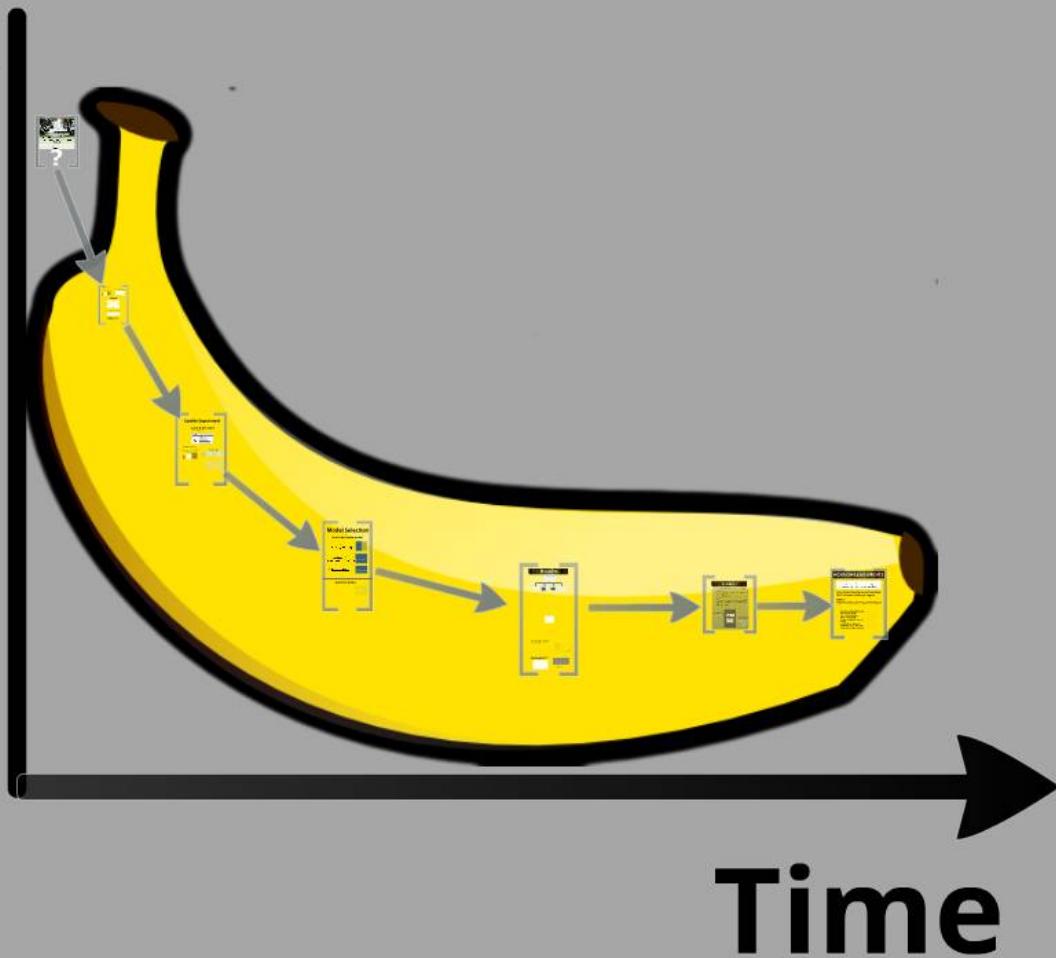


Dissolved P

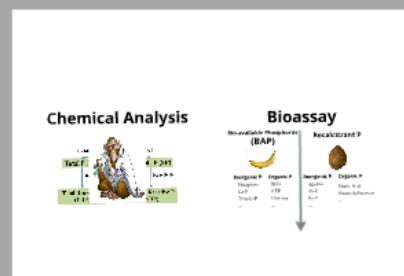




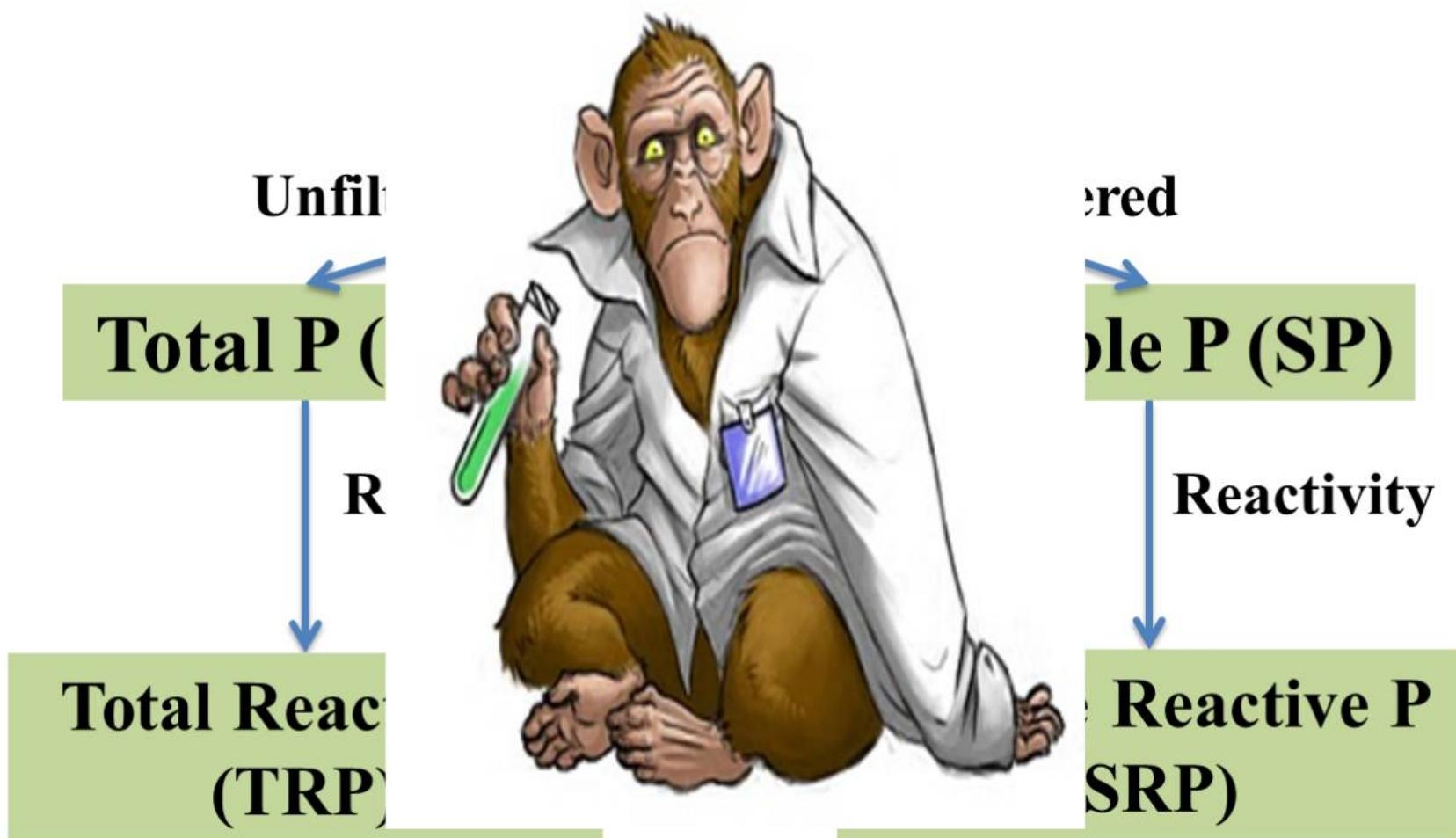
Bioavailable Phosphorus in Advanced Phosphorus Removal Facility Effluent Phase II

Bo Li, Michael T. Brett

Department of Civil and Environmental Engineering, University of Washington,
Seattle, Washington 98195, USA;
libo@u.washington.edu



Chemical Analysis



Bioassay

Bio-available Phosphorus (BAP)



Inorganic P Organic P

Phosphate

DNA

Ca-P

ATP

Tripoly-P

Lipsome

...

Recalcitrant P



Inorganic P Organic P

Apatite

Phytic Acid

Al-P

Humic Substances

Fe-P

...

...

Experiment Setting

Selenastrum
capricornutum 10,
000 cells/ml

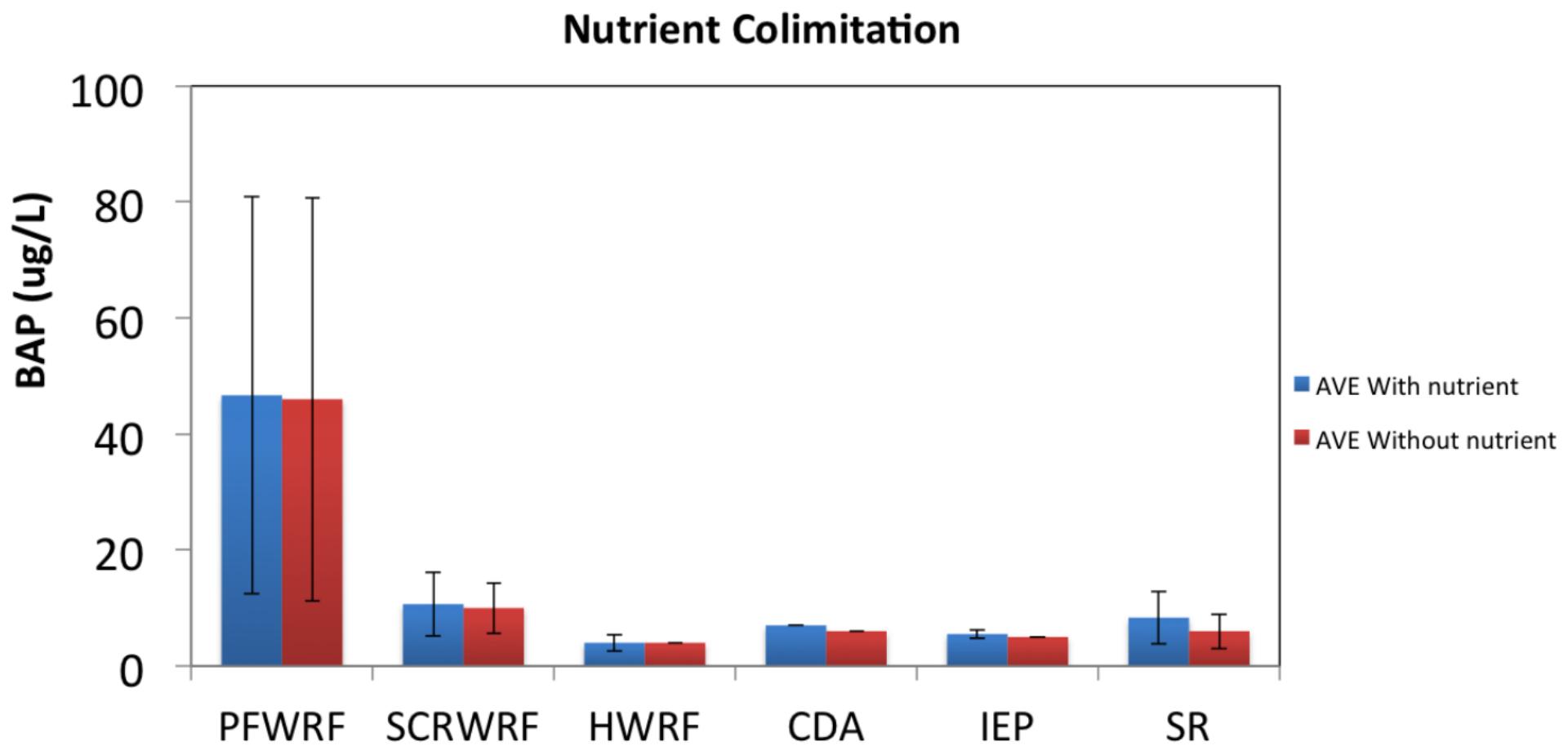
Culturing condition:

1. Continuous Illumination
2. Temperature: $24 \pm 2^{\circ}\text{C}$
3. Shake at 110 rpm.

Analyze Cell counts

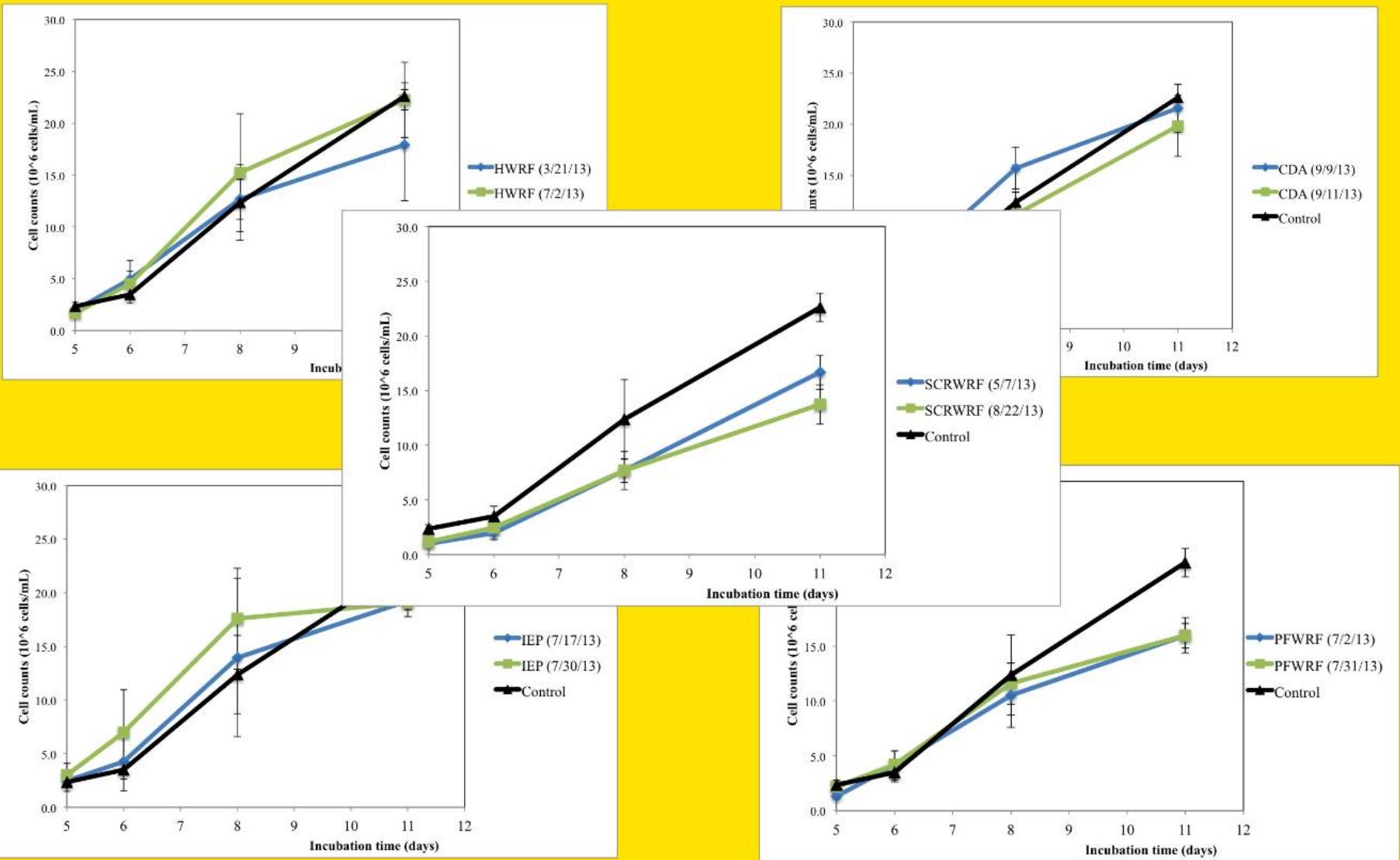


Nutrient Limitation



- Marginal impact of nutrient limitation for effluents (<2 $\mu\text{g}/\text{L}$).

Toxicity



Repeated Measures ANOVA

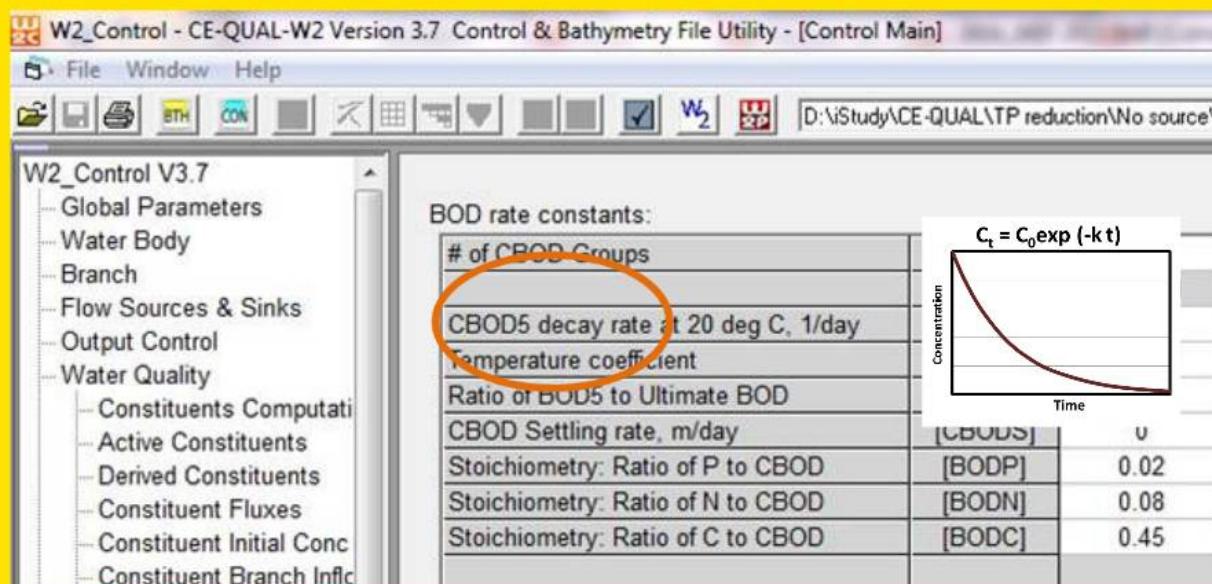
	Cell Density (10^6 cell/mL)				Repeated Measure ANOVA				
	Day 5	Day 6	Day 8	Day 11	N	df	SS	F	P
Control	2.3 ± 0.4	3.5 ± 0.9	12.4 ± 3.6	22.6 ± 1.3	6				
PFWRF	1.7 ± 0.7	4.1 ± 1.2	11.0 ± 2.4	16.0 ± 1.3	8	1	53.8	16.76	0.001
SCRWRF	1.1 ± 0.2	2.2 ± 0.6	7.7 ± 1.4	15.2 ± 2.2	8	1	185.2	71.49	0.000
HWRF	1.8 ± 0.2	4.7 ± 1.4	14.0 ± 4.18	20.1 ± 4.8	8	1	0.04	0.01	0.934
CDA	2.8 ± 1.1	4.7 ± 2.6	13.4 ± 3.1	20.6 ± 2.5	8	1	0.44	0.06	0.811
IEP	2.7 ± 1.0	5.6 ± 3.5	15.8 ± 6.1	19.2 ± 1.1	8	1	5.1	0.08	0.403

- For most effluents there was no consistent evidence of a toxic growth inhibition.
- For SCRWRF effluents, there was some evidence of about a 30% growth inhibition.
- For PFWRF effluents, there might be growth inhibition towards end of incubation.

Uptake Experiment

CE-QUAL-W2 model

a water quality and hydrodynamic model in 2D
783 applications in United States



CE-QUAL-W2 model

a water quality and hydrodynamic model in 2D
783 applications in United States

W2_Control - CE-QUAL-W2 Version 3.7 Control & Bathymetry File Utility - [Control Main]

File Window Help

BTH CON

D:\iStudy\CE-QUAL\TP reduction\No source\

W2_Control V3.7

- Global Parameters
- Water Body
- Branch
- Flow Sources & Sinks
- Output Control
- Water Quality
 - Constituents Computation
 - Active Constituents
 - Derived Constituents
 - Constituent Fluxes
 - Constituent Initial Conc
 - Constituent Branch Inflo

BOD rate constants:

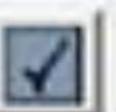
of CBOD Groups
CBOD5 decay rate at 20 deg C, 1/day
Temperature coefficient
Ratio of BOD5 to Ultimate BOD
CBOD Settling rate, m/day
Stoichiometry: Ratio of P to CBOD
Stoichiometry: Ratio of N to CBOD
Stoichiometry: Ratio of C to CBOD

$C_t = C_0 \exp (-k t)$

Concentration

Time

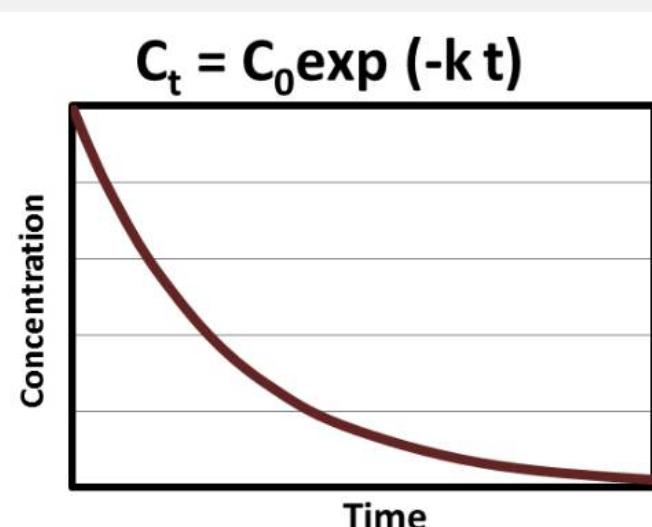
[CBODS]	v
[BODP]	0.02
[BODN]	0.08
[BODC]	0.45



BOD rate constants:

of CBOD Groups
CBOD5 decay rate at 20 deg C, 1/day
Temperature coefficient
Ratio of BOD5 to Ultimate BOD
CBOD Settling rate, m/day
Stoichiometry: Ratio of P to CBOD
Stoichiometry: Ratio of N to CBOD
Stoichiometry: Ratio of C to CBOD

$$C_t = C_0 \exp (-k t)$$



[CBODS]	0
[BODP]	0.02
[BODN]	0.08
[BODC]	0.45

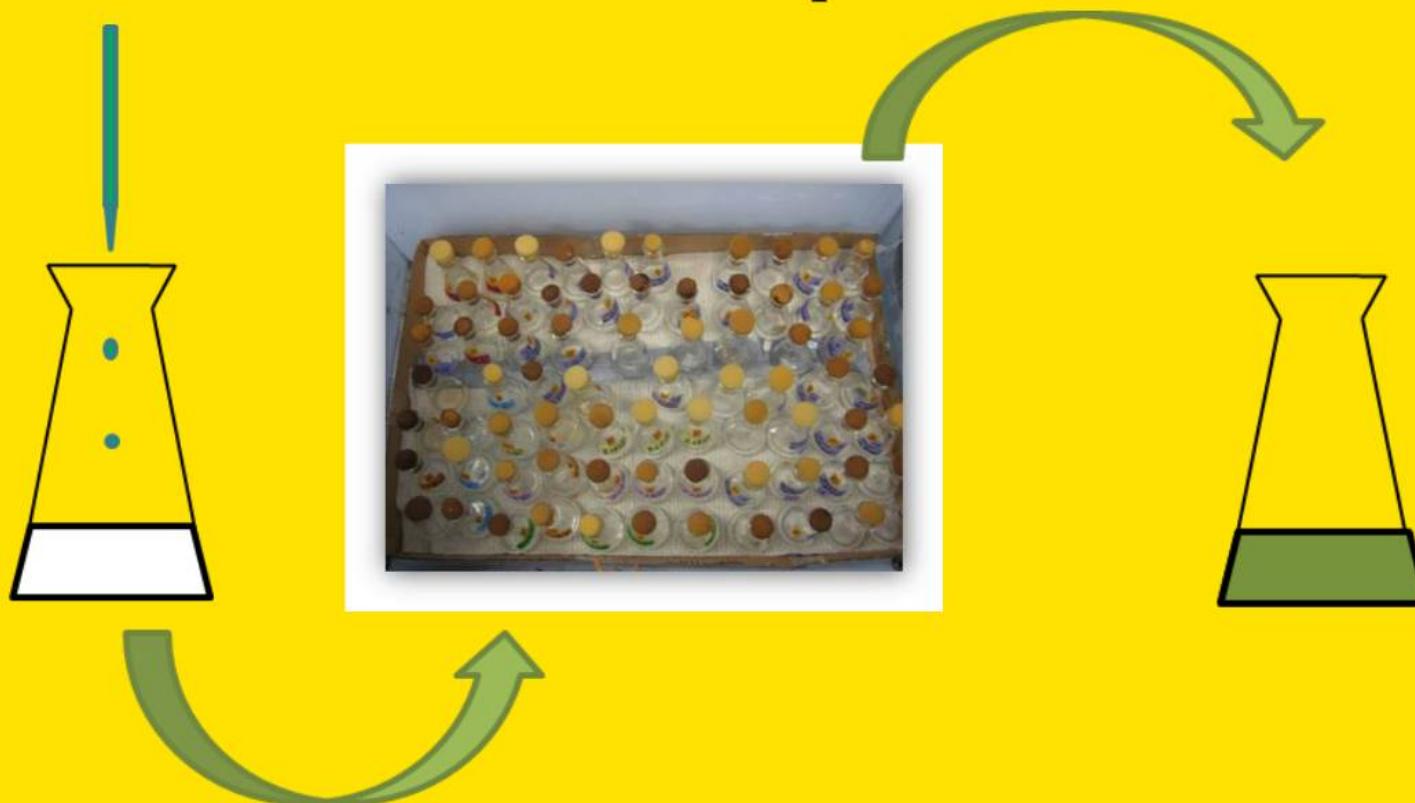
Experiment Setting

Selenastrum
capricornutum
10,000 cells/ml

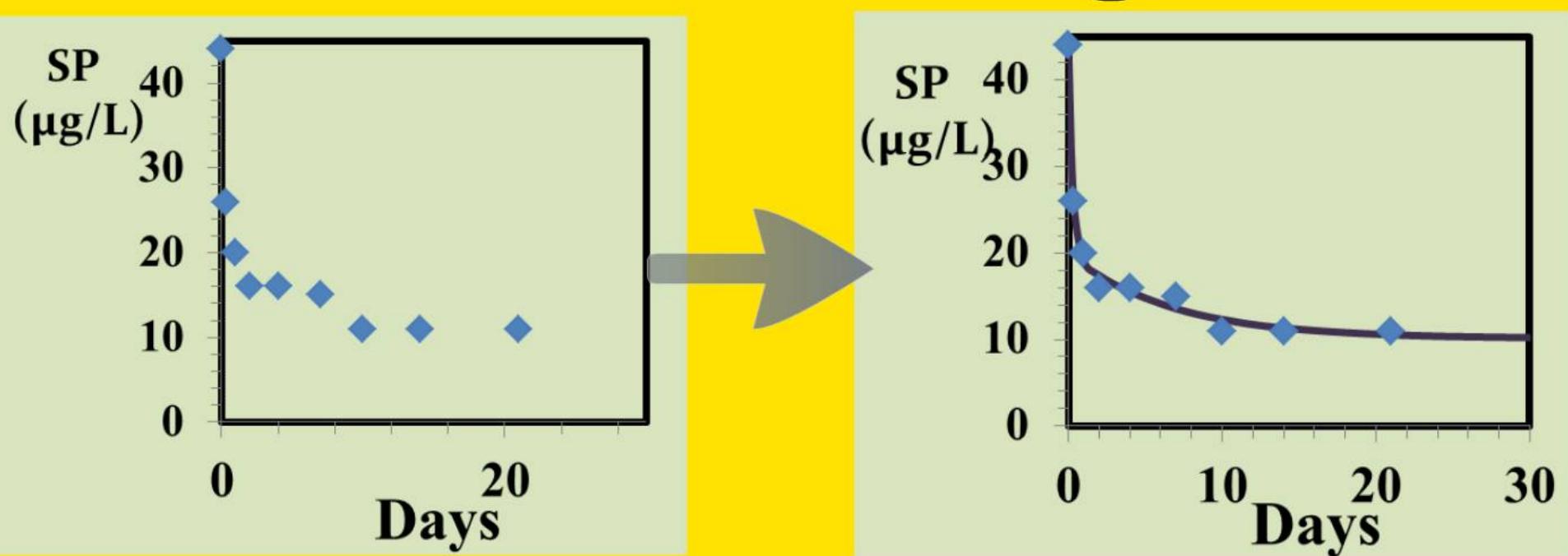
Culturing condition:

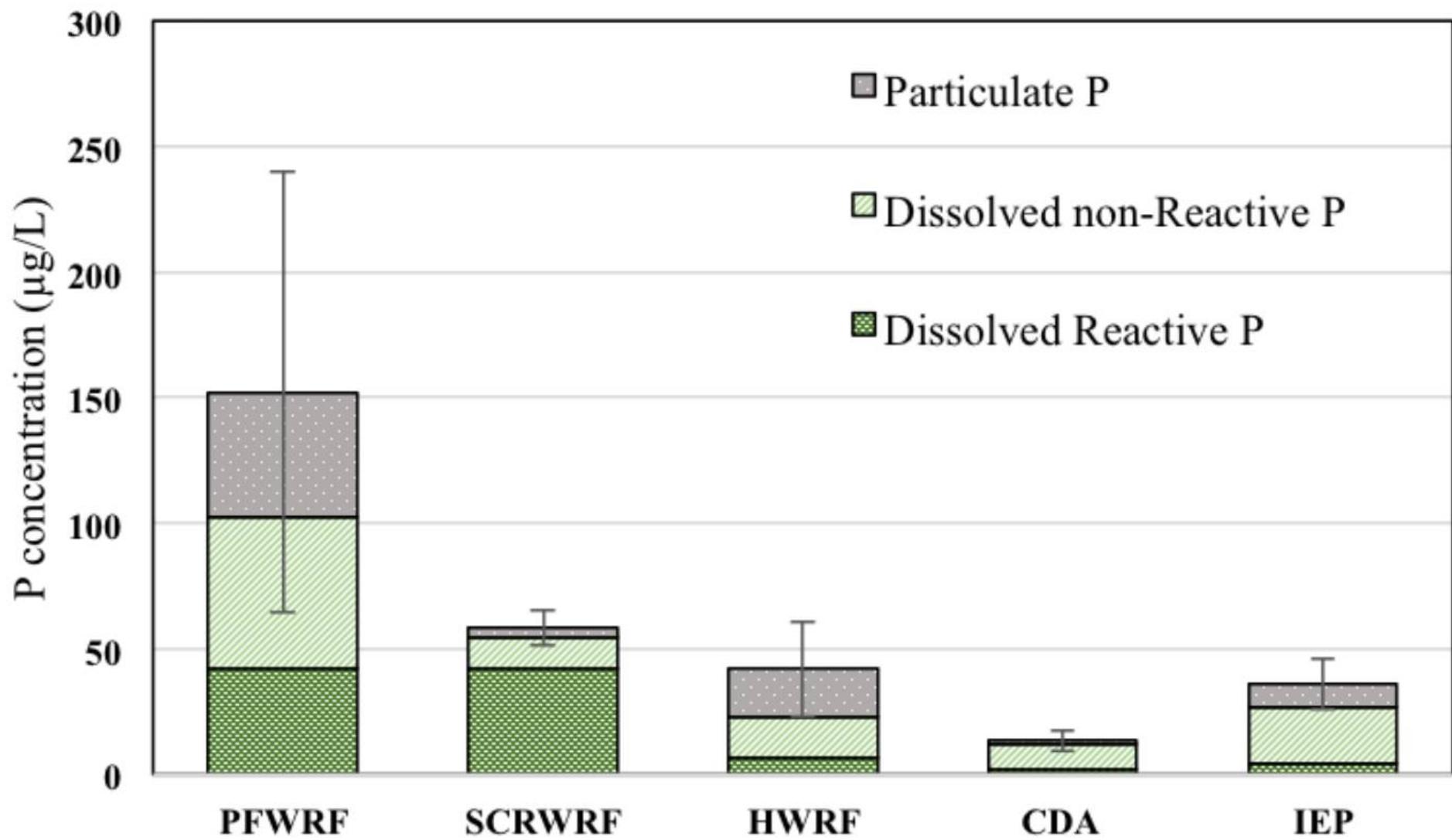
1. Continuous Illumination
2. Temperature: $24 \pm 2^{\circ}\text{C}$
3. shake at 110 rpm.

Soluble P Analysis:
Day 0, 0.33, 1, 2, 4, 7,
10, 14, 21



Model Fitting



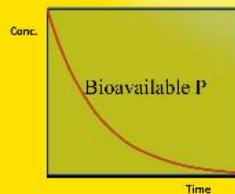


Model Selection

First order kinetic model

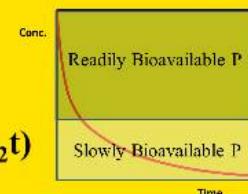
- 1 pool G Model

$$C_t = C_0 \exp (-k t)$$



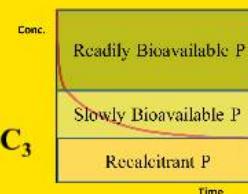
- 2 pool G model

$$C_t = C_1 \exp (-k_1 t) + C_2 \exp (-k_2 t)$$



- 3 pool G model

$$C_t = C_1 \exp (-k_1 t) + C_2 \exp (-k_2 t) + C_3$$

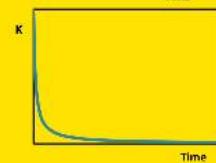
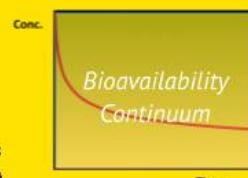


Gamma model

$$C_t = C_0 (a(a+t)^{-1})^v$$

a: average life time of more reactive components
v: the shape of the gamma distribution near k = 0

$$k = v(a+t)^{-1}$$

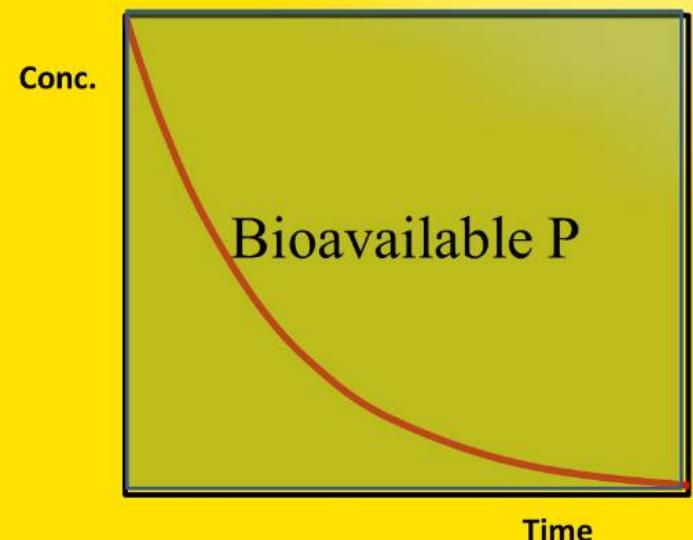


IV MODELS SELECTION

First order kinetic model

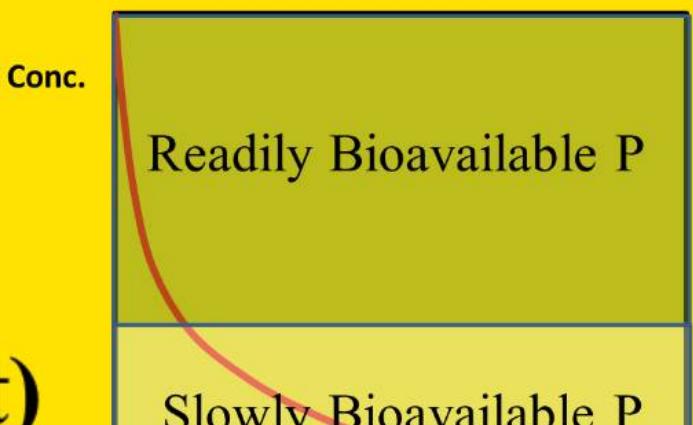
- 1 pool G Model

$$C_t = C_0 \exp (-k t)$$



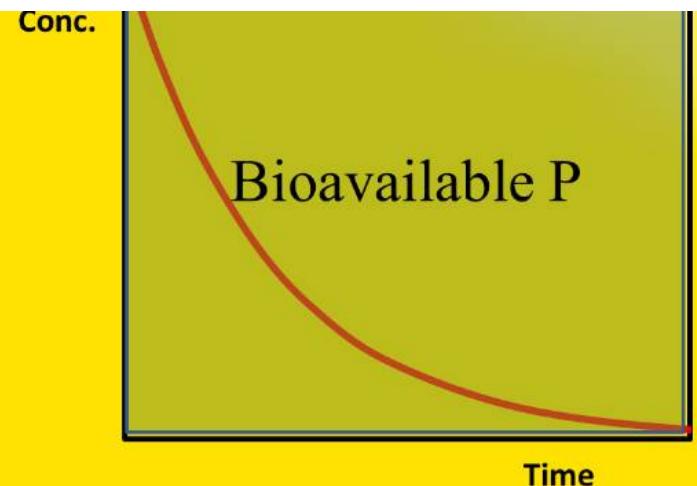
- 2 pool G model

$$C_t = C_1 \exp (-k_1 t) + C_2 \exp (-k_2 t)$$



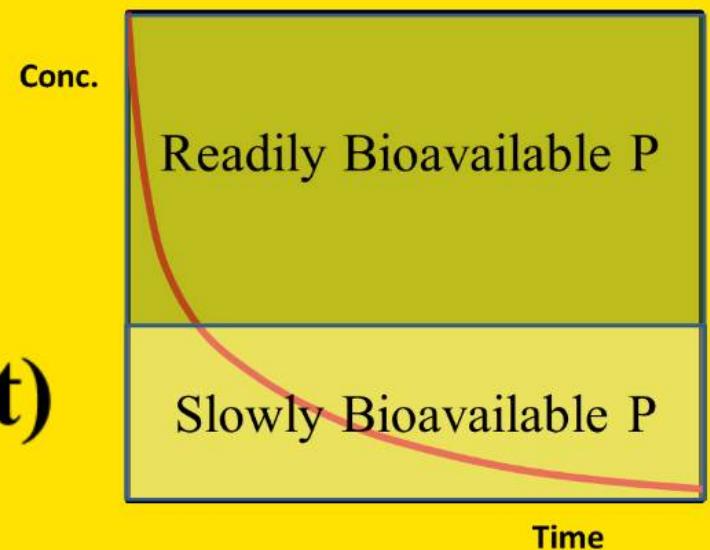
- 1 pool G Model

$$C_t = C_0 \exp (-k t)$$



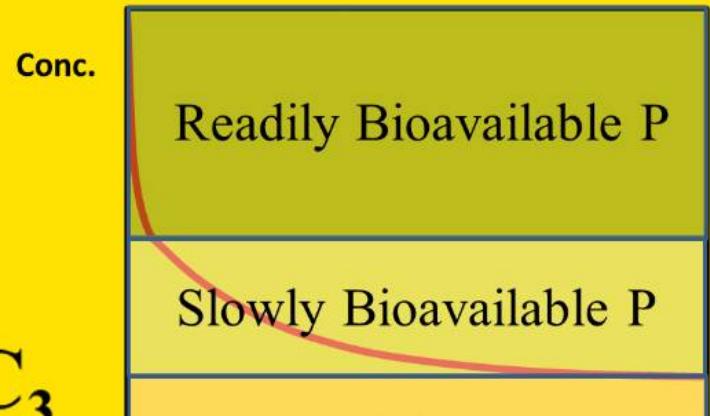
- 2 pool G model

$$C_t = C_1 \exp (-k_1 t) + C_2 \exp (-k_2 t)$$



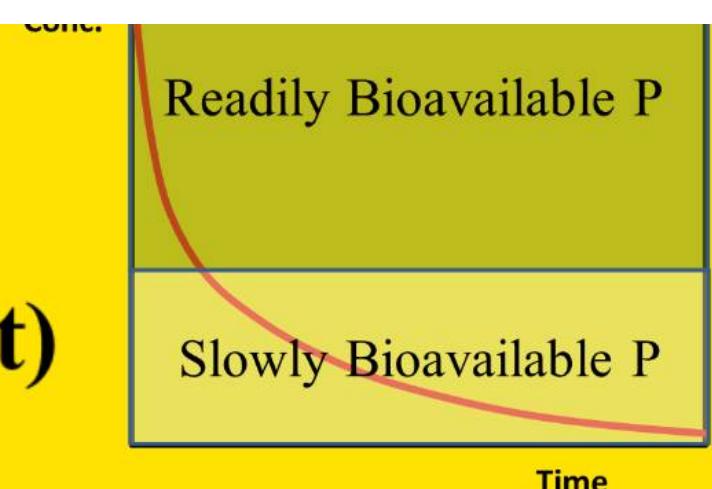
- 3 pool G model

$$C_t = C_1 \exp (-k_1 t) + C_2 \exp (-k_2 t) + C_3$$



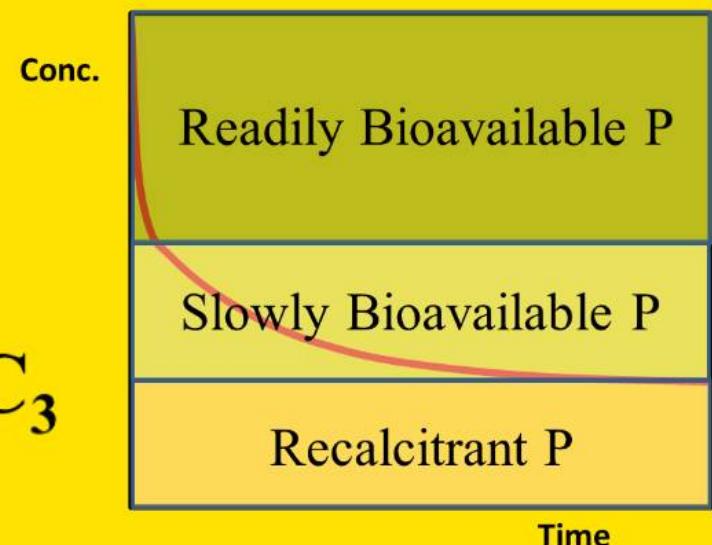
- 2 pool G model

$$C_t = C_1 \exp(-k_1 t) + C_2 \exp(-k_2 t)$$



- 3 pool G model

$$C_t = C_1 \exp(-k_1 t) + C_2 \exp(-k_2 t) + C_3$$



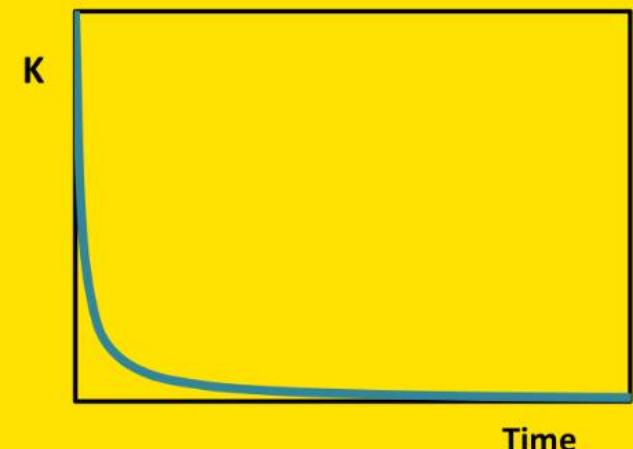
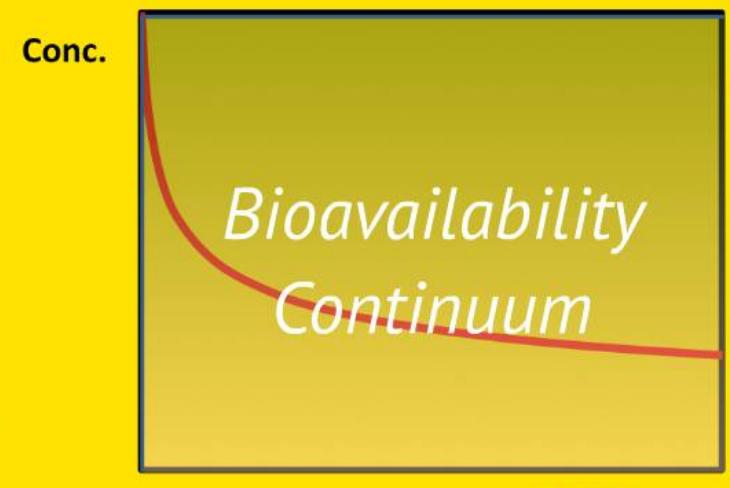
Gamma model

Gamma model

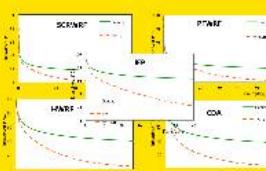
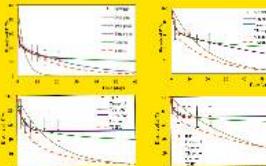
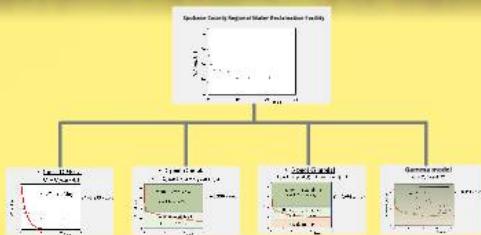
$$C_t = C_0 (a(a+t)^{-1})^v$$

- a: average life time of more reactive components
v: the shape of the gamma distribution near $k = 0$

$$k = v(a+t)^{-1}$$



Results



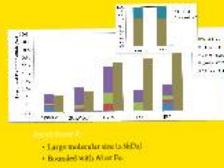
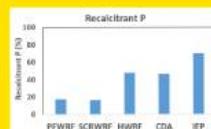
Bio-availability continuum

- Gamma Model k value:

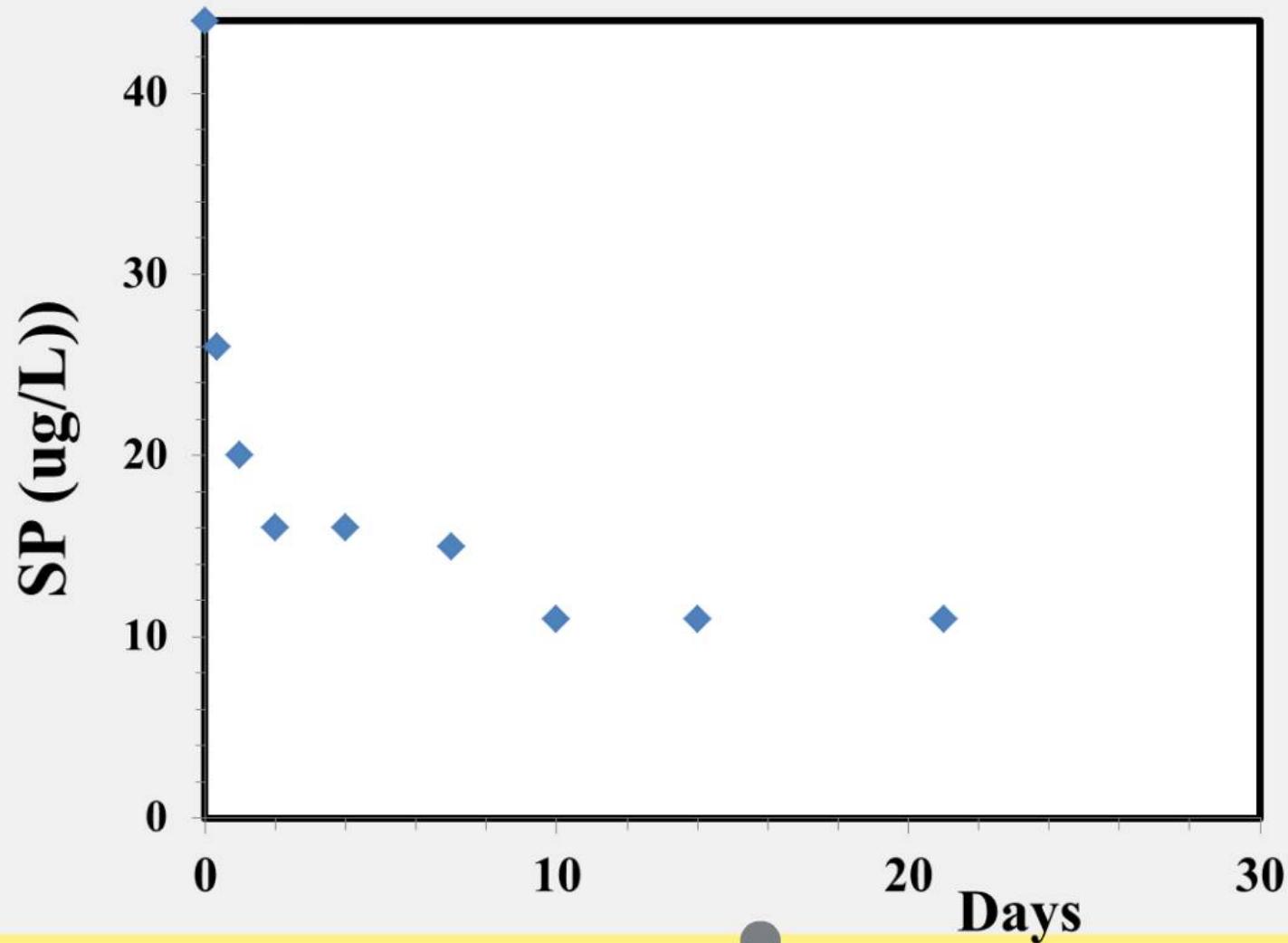


- Phagotrophic species which can benefit from K⁺ ions have a more active metabolism all year long

Recalcitrant P

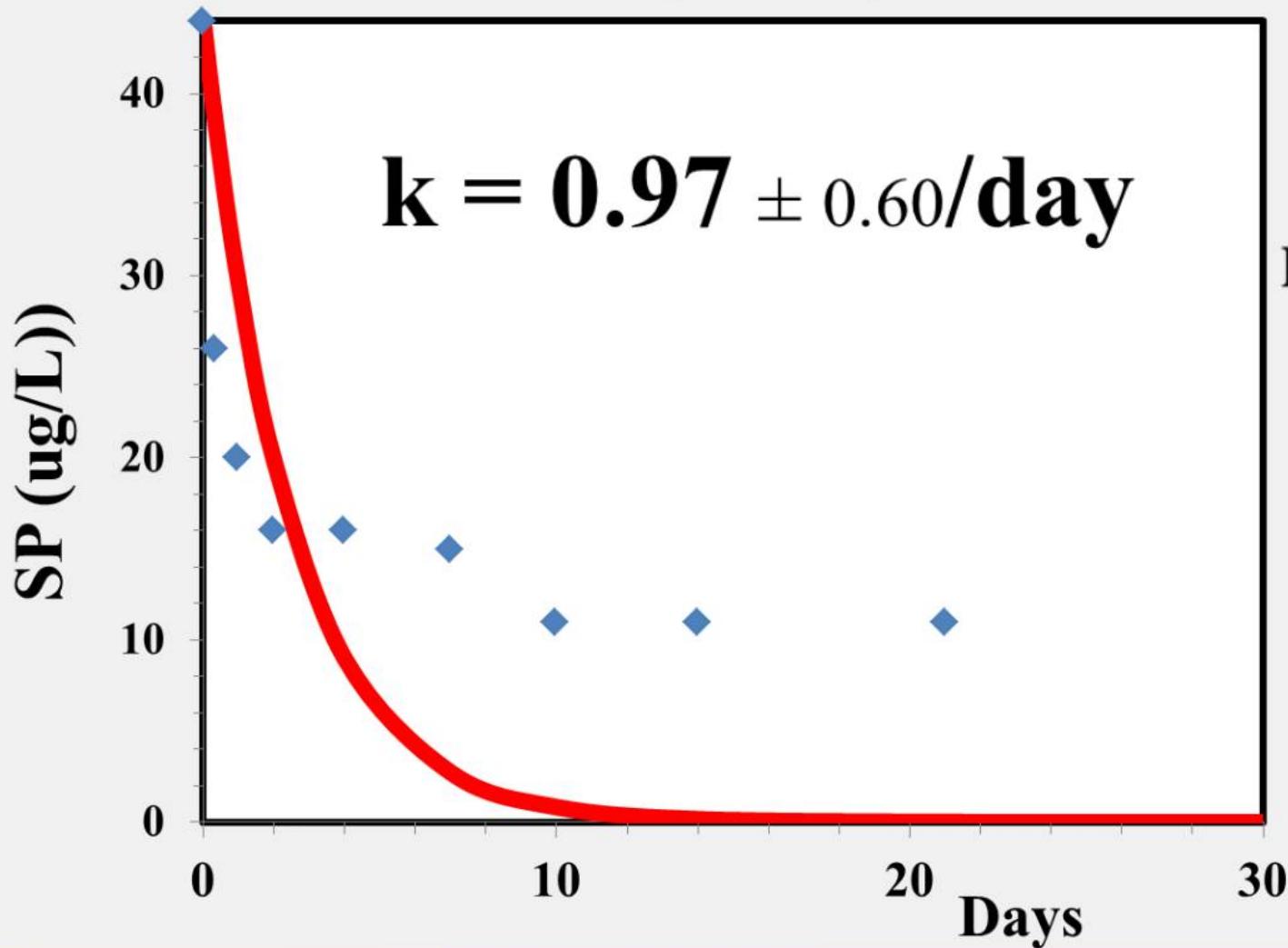


Spokane County Regional Water Reclamation Facility



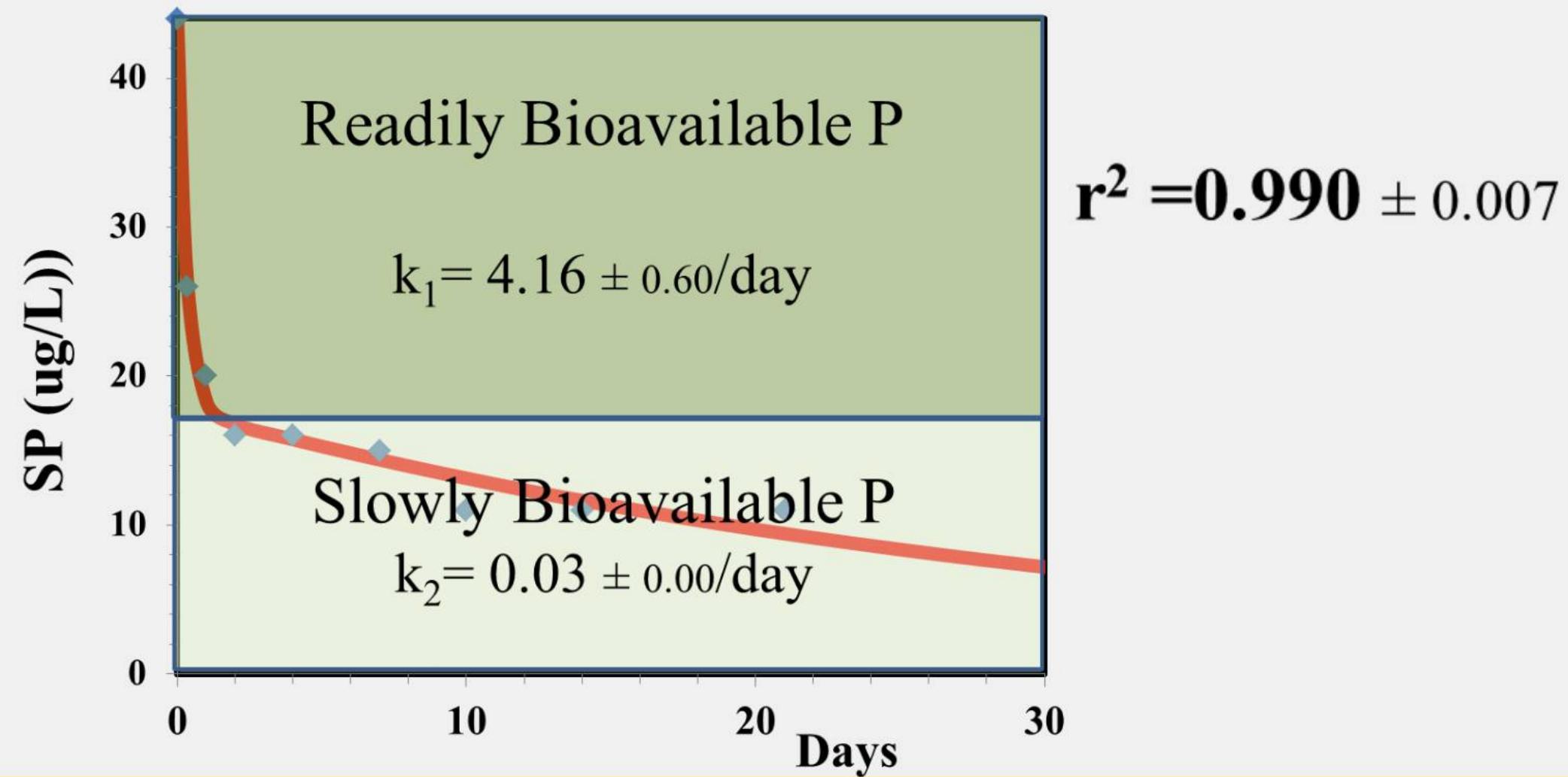
- 1 pool G Model

$$C_t = C_0 \exp (-k t)$$



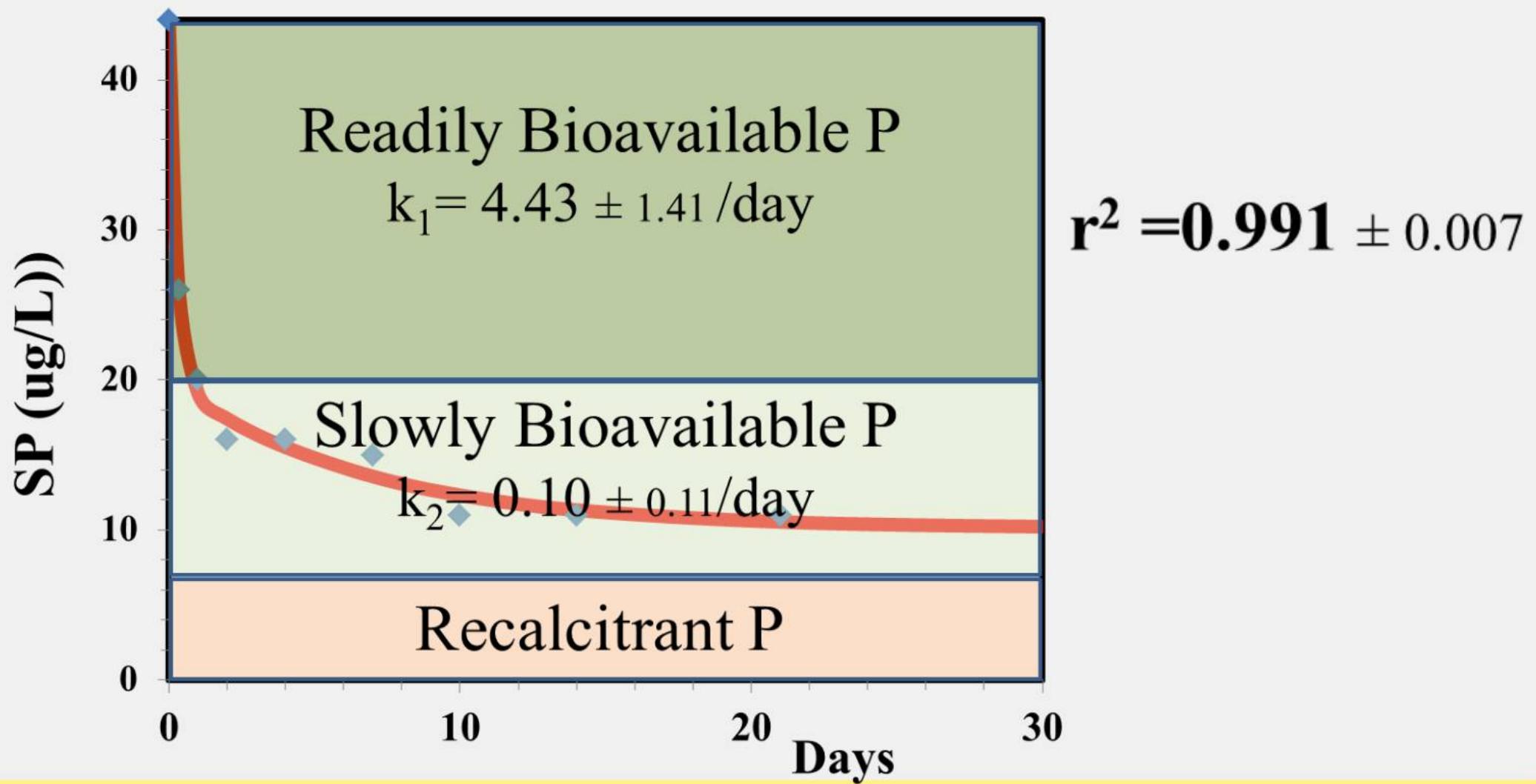
- 2 pool G model

$$C_t = C_1 \exp(-k_1 t) + C_2 \exp(-k_2 t)$$



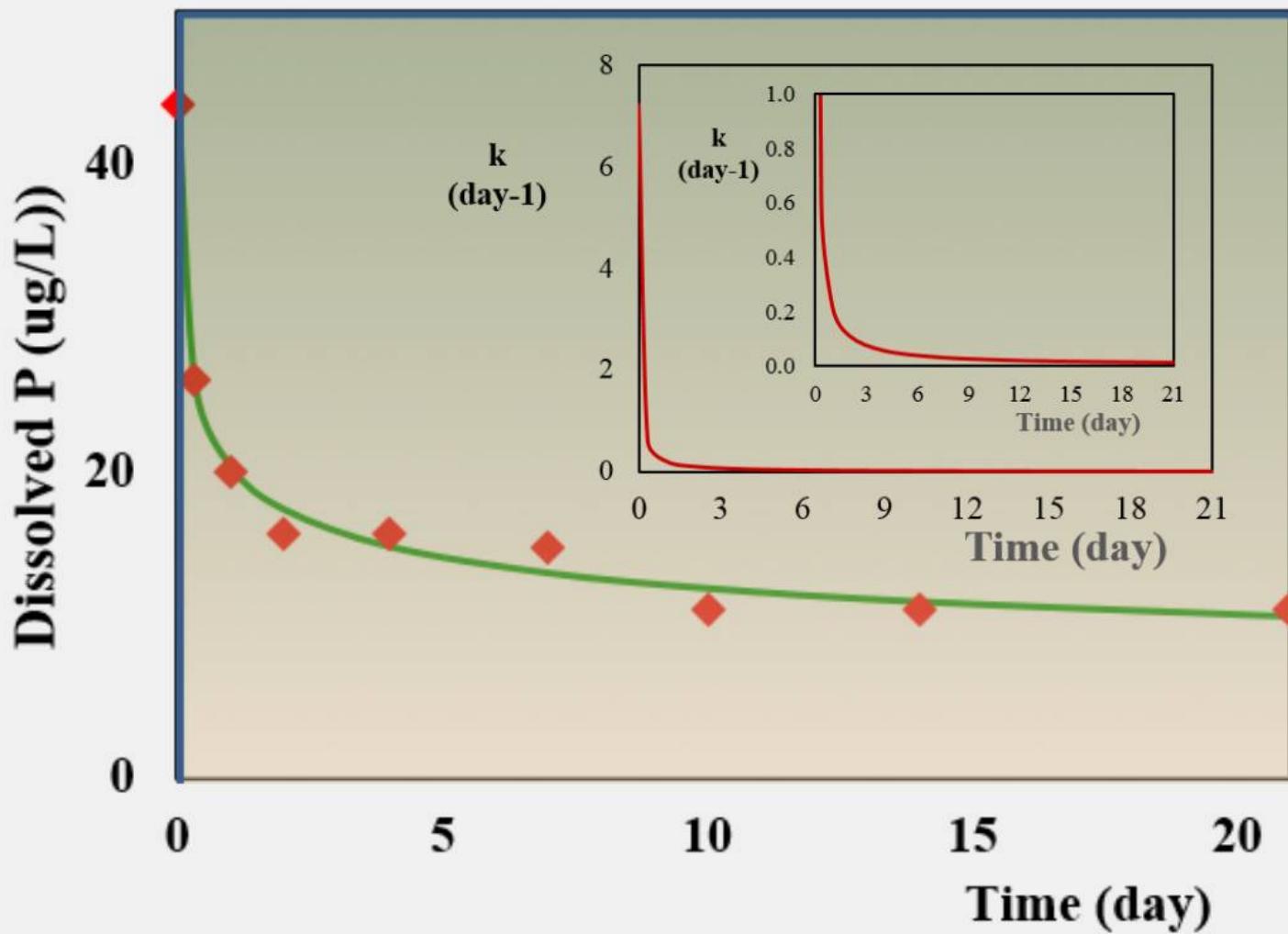
- 3 pool G model

$$C_t = C_1 \exp(-k_1 t) + C_2 \exp(-k_2 t) + C_3$$



Gamma model

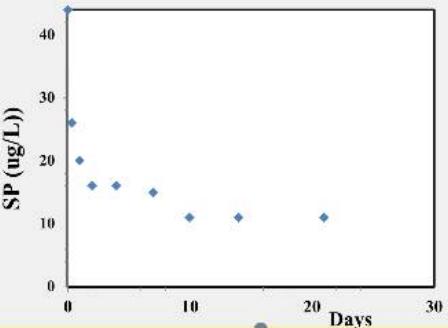
$$C_t = C_0 (a(a+1)^{-1})^v$$



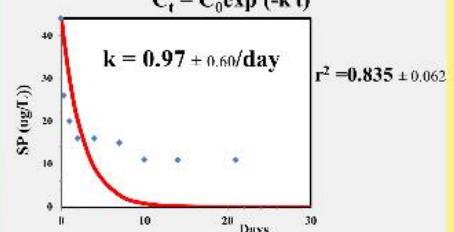
$r^2 = 0.991 \pm 0.007$

RESULTS

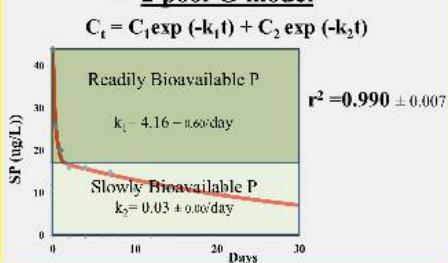
Spokane County Regional Water Reclamation Facility



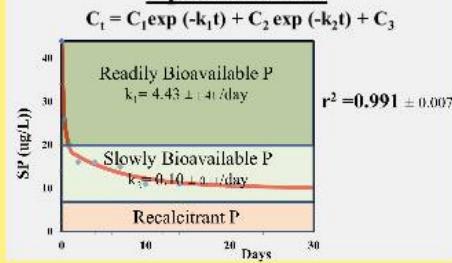
- **1 pool G Model**
 $C_t = C_0 \exp(-k t)$



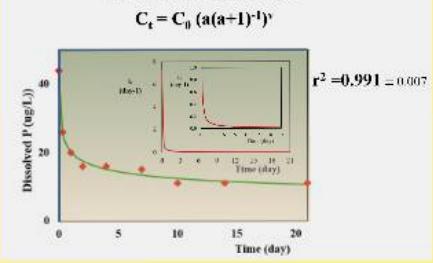
- **2 pool G model**

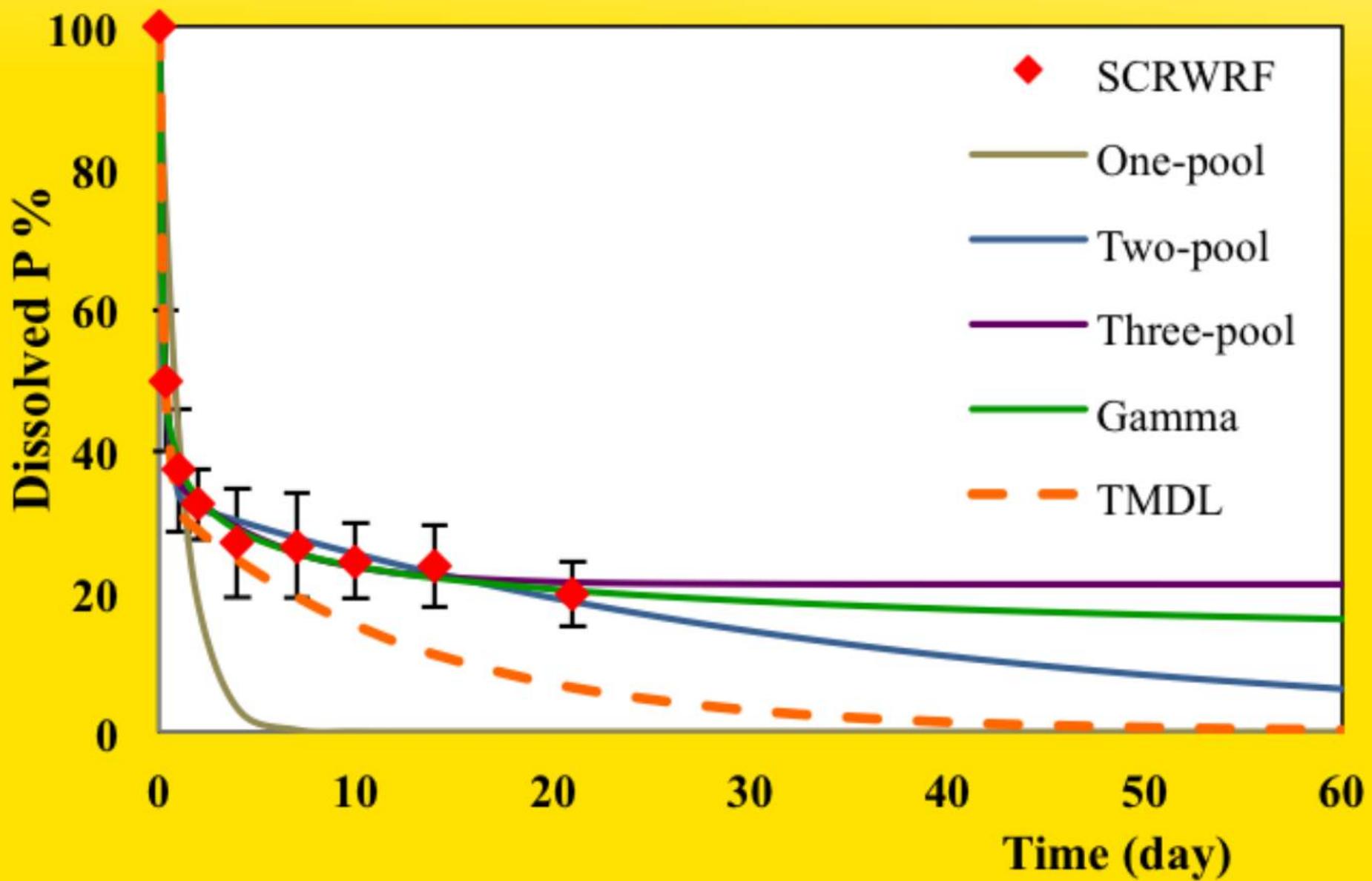


- **3 pool G model**



- **Gamma model**





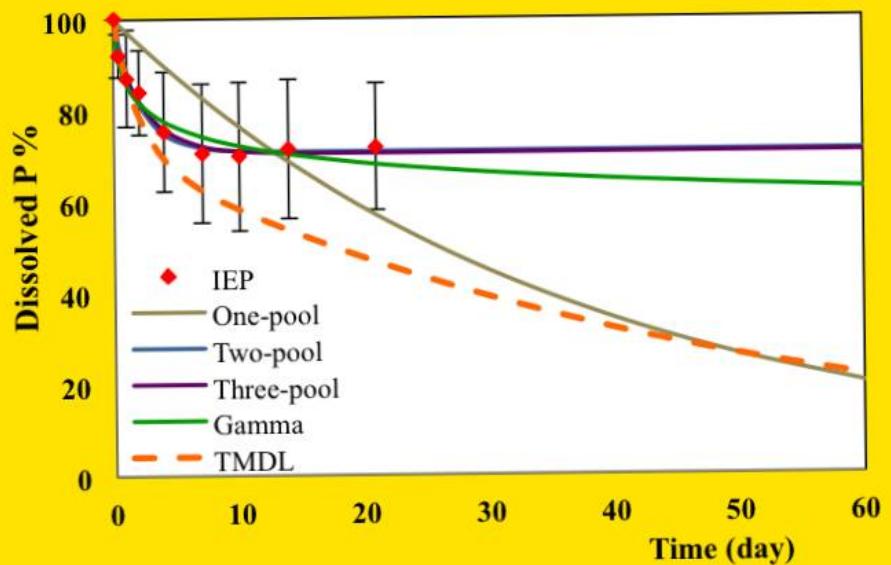
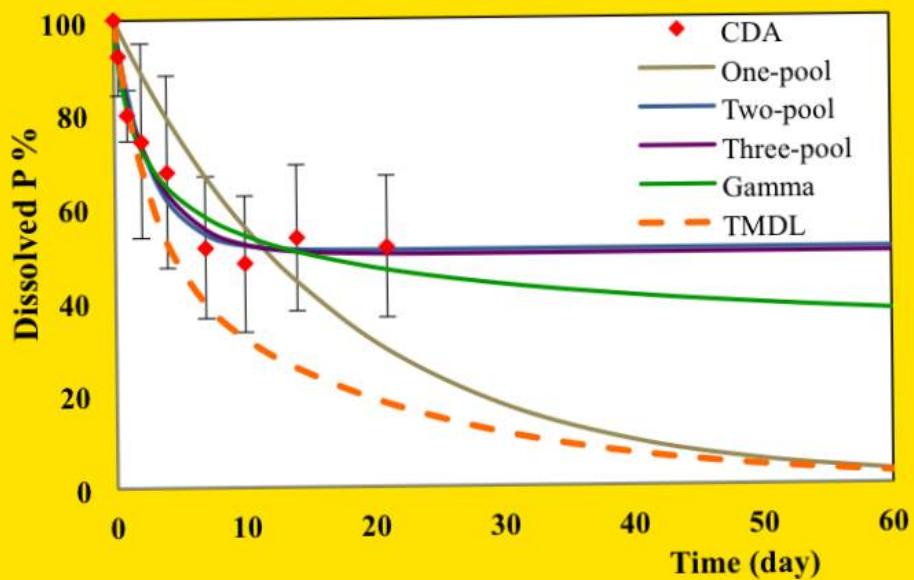
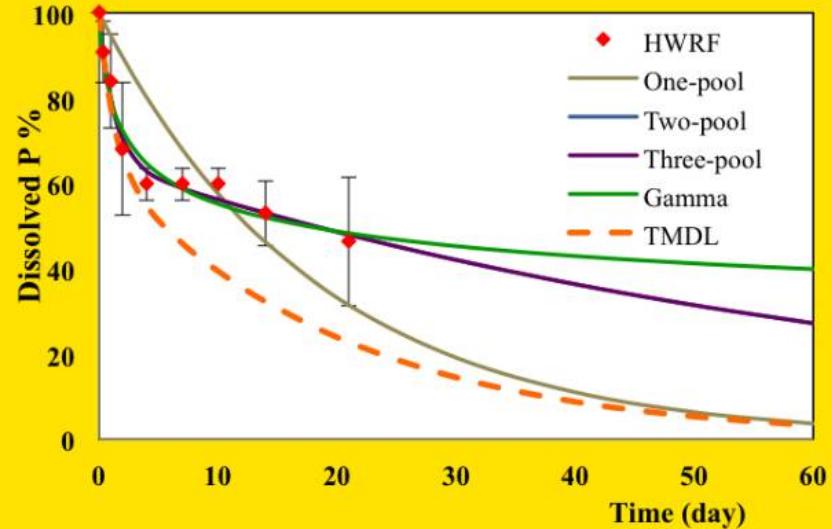
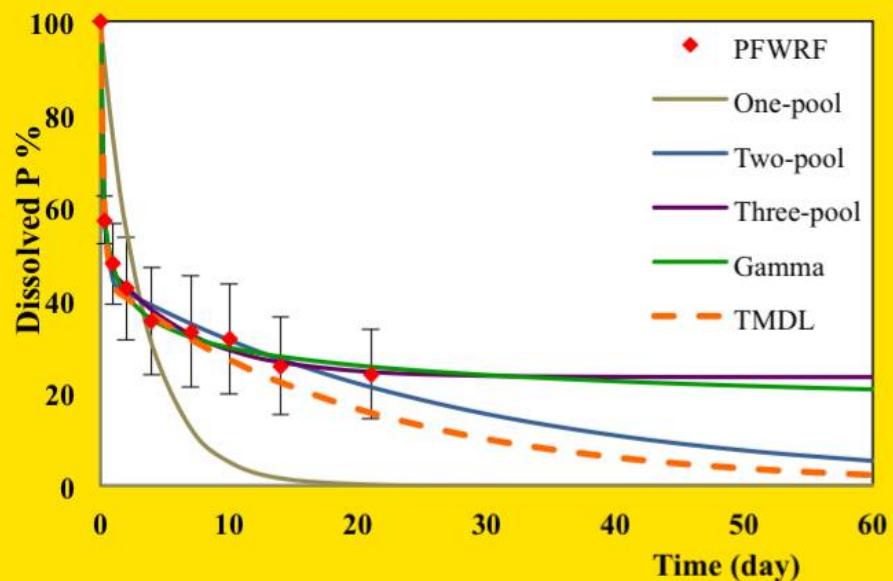


Table 4-11 Model performance based on AIC criteria.

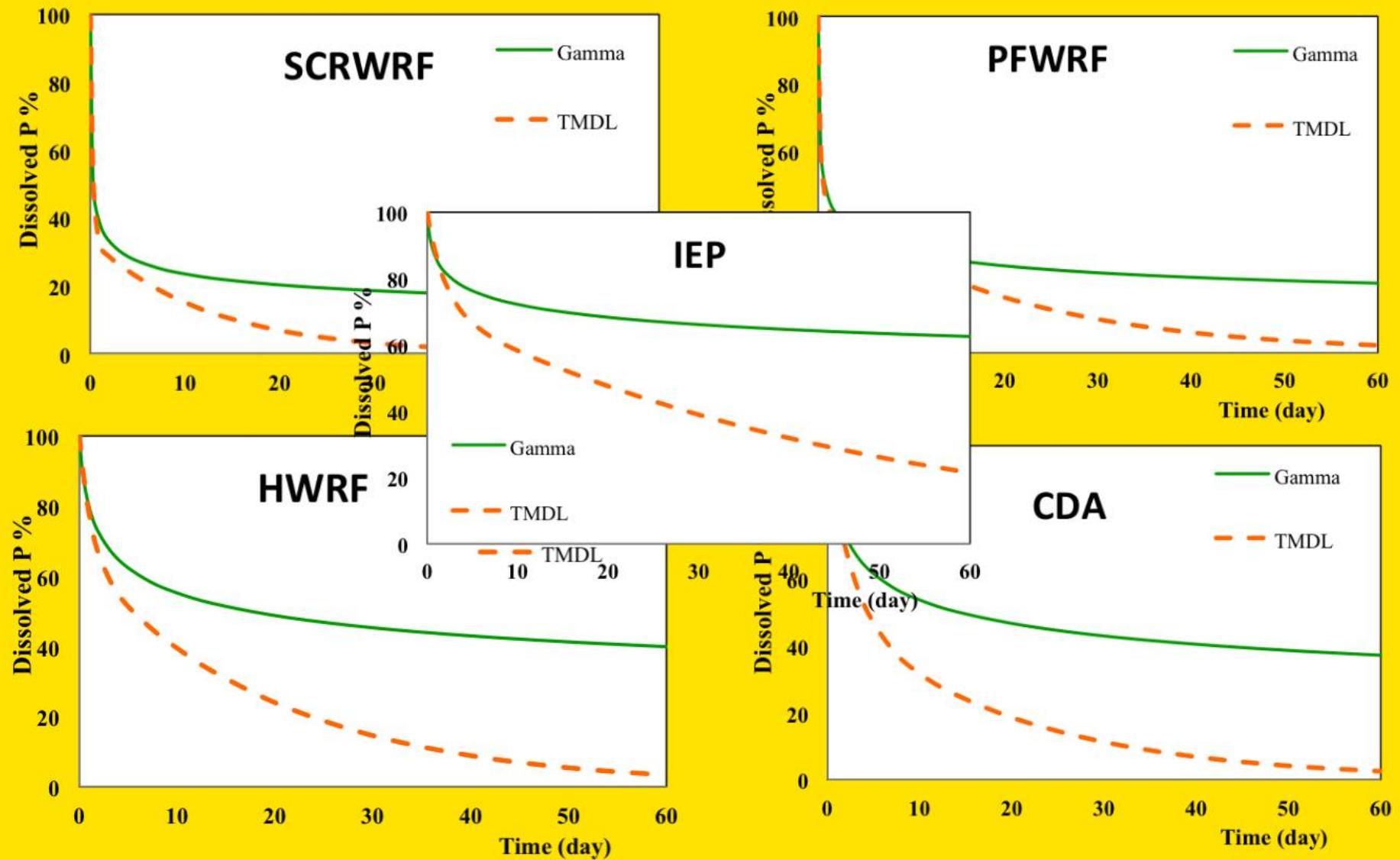
(Note: ESS represents the error sum of squares, N represents sample size, n_v represents the number of variables in the models, AIC is the Akaike Information Criterion value, and $Ak_{\text{Wt.}}$ represents the Akaike Weight.)

	ESS	N	n_v	AIC	ΔAIC	$Ak_{\text{Wt.}}$
1 Pool	24797	45	1	127	36	0

Table 4-11 Model performance based on AIC criteria.

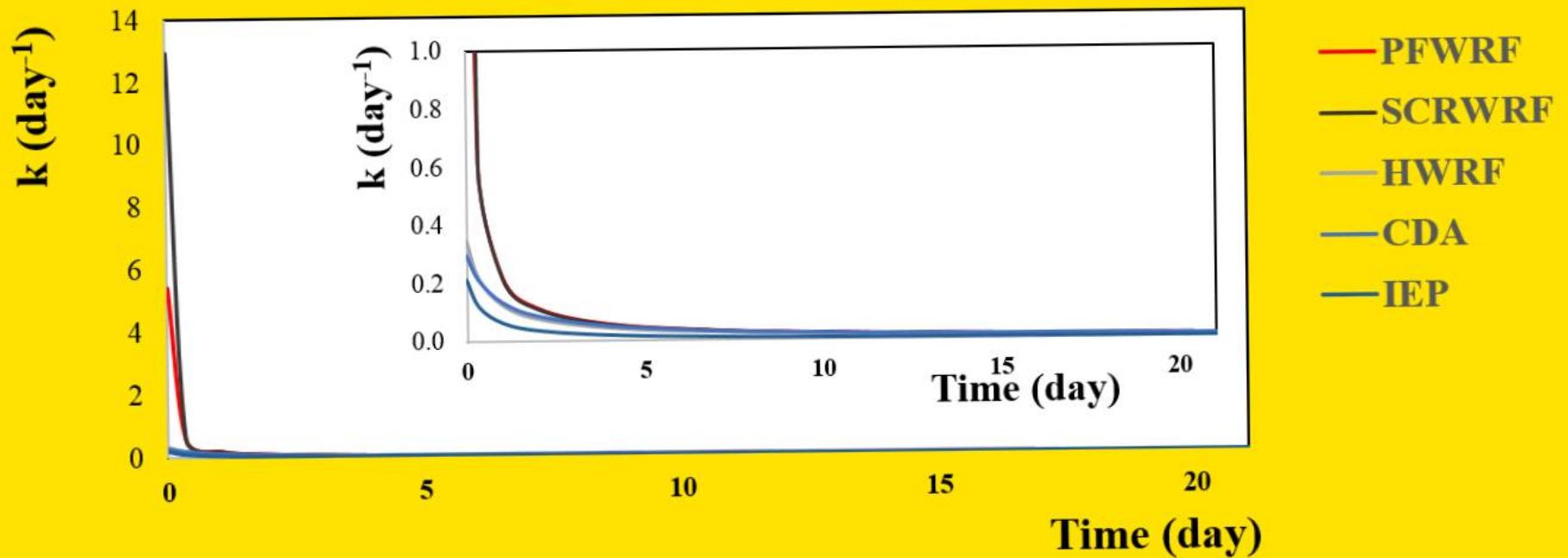
(Note: ESS represents the error sum of squares, N represents sample size, n_v represents the number of variables in the models, AIC is the Akaike Information Criterion value, and Ak. Wt. represents the Akaike Weight.)

		ESS	N	n_v	AIC	ΔAIC	Ak. Wt.%
PFWRF	1 Pool	24797	45	1	127	36	0
	2 Pool	3585	45	4	96	5	9
	3 Pool	3585	45	5	98	7	3
	Gamma	3464	45	2	91	0	88
SCRWRF	1 Pool	19735	45	1	123	46	0
	2 Pool	1729	45	4	81	5	8
	3 Pool	1729	45	5	83	7	3
	Gamma	1657	45	2	76	0	89
HWRF	1 Pool	3311	18	1	45	10	1
	2 Pool	632	18	4	38	3	17
	3 Pool	632	18	5	40	5	6
	Gamma	711	18	2	35	0	77
CDA	1 Pool	14807	45	1	117	10	1
	2 Pool	7925	45	4	111	3	14
	3 Pool	7925	45	5	113	5	5
	Gamma	8144	45	2	108	0	80
IEP	1 Pool	9758	45	1	109	9	1
	2 Pool	5348	45	4	103	4	14
	3 Pool	5348	45	5	105	6	5
	Gamma	5483	45	2	100	0	80

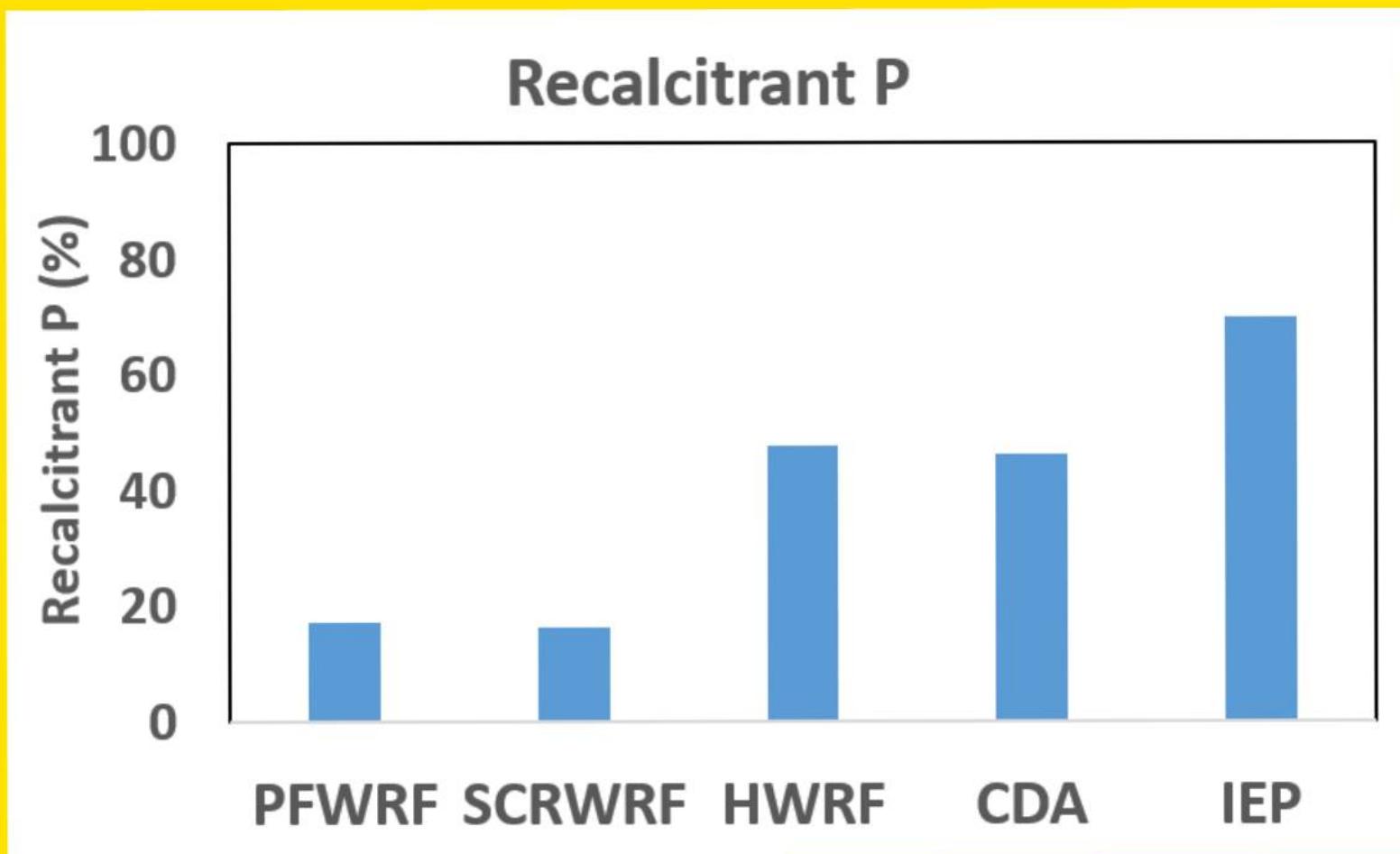


Bio-availability continuum

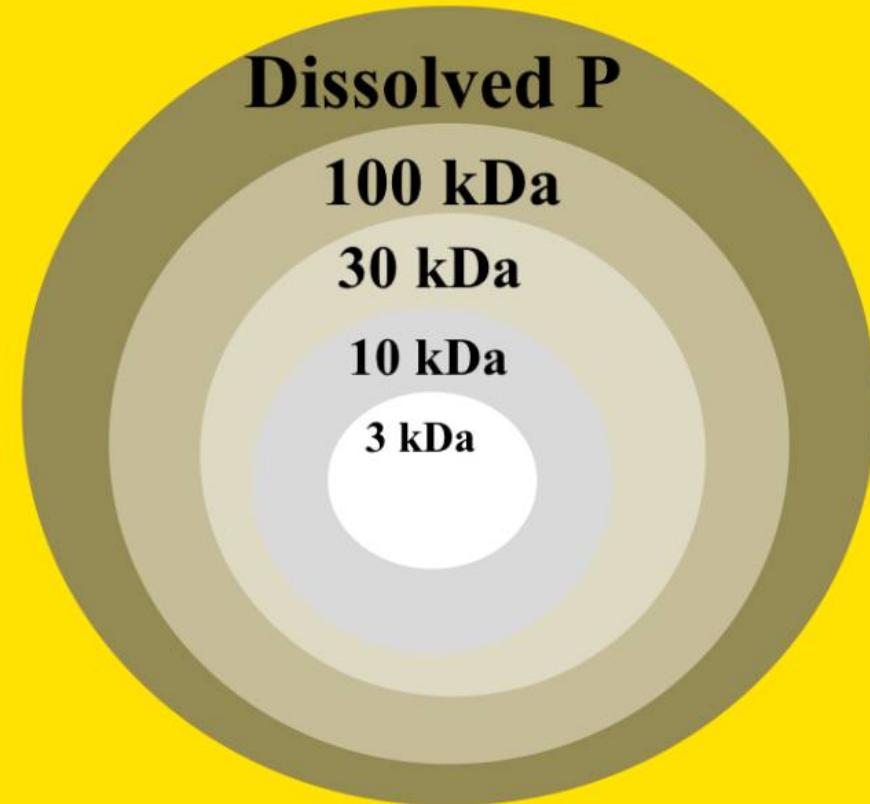
- Gamma Model k value:



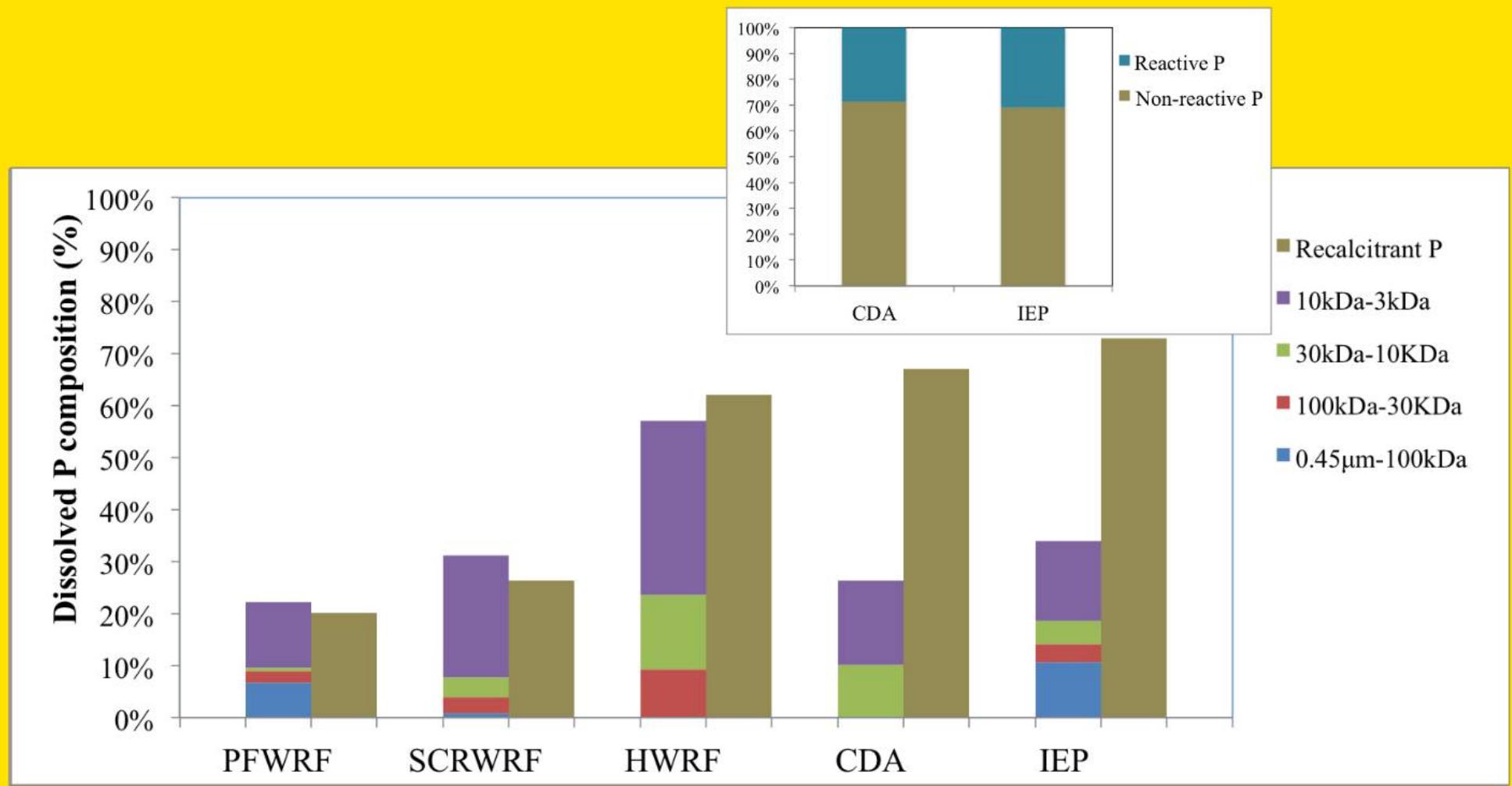
Recalcitrant P



Molecule-weight fractionation



- Phosphorus species which are larger than 2 kDa are too large to cross phytoplankton cell membranes.



Recalcitrant P:

- Large molecular size ($>3\text{kDa}$)
- Bounded with Al or Fe.

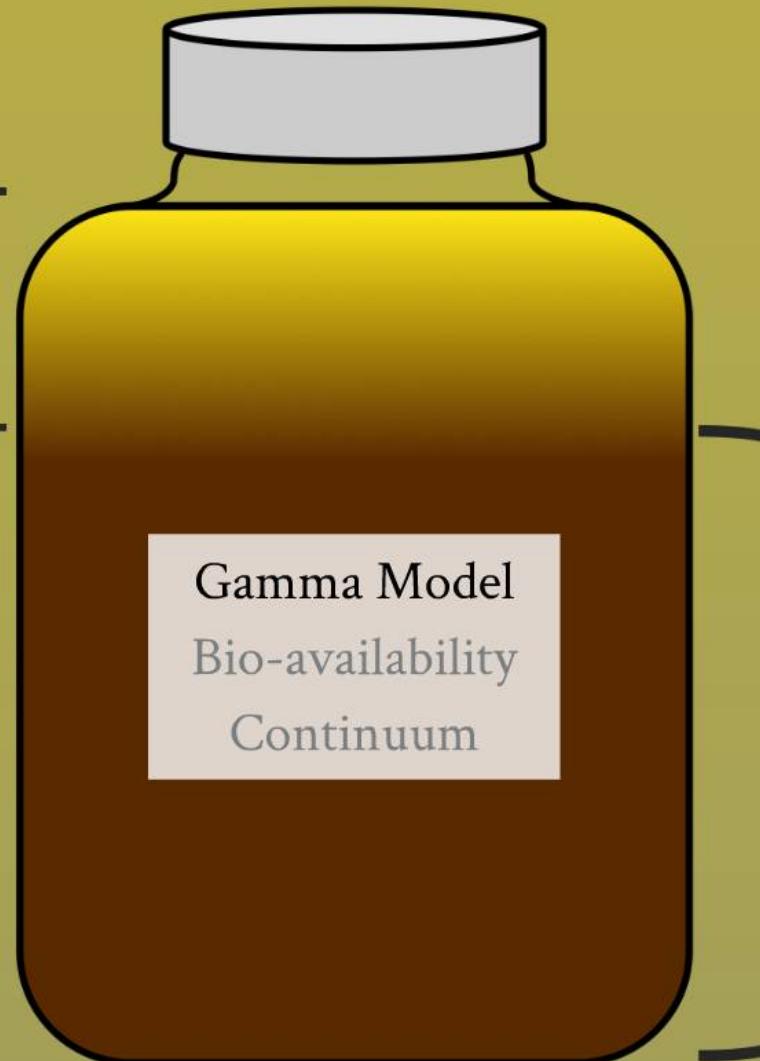
Summary

- There was no evidence for N co-limitation for the effluents tested.
- For most effluents there was no consistent evidence of a toxic growth inhibition.
- Gamma model gave by far the most parsimonious fit to the data.
- The Gamma model predicts that with a 2 month HRT approximately 10-50% of the dissolved P will not be utilized in Long Lake.

utinized in Long Lake.

Bio-available Phosphorus

- Can be easily used by algae
- Unlikely to persist in natural system



Recalcitrant Phosphorus

- Undergoes a much slower uptake process
- Up to 70% of P in the effluents could be recalcitrant
- May consist of large molecules (>3 kDa) or bounded with Al/Fe.
- Could sustain in systems for years

ACKNOWLEDGEMENTS

Spokane River Stewardship Partners

Working every day for a healthy river

Spokane County • City of Spokane • Liberty Lake Sewer & Water District • City of Coeur d'Alene • City of Post Falls • Hayden Area Regional Sewer Board
Avista • Inland Empire Paper Company • Kaiser Aluminum

Water Environment Research Foundation (WERF) Nutrient Challenge Program

Adviser:

Michael T. Brett, University of Washington

- Spokane County Regional Water Reclamation Facility
- City of Post Falls Water Reclamation Facility
- Hayden Wastewater Research Facility
- Coeur d'Alene Advanced Wastewater Treatment Plant
- Inland Empire Paper Company



Spokane River Stewardship Partners

Working every day for a healthy river

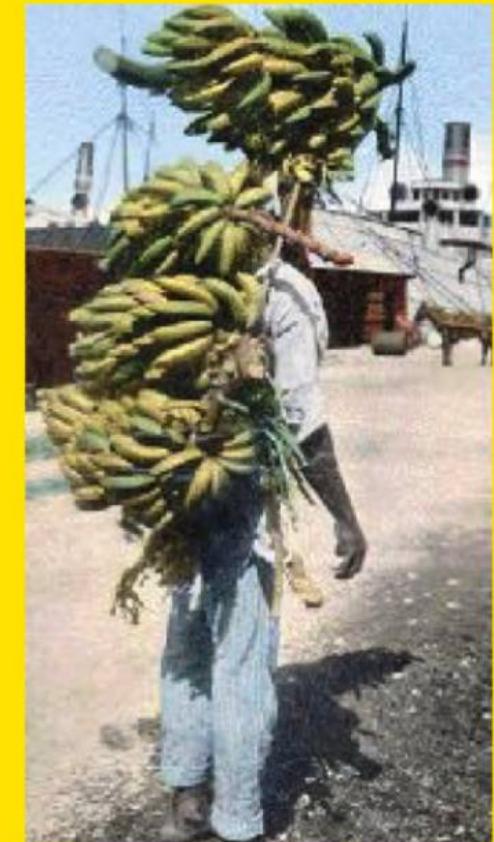
Spokane County • City of Spokane • Liberty Lake Sewer & Water District • City of Coeur d'Alene • City of Post Falls • Hayden Area Regional Sewer Board
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Dissolved P

