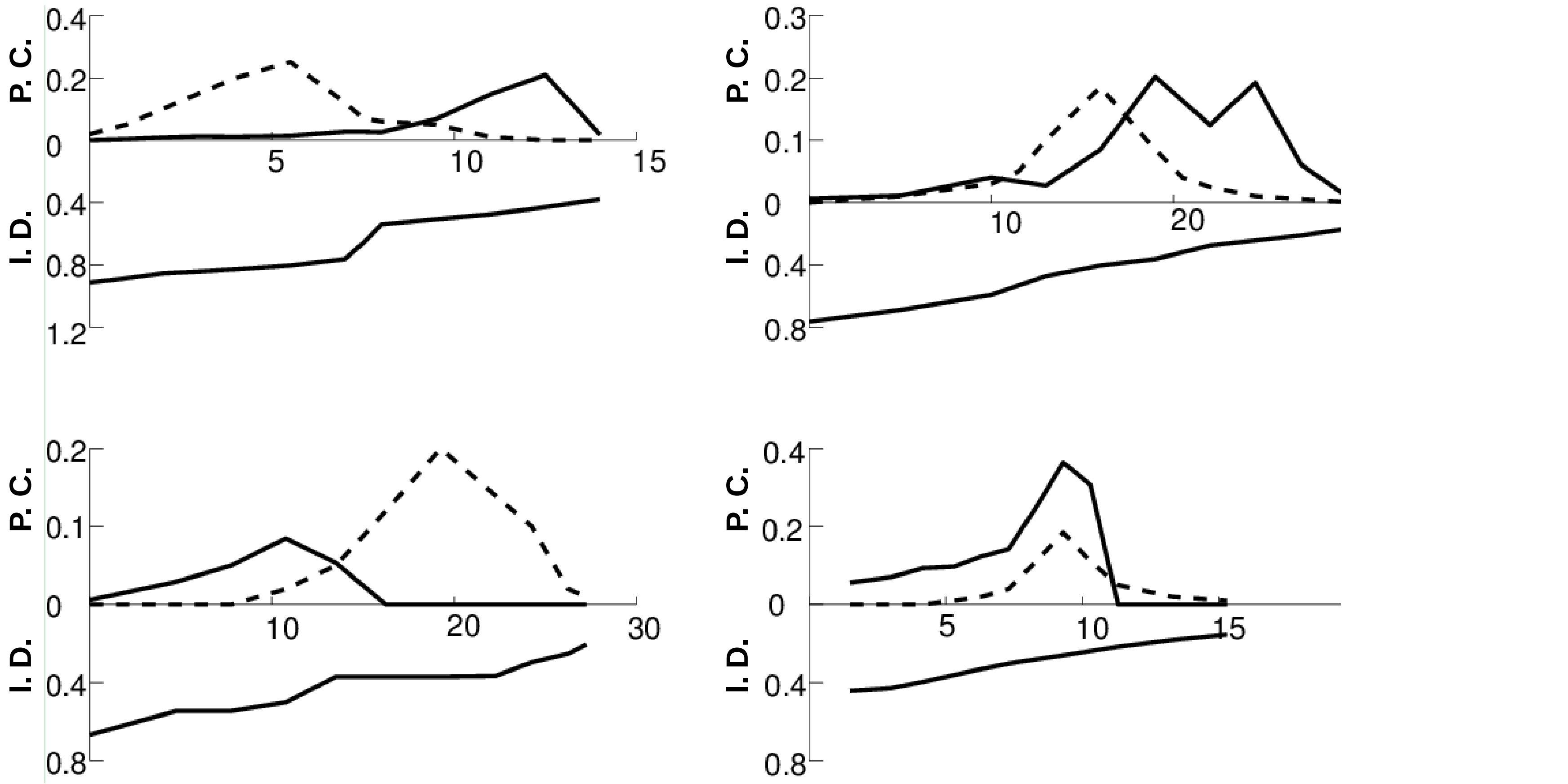
3. Applications in ecohydraulics

❑ *P. hydropiper* dynamics in 2010 – model validation



3. Applications in ecohydraulics

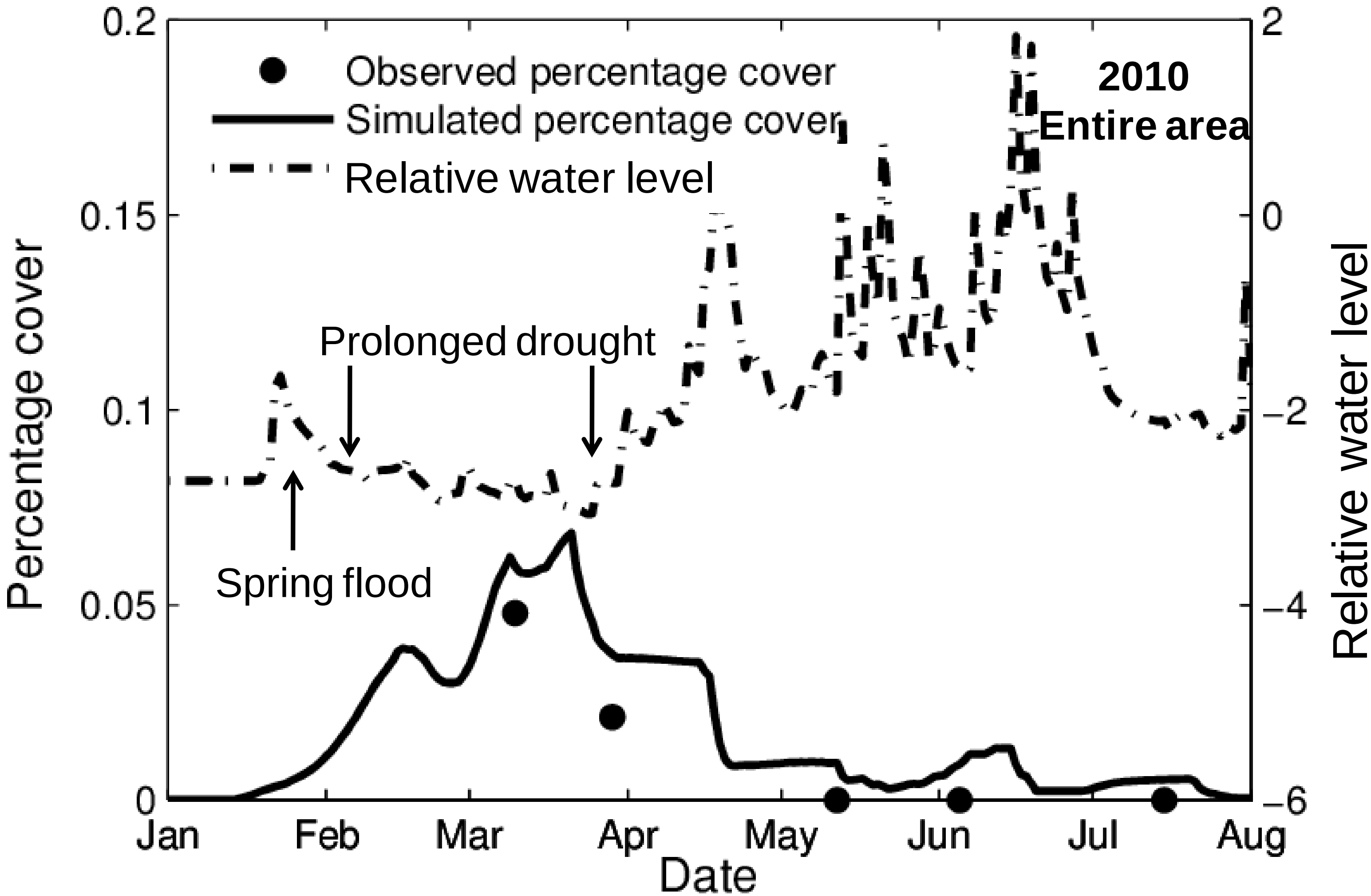
❑ *P. hydropiper* transect in 2010 – model validation



Legend: (above x-axis) ——— simulated - - - - measured

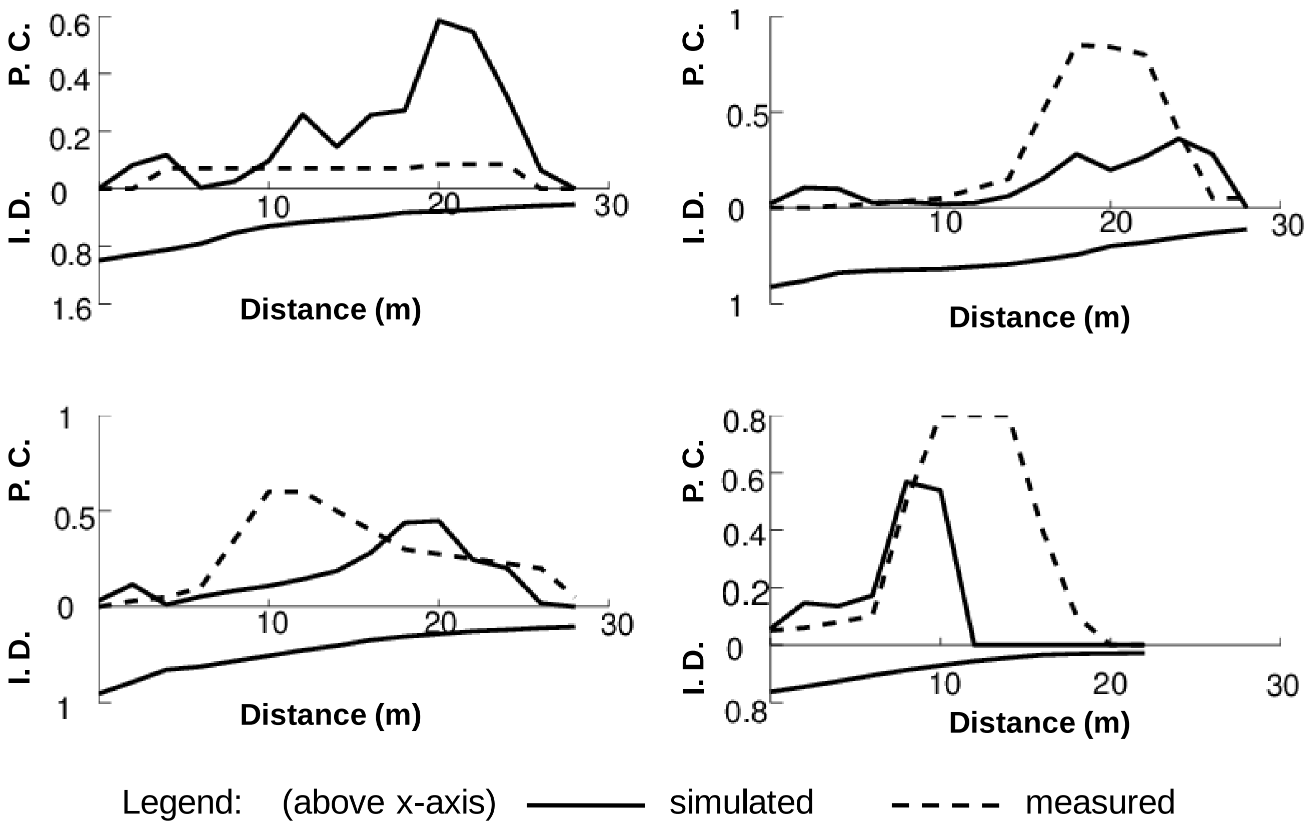
3. Applications in ecohydraulics

❑ *R. maritimus* dynamics in 2010 – model validation



3. Applications in ecohydraulics

- **_R. maritimus_ transect in 2010 – model validation**



3. Applications in ecohydraulics

❑ Riparian vegetation dynamics – model comparison

$$\log(Y) = -49.3294 + 62.4774 \cdot i - 43.9644 \cdot i^2 + 74.3 \cdot aw - 58.623 \cdot aw^2 + 11.3704 \cdot mw - 23.2815 \cdot mw^2 + 7.6828 \cdot ad$$

Y: coverage of vegetation (*P. hydropiper*) by the end of growth period;

i: ratio of inundation time;

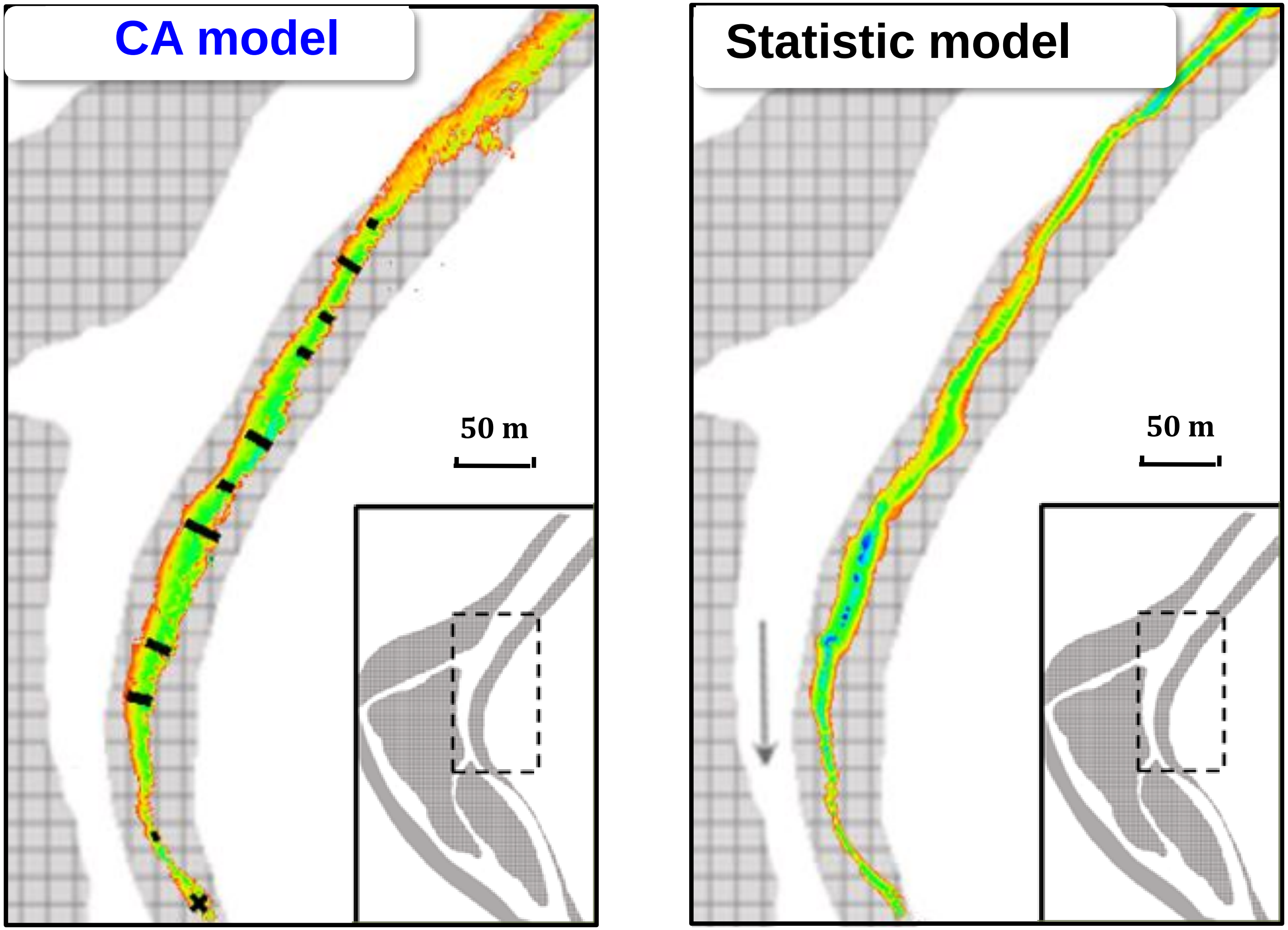
mw: maximum inundation time;

aw: averaged inundation depth;

ad: ground water depth.

C. Camporeale & Ridolfi L., WRR, 42: 10415

3. Applications in ecohydraulics

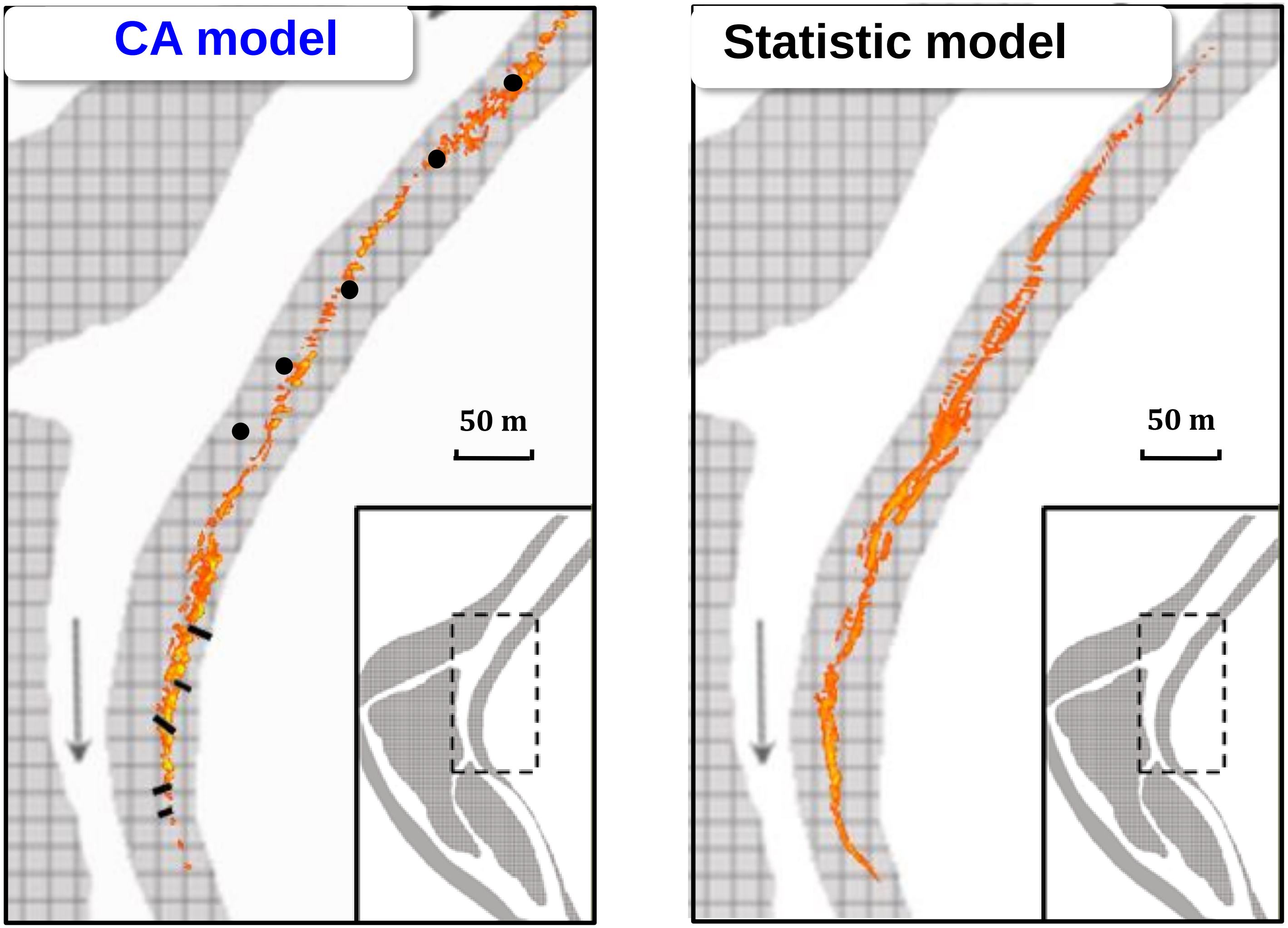


Legend: Channel shelf and bars → Flow direction

•Sampled transects: Location and length of plant belt ● Quadrats with <5% cover

•Simulated percent cover: 0% 100%

3. Applications in ecohydraulics



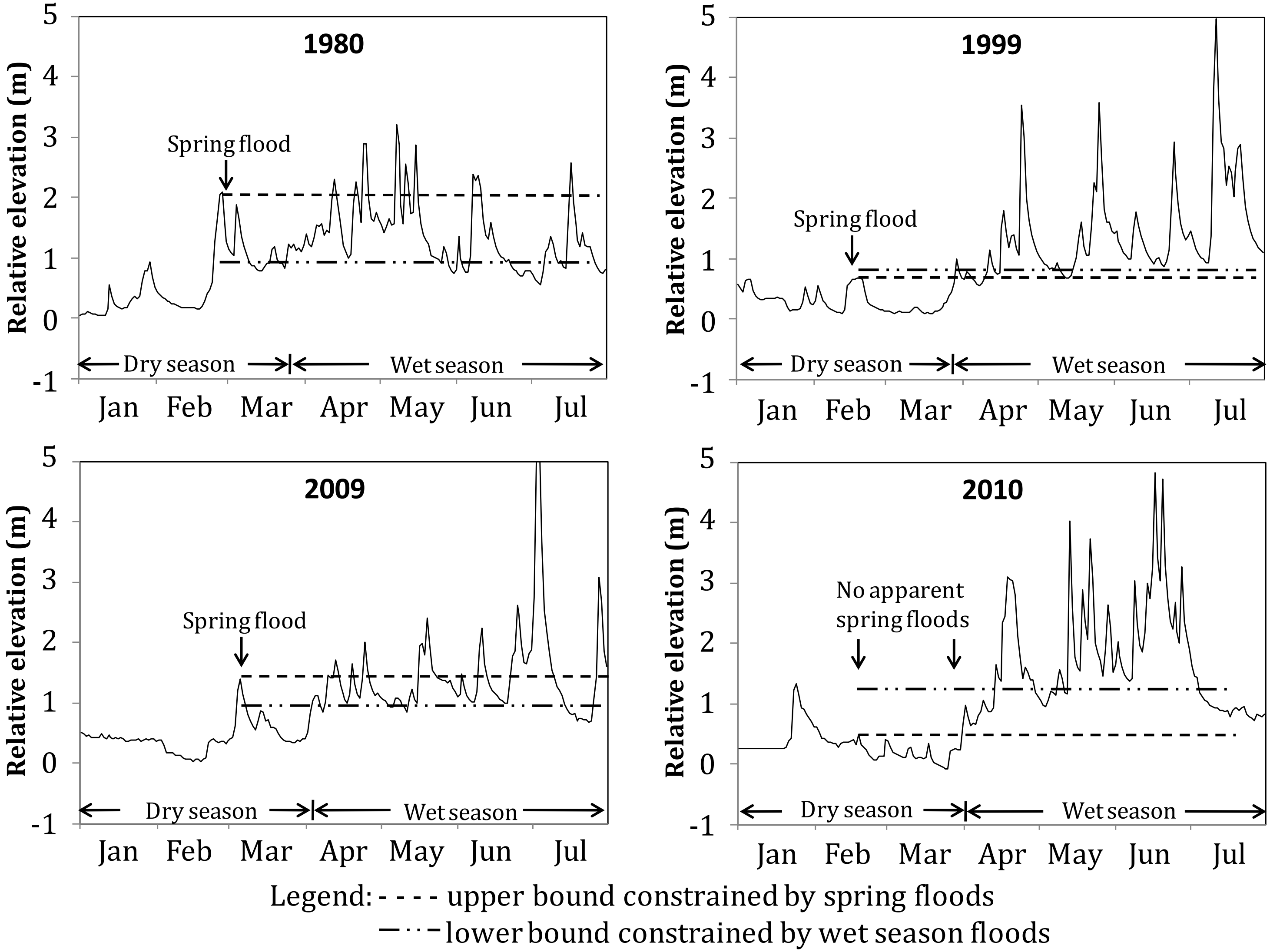
Legend: Channel shelf and bars — Flow direction

•Sampled transects: Location and length of plant belt ● Quadrats with <5% cover

•Simulated percent cover: 0% 100%

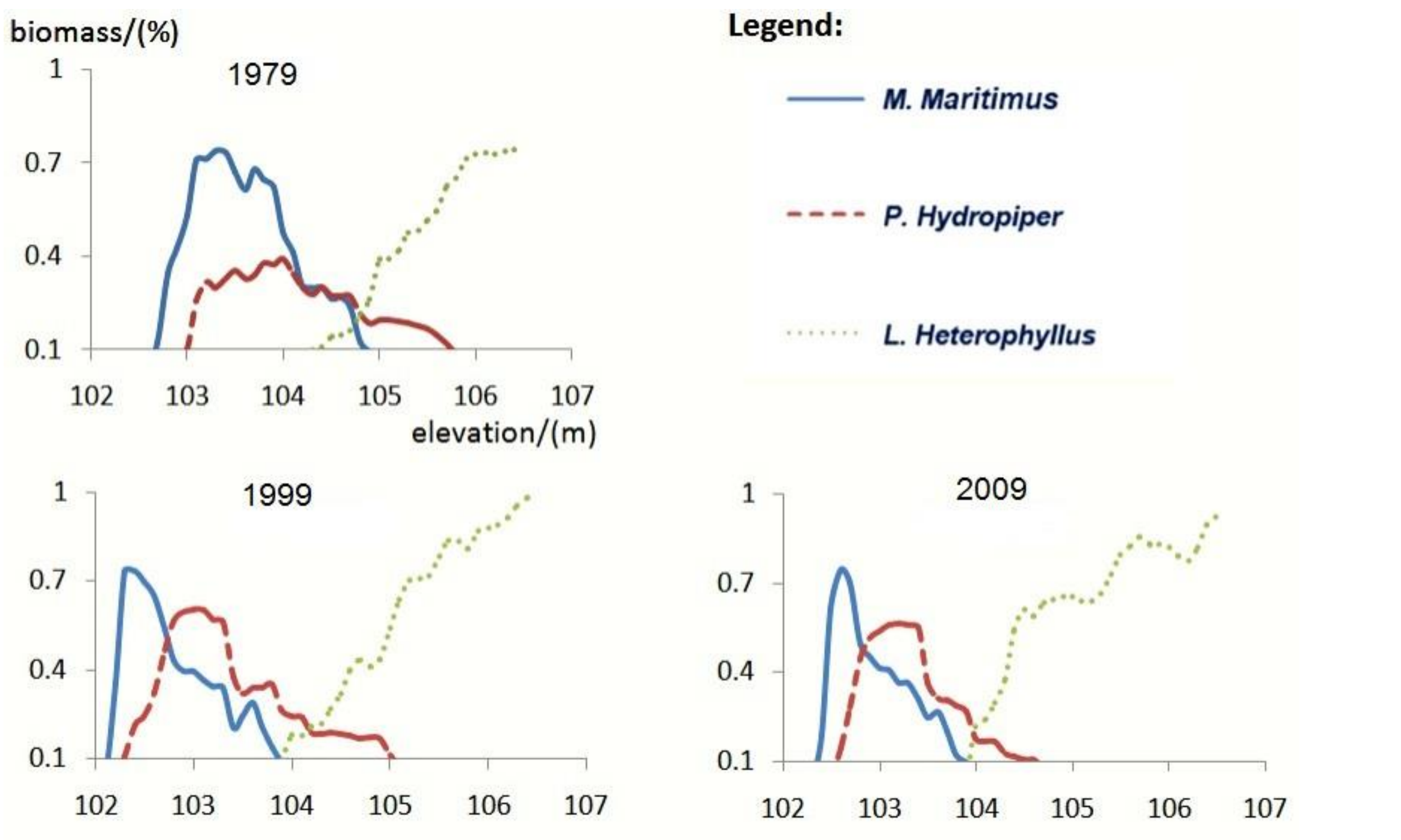
3. Applications in ecohydraulics

❑ Riparian vegetation dynamics – vegetation succession



3. Applications in ecohydraulics

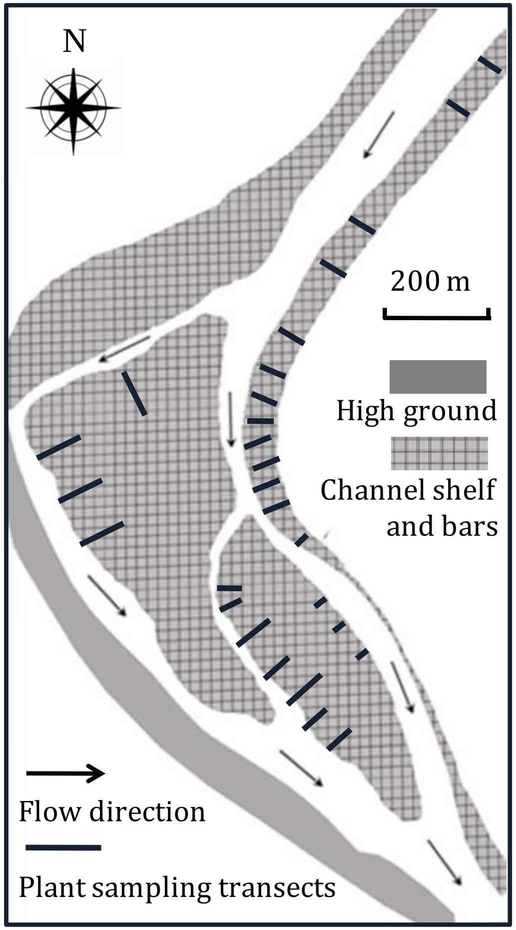
❑ Riparian vegetation dynamics – vegetation succession

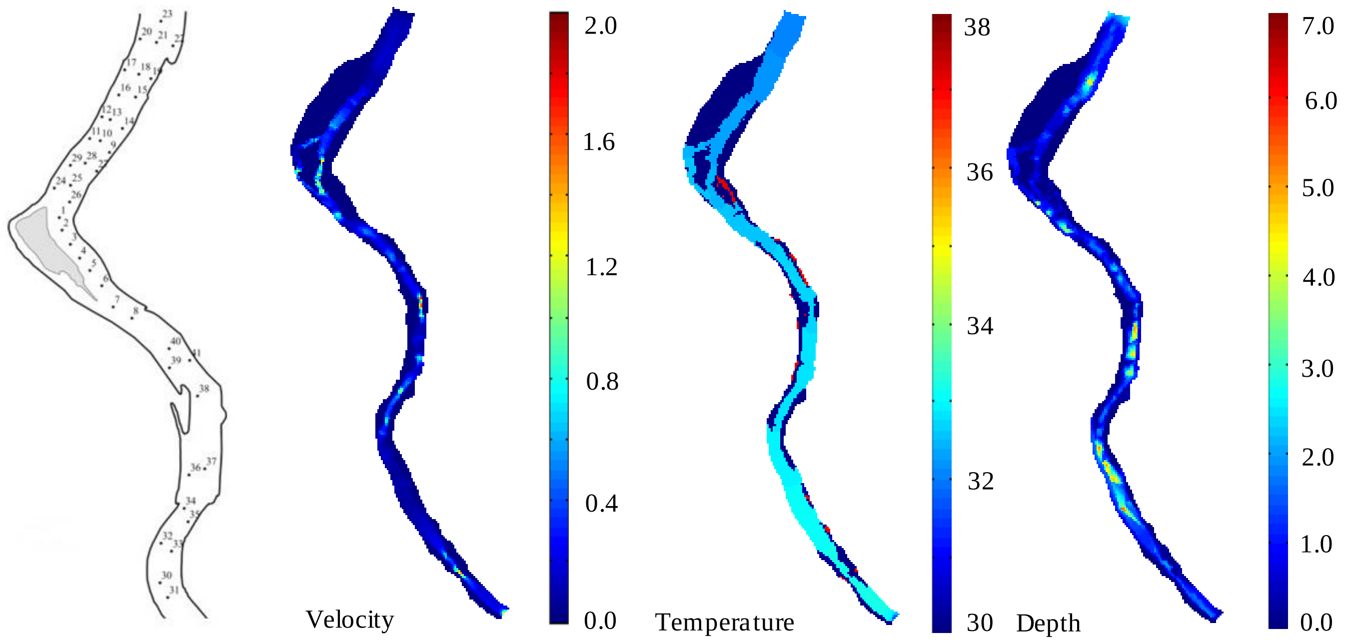


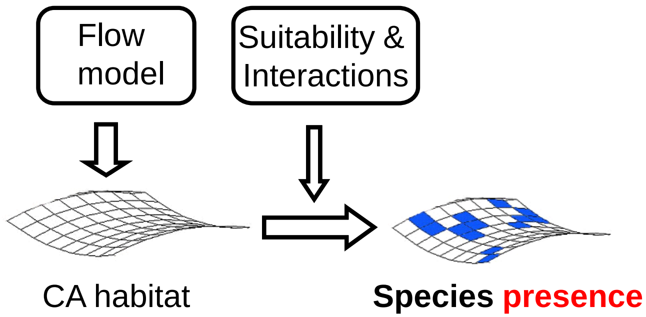
Ye F., et al., 2010, *Eco Inf*, 5: 108-114; Liu R., et al., 2014, *Scientific Report*, 4: 5507

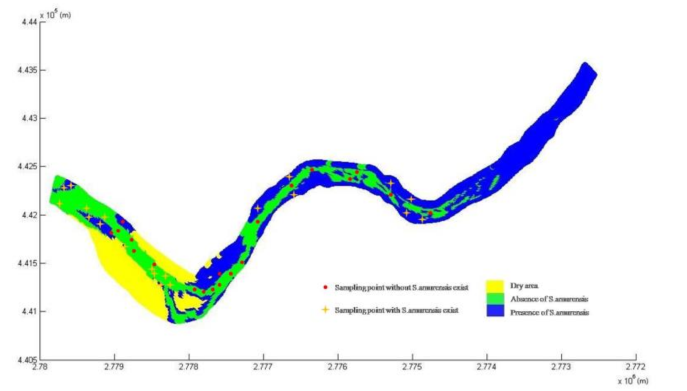
3. Applications in ecohydraulics

❑ River macroinvertebrates inhabitant: flow → local movement





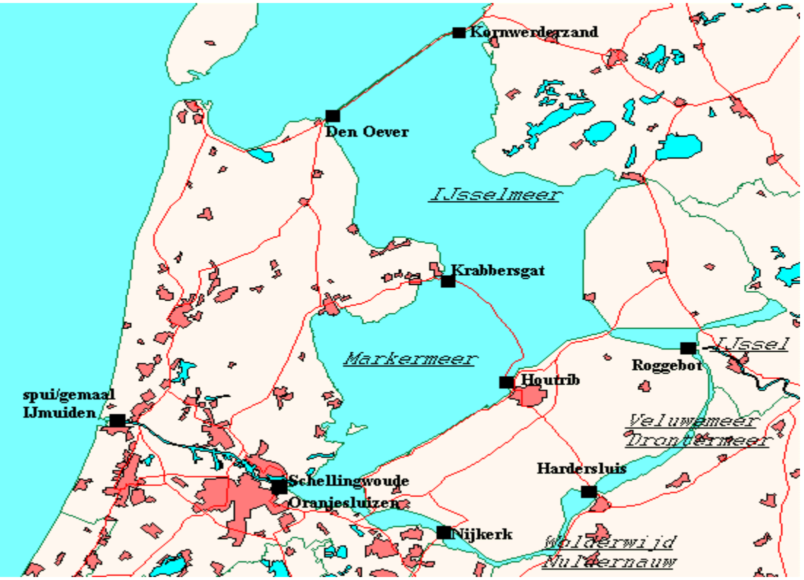


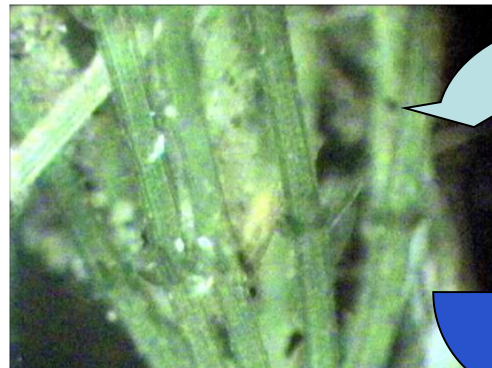


Chen et al., 2011, *Eco. Info*, 6: 407-413

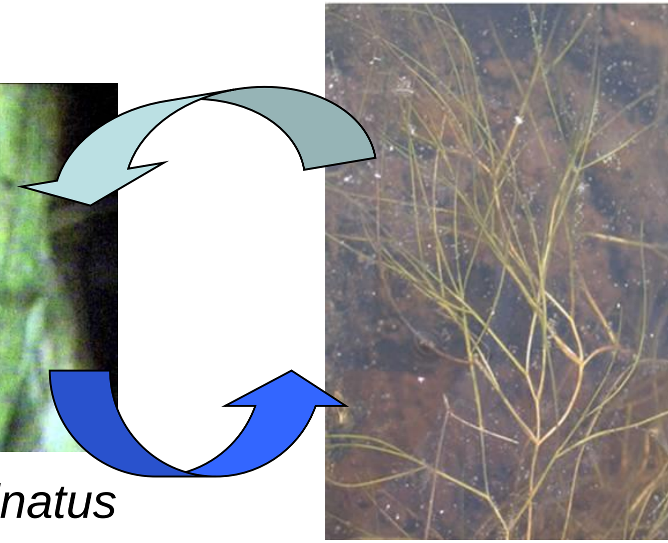
3. Applications in ecohydraulics

❑ Macrophytes succession: vertical mixing → local competition





Potamogeton pectinatus



Chara aspera

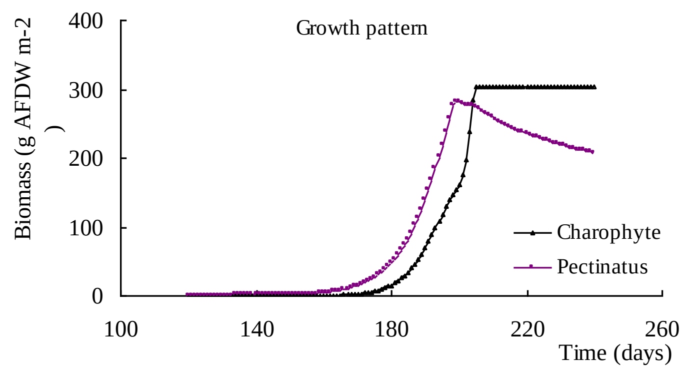
Before 1968, various species

↓ Eutrophication

1970~1989, algae and *Potamogeton pectinatus*

↓ Restoration

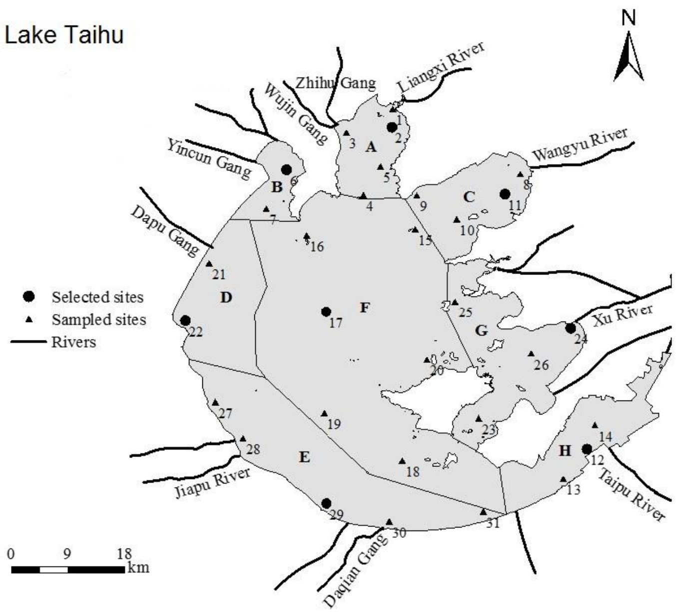
1990~, *Chara aspera* back and dominant

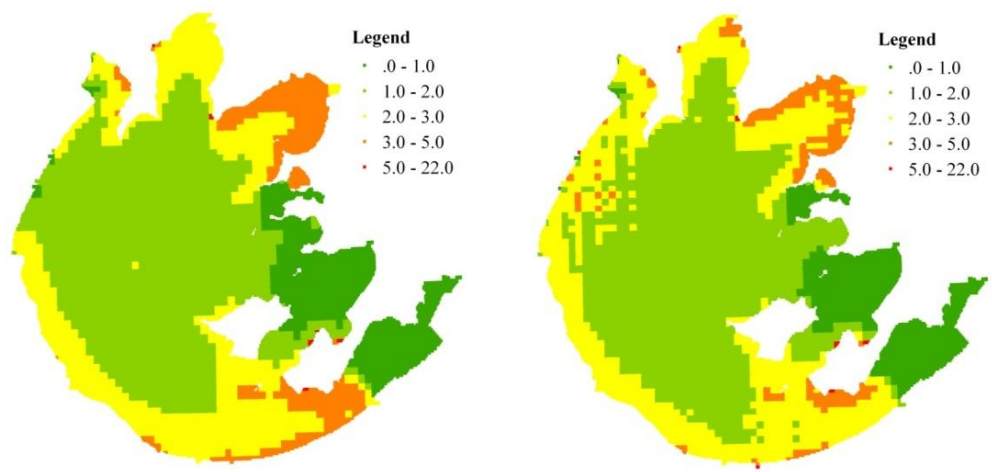


Chen and Mynett., 2003, *Eco Mod*, 147: 253-262 (Citations: 53)

3. Applications in ecohydraulics

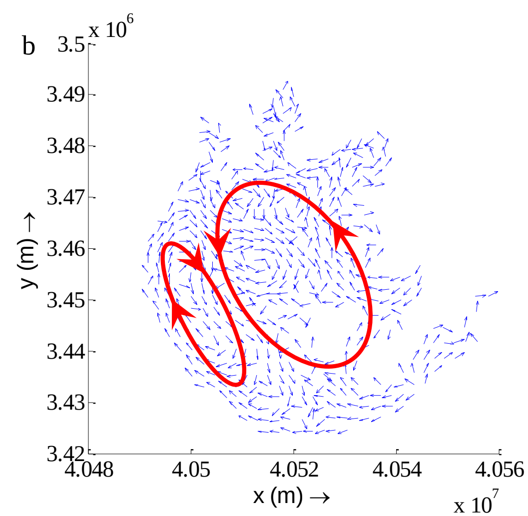
❑ Lake algae bloom: flow + wind drifting → algae patchiness





$$R_i^{t+2} = (7.66 + NO_{3i}^{t} + 0.0441 * \mathrm{WT}_i^{t} - 0.14 * PO_{4i}^{t}) / (1.2 + (\mathrm{NO}_{3i}^{t})^2)$$

$$C_i^{t+2} = R_i^{t+2} + C_i^{t} \qquad C_i^{t+2} = a_i C_i^{t+2} + \sum a_j C_j^{t+2}$$

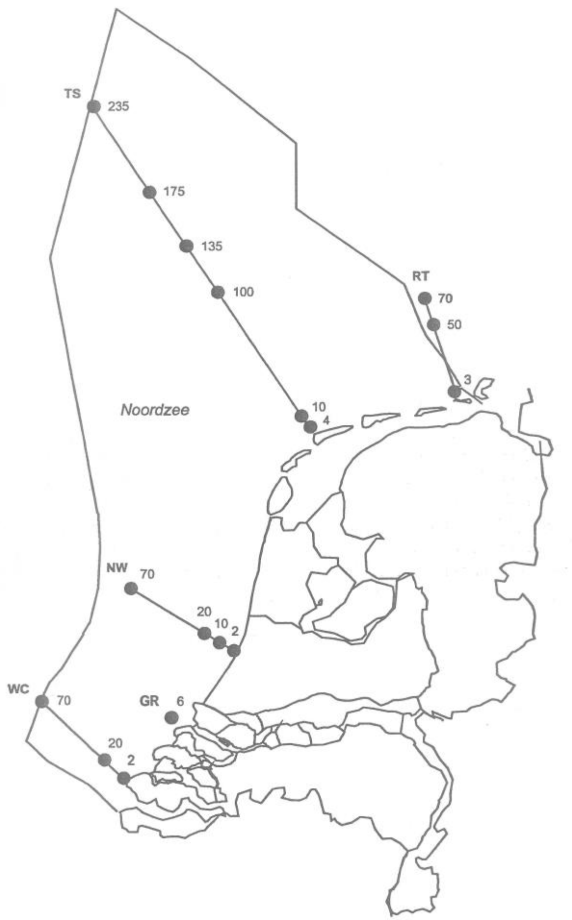


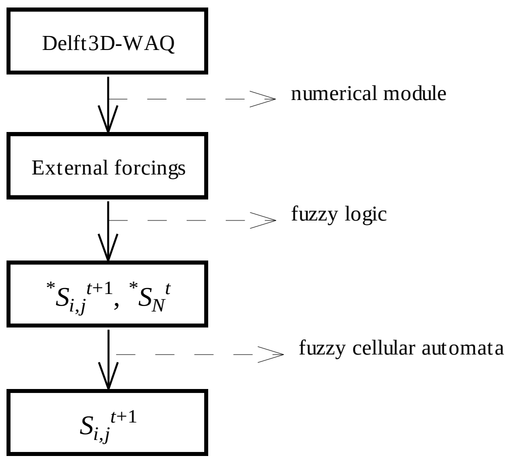
✧ Δt: 12 hours in algae model; cell size Δx: drifting speed × Δt

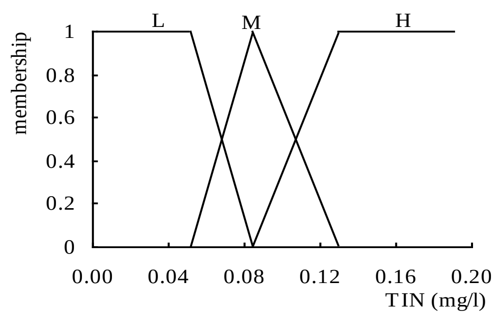
Lin et al., 2017, *Eco. Mod.* (submitted)

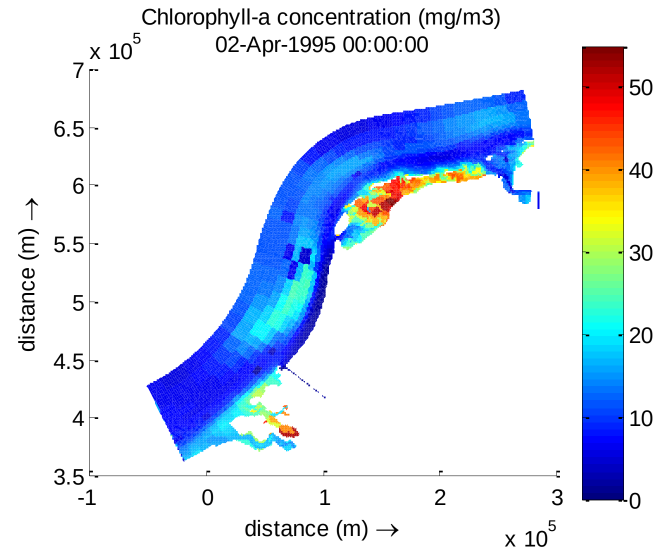
3. Applications in ecohydraulics

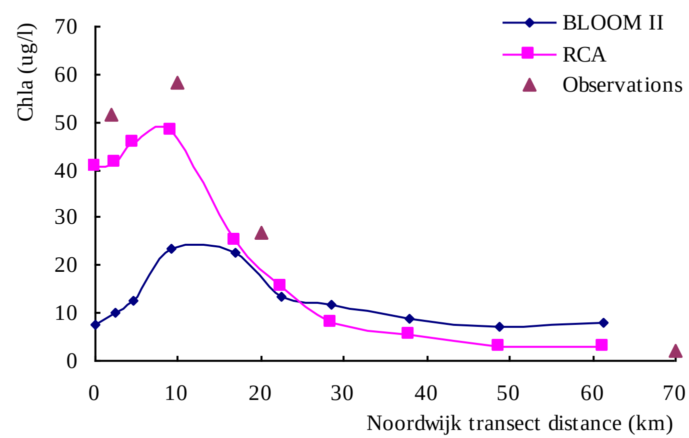
❑ Coastal algal bloom: current → algae patchiness







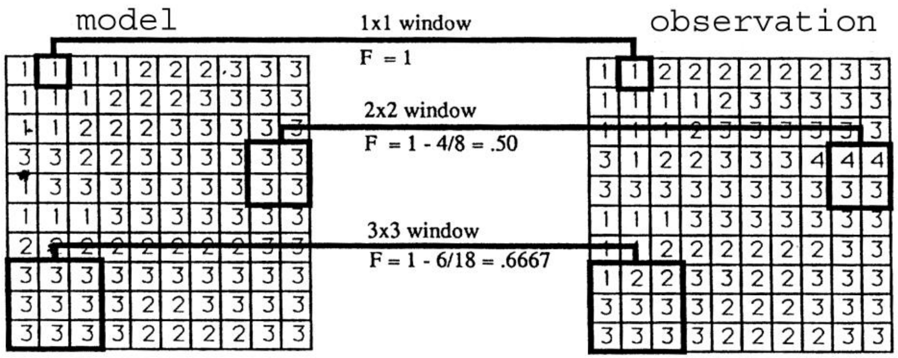




Chen and Mynett, 2006, *Eco. Mod*, 199: 73-81 (Citations: 55)

3. Applications in ecohydraulics

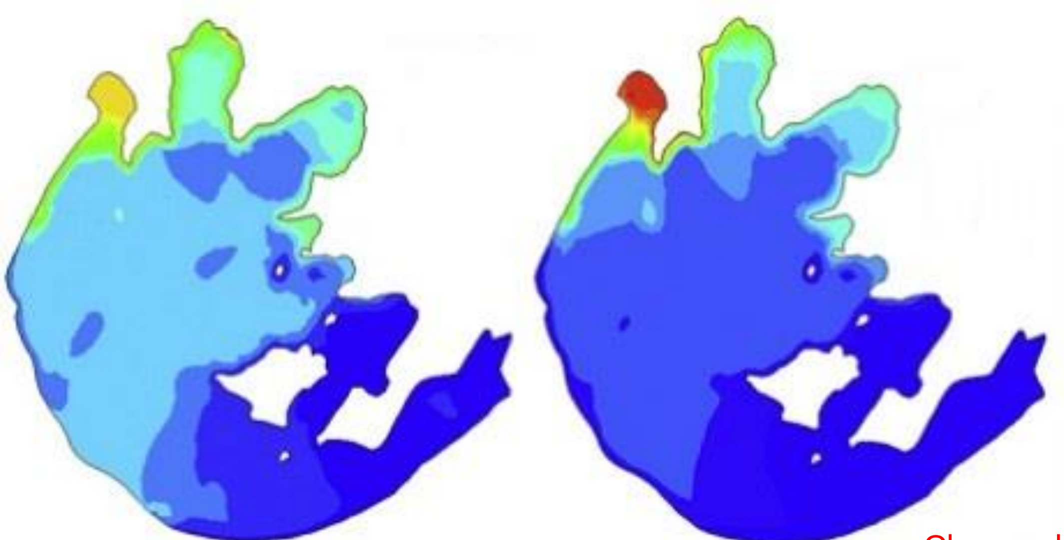
❑ Spatially-explicit evaluation of CA model

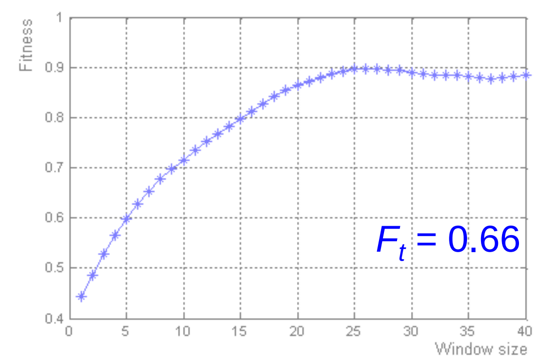


R. Costanza, Ecol. Mod., 1989

$$F_w = \frac{\sum_{s=1}^{t_w} \left[1 - \frac{\sum_{i=1}^{n} | a_{1i} - a_{2i} |}{2w^2}\right]_s}{t_w}$$

$$F_t = \frac{\sum_{w=1}^{n} F_w e^{-k(w-1)}}{\sum_{w=1}^{n} e^{-k(w-1)}}$$





Chen and Mynett, 2003, *Eco. Mod*, 162: 55-67 (Citations: 142)

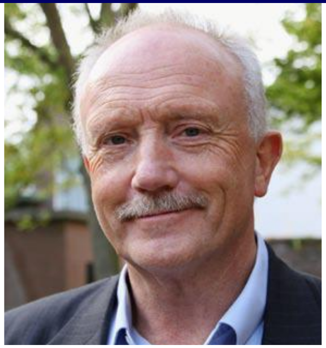
Final remarks

(1) Through hierarchical scale coupling, the fluid dynamics is linked to aquatic eco-dynamics

(2) The adoption of cellular automata offers a novel approach to describe aquatic eco-dynamics featured by spatial heterogeneity, local interactions and discrete processes

(3) The developed ecohydraulic models provide a broad range of applications with promising potential.

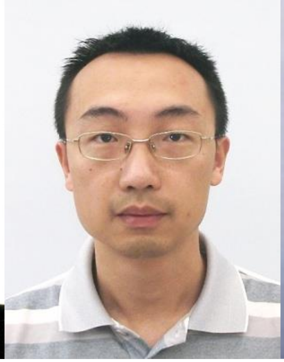
The persons & the path……



Prof. Arthur Mynett

Dr. Tony Minns

Ruonan Li



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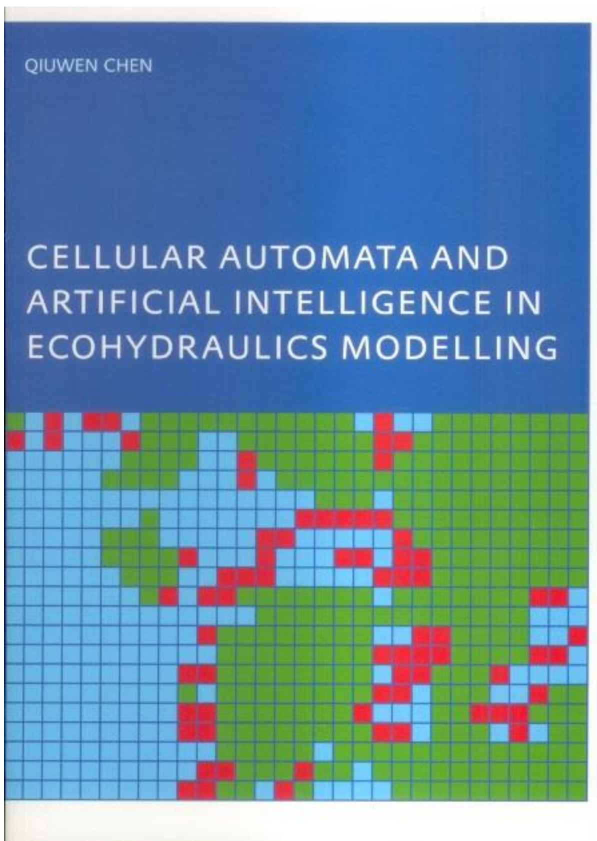

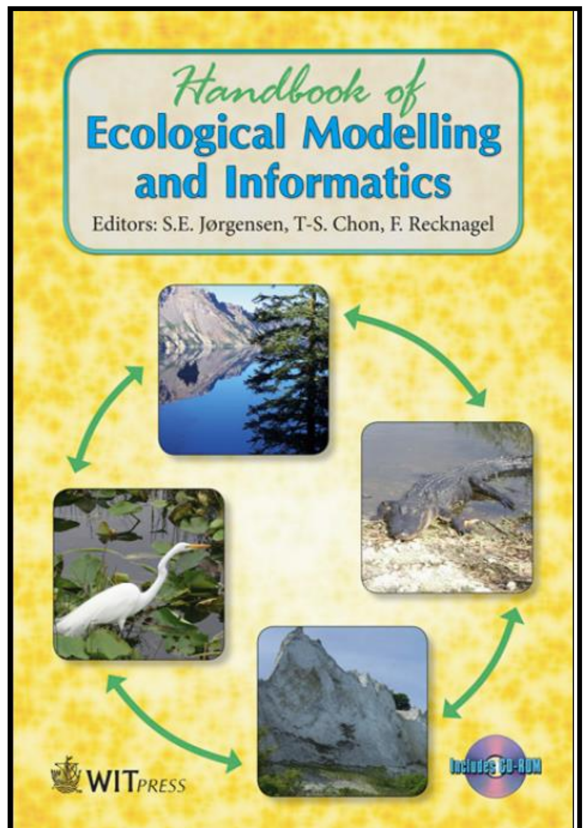

CHAPTER 16

Cellular automata

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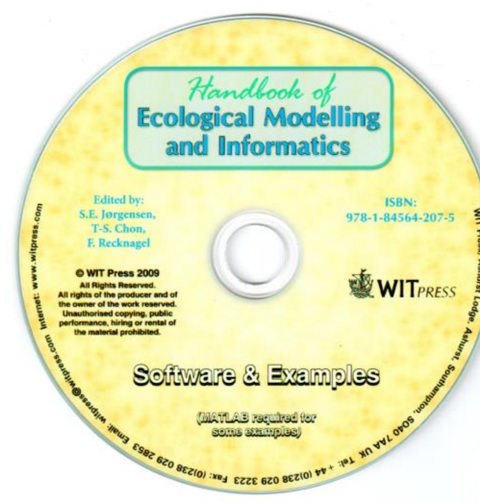
State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing China.




Thank You !