

MODELING AND OPTIMIZING THE PERFORMANCE OF NITRIFYING TRICKLING FILTERS (NTFs)

Course notes: CE572 Biological Wastewater Treatment
Instructor: B. E. LOGAN

Trickling filter programs can be obtained at:
www.engr.psu.edu/ce/enve

What is needed to promote nitrifying biofilms in fixed-film systems?

- P Low concentration of BOD (<20 mg/L) to eliminate biofilm competition (space and oxygen)
- P Conditions that promote high oxygen transfer rates
- P Conditions that permit a thick biofilm to be maintained

High Concentrations of BOD reduce nitrification rates

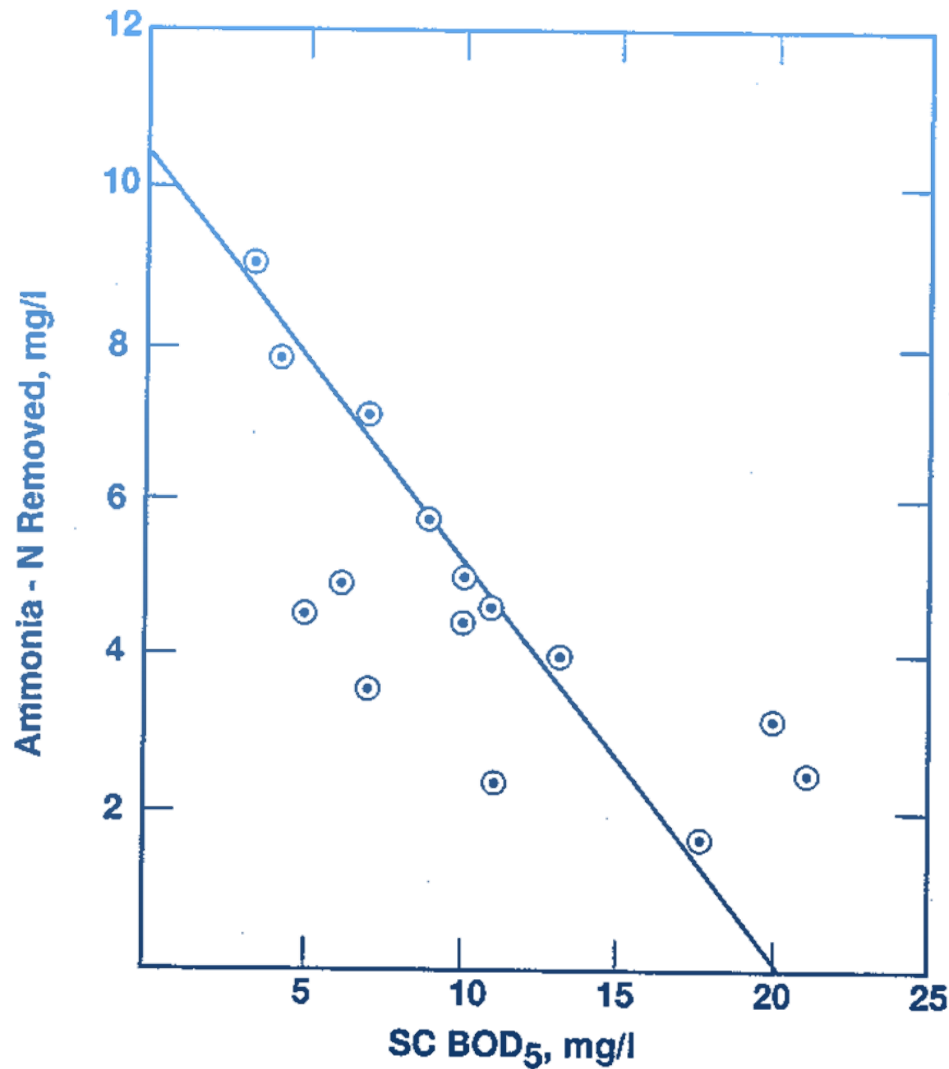


Figure 4 from
Parker et al. (1998)

Oxygen transport rates in cross-flow (XF) and vertical-flow (VF) media

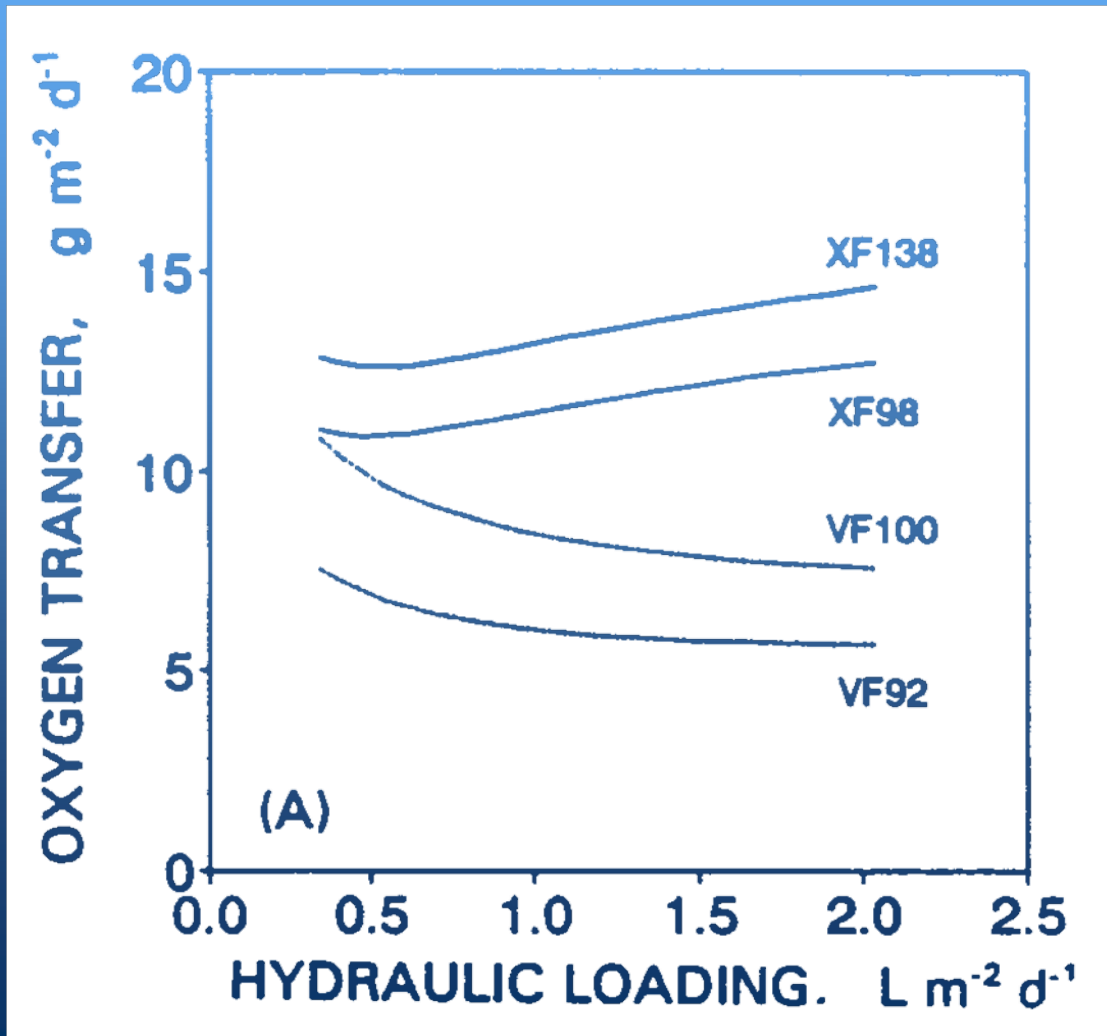


Figure 5 from:
Logan (1993)

Different approaches used to maintain thick biofilms

- Biofilm control through flooding
- Alkaline washing to remove predators
- Two filters in series, with alternating units receiving influent flow

OBJECTIVES

Remove sBOD to $< 12 \text{ mg/L}$

- Predict sBOD removal using LTF
- Add solids Contact if necessary

Nitrifying Trickling Filter (NTF) model

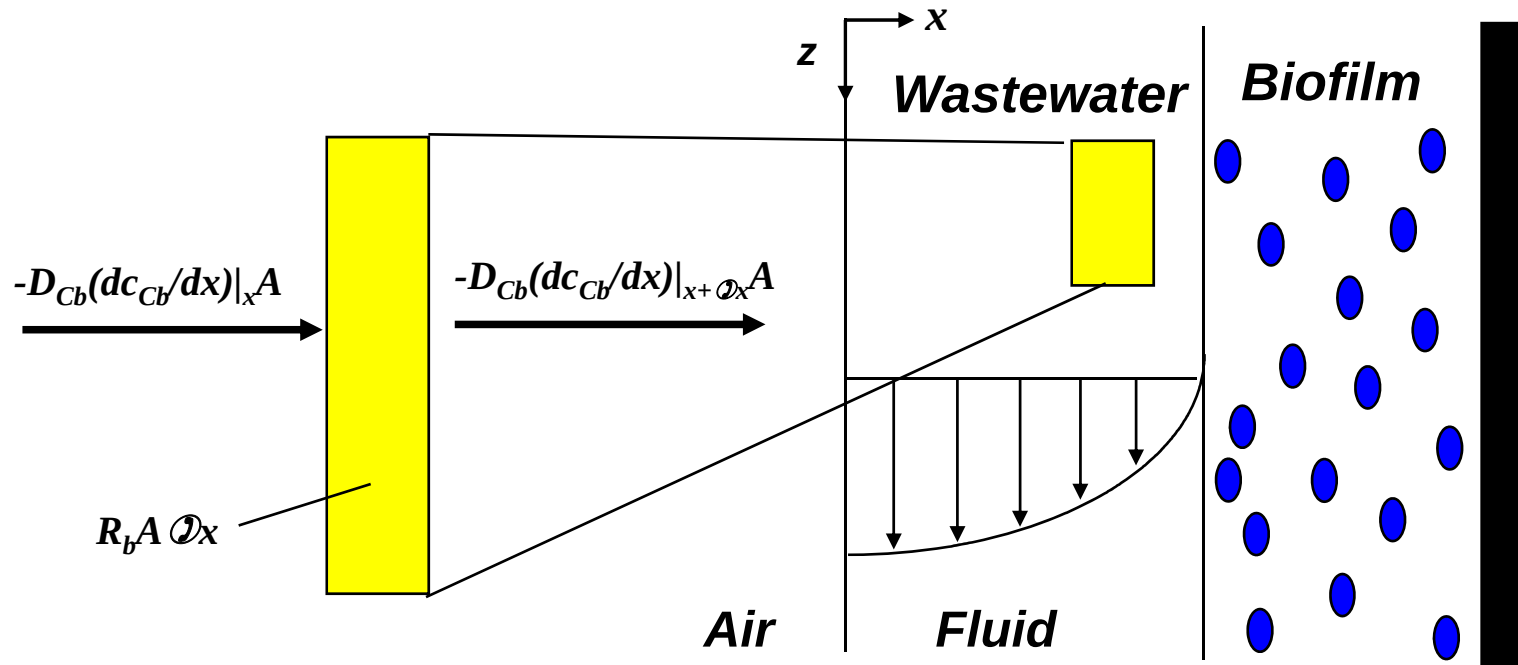
- Key is oxygen transport
- Calculate oxygen transfer using NTF

NTF Design approach

Solving operational problems of NTFs

Modeling TF Performance: The LTF Model

LTF model= WW model + Biofilm model



The control volume used to construct a transport equation for chemical transport within the biofilm.

*From Logan
(1999)*

LTF Model: Governing Equations

Governing Equation (written about fluid layer)

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} - u(x) \frac{\partial c}{\partial z}$$

Boundary conditions:

$z=0$	$c=c_{s,in}$
$x=0$	$J_s=0$
$x=\delta$	$J_s=k^{1/2}D_s c_s$

where:

$c=$	sBOD
$u(x)=$	parabolic velocity profile in ww liquid film
$J_s=$	BOD flux into the biofilm
$k=$	biofilm kinetic constant (first-order)

LTF Model Summary

- Is TF operation satisfactory in terms of a low sBOD? If not, need to improve.
- If sBOD removal well predicted by LTF, then you can predict changes in operation due to:
 - Media type
 - Hydraulic load
 - Temperature
 - Recycle
- Is it necessary to use TF/SC process? If so, run LTF subroutine to predict performance.
- Make sure oxygen transfer in TF is sufficient for sBOD removal

sBOD Removal- Hydraulic Load

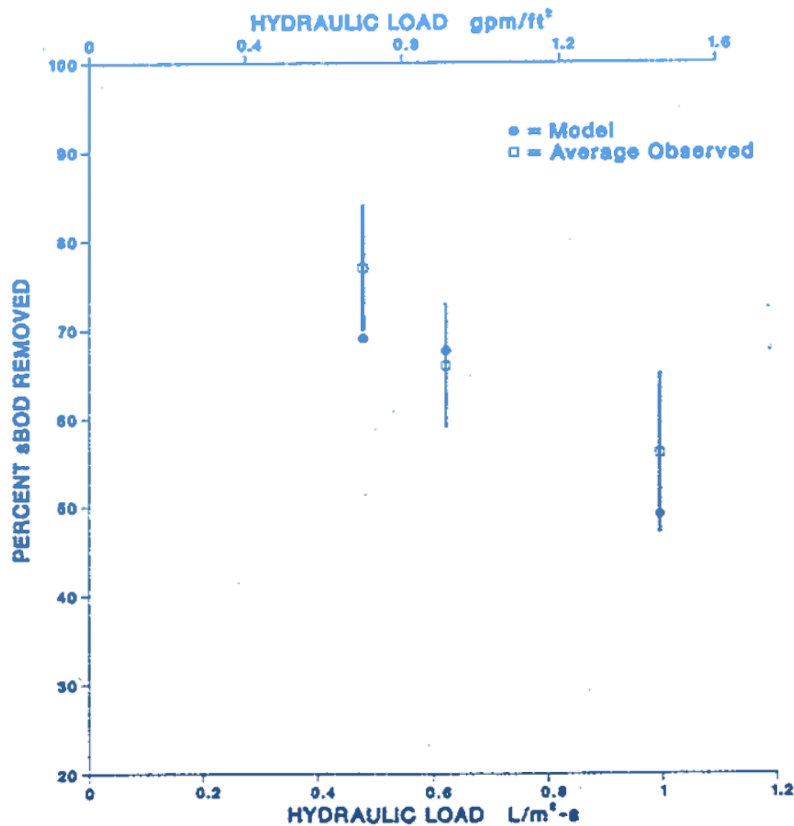


Figure 6—Predicted hydraulic load effect on sBOD removal for vertical-flow (VFb-100) media compared with the data of Richards.⁶⁰

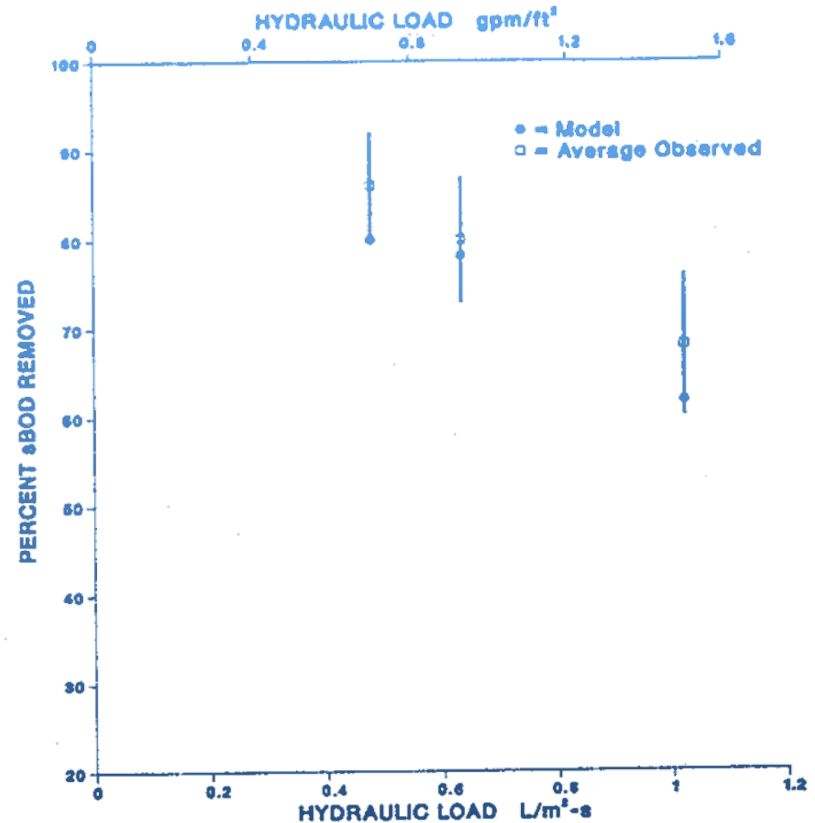
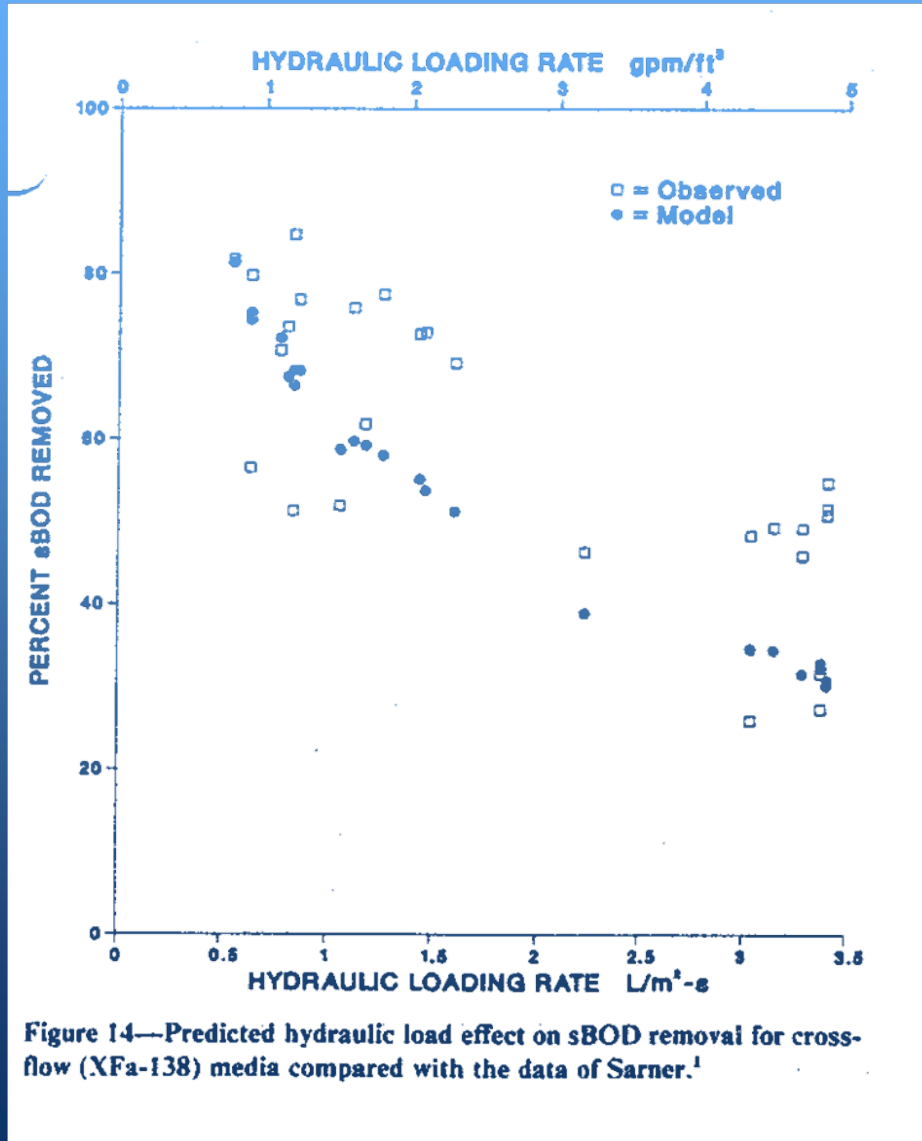


Figure 7—Predicted effect of hydraulic load on sBOD removal for cross-flow (XFa-98) media compared with the data of Richards.⁶⁰

sBOD Removal- Hydraulic Load

Data of Sarner [From Logan et al. (1987a): Figure 14]



sBOD Removal- sBOD profile

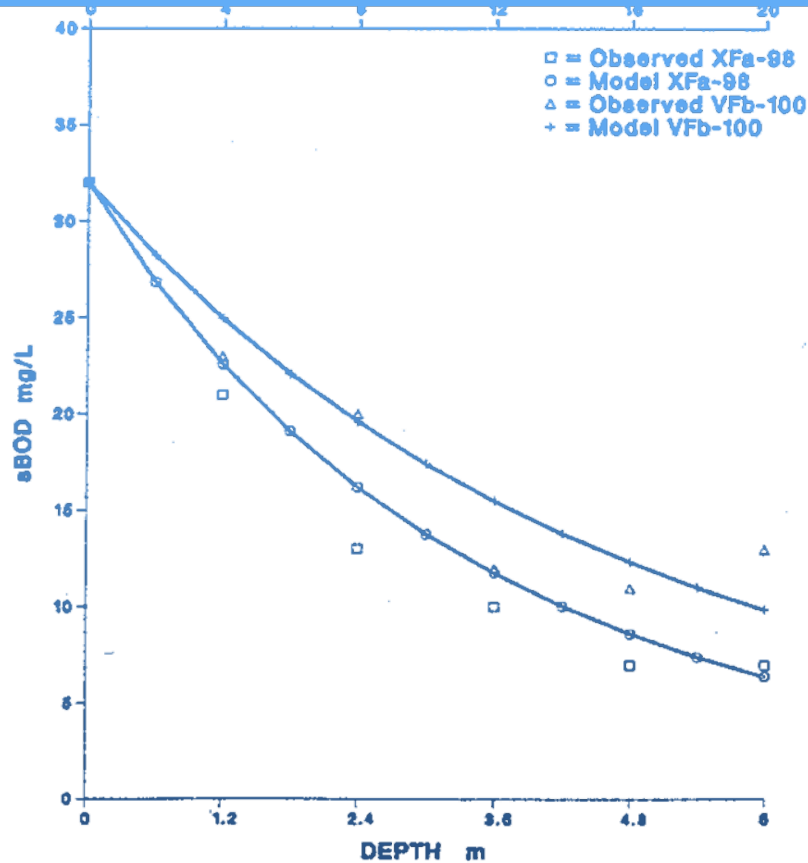


Figure 9—Predicted sBOD profiles for cross-flow (XFa-98) and vertical-flow (VFb-100) trickling filters versus the data of Richards,⁶⁰ for an average hydraulic load of 0.48 L/m²s (0.7 gpm/ft²).

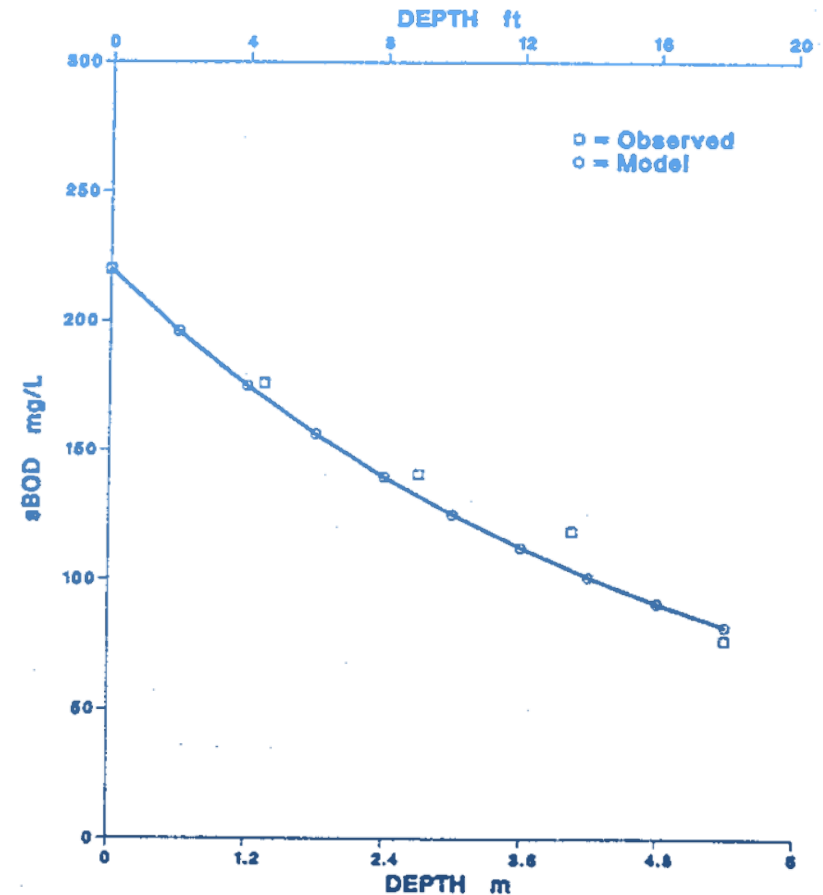
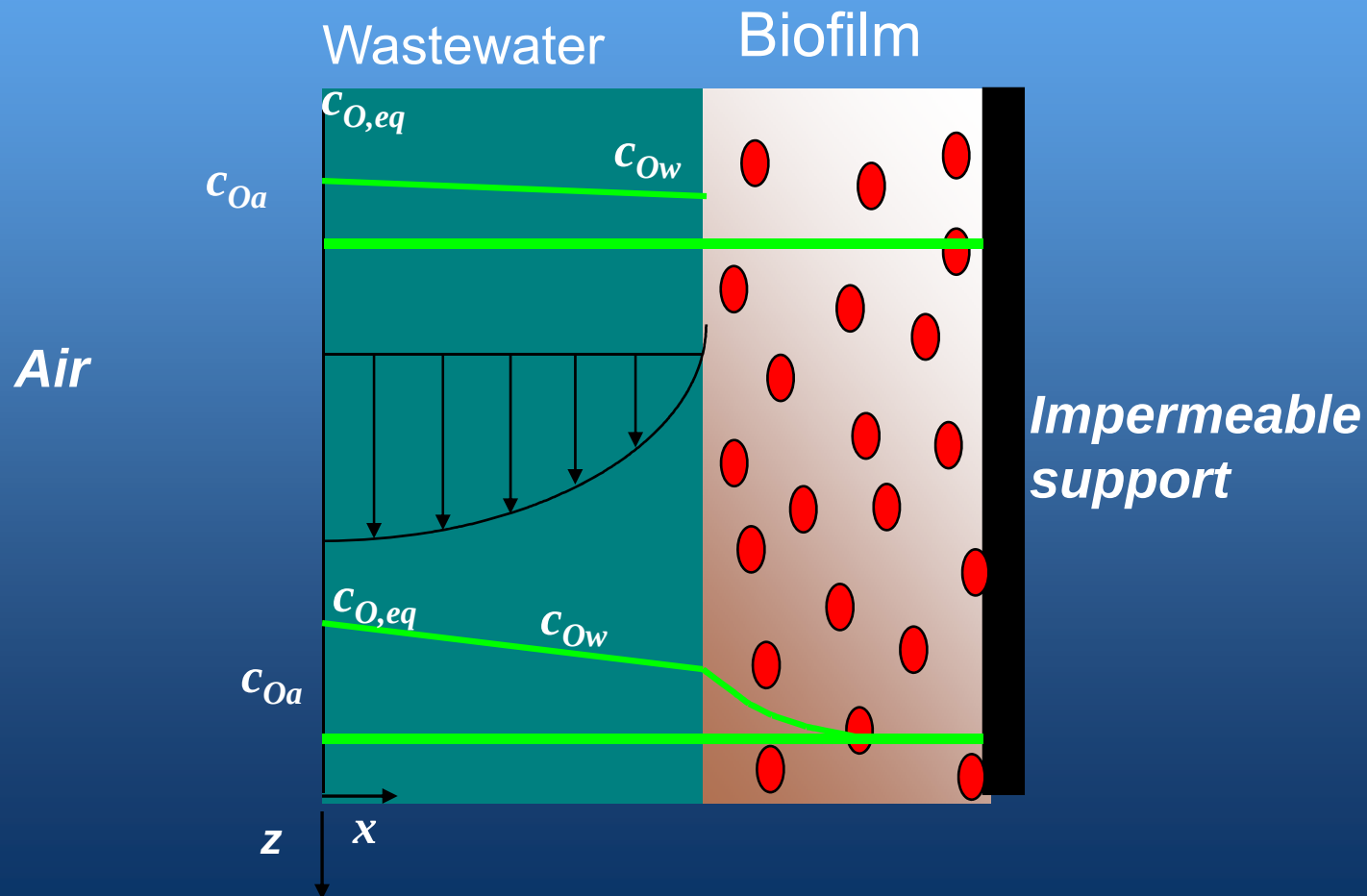


Figure 10—Predicted hydraulic load effect on sBOD removal for vertical-flow (VFc-92) media versus the data of Hutchinson⁶² for an average hydraulic load of 0.41 L/m²s (0.6 gpm/ft²).

NTF MODEL DEVELOPMENT

Transport of oxygen based on same approach used for sBOD



NTF Model: Governing Equations

Governing Equation: based on dissolved oxygen (c_{O_2})

$$\frac{\partial c_o}{\partial t} = D \frac{\partial^2 c_o}{\partial x^2} - u(x) \frac{\partial c_o}{\partial z}$$

Boundary conditions:

$z=0$	$c=c_{O,in}$
$x=0$	$c_o=c_{O,eq}$
$x=\delta$	J_o

where:

$c_o =$	Dissolved oxygen concentration
$J_o =$	Oxygen flux into the biofilm; a function of BOD removal kinetics

Conditions linking ammonia and oxygen fluxes

Mass of oxygen to mass of ammonia used is:

$$Y_{O/N} = 4.33 \frac{mg - O_2}{mg - NH_3}$$

Biofilm kinetics based on Monod kinetics, or

$$\frac{\partial c_N}{\partial t} = -\frac{\mu X}{Y} = -\frac{X}{Y} \frac{\mu_{\max} c_N}{K_N + c_N}$$

where:

c_N	$=$	NH_3 concentration
$\mu_{\max}$	$=$	maximum growth rate
K_N	$=$	half saturation constant for NH_3
X	$=$	Cell concentration in the biofilm
Y	$=$	Yield constant (cells per substrate)

The ammonia flux depends on the concentration of ammonia at the biofilm surface:

For $c_{Ni} < 2K_N$

$$x = \delta \quad J_N = \left(\frac{\mu_{\max} X}{K_N Y_{X/N}} \right)^{1/2} D_N^{1/2} c_{Ni}$$

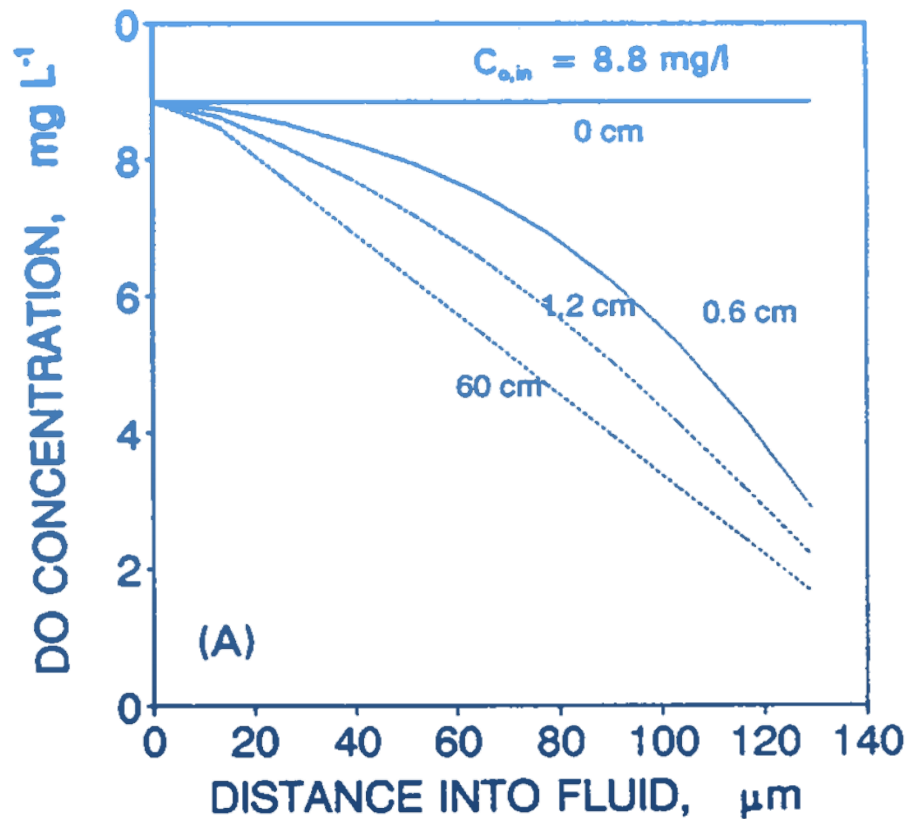
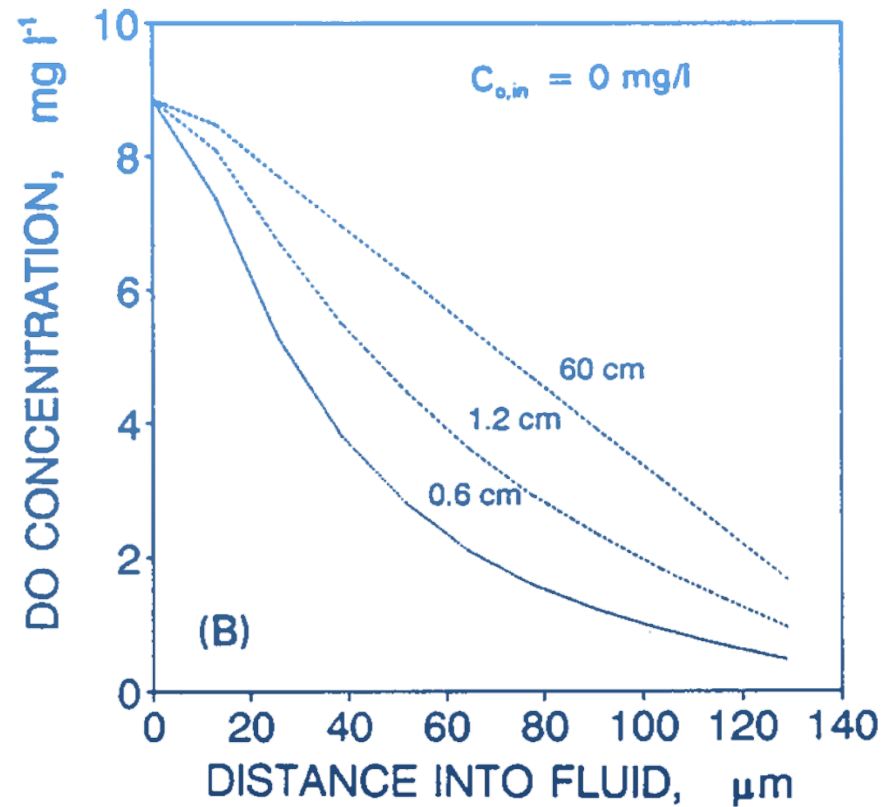
For $c_{Ni} \geq 2K_N$

$$x = \delta \quad J_N = \left(\frac{2\mu_{\max} X}{Y_{X/N}} \right)^{1/2} (D_N c_{Ni})^{1/2}$$

Constants used in NTF model simulations

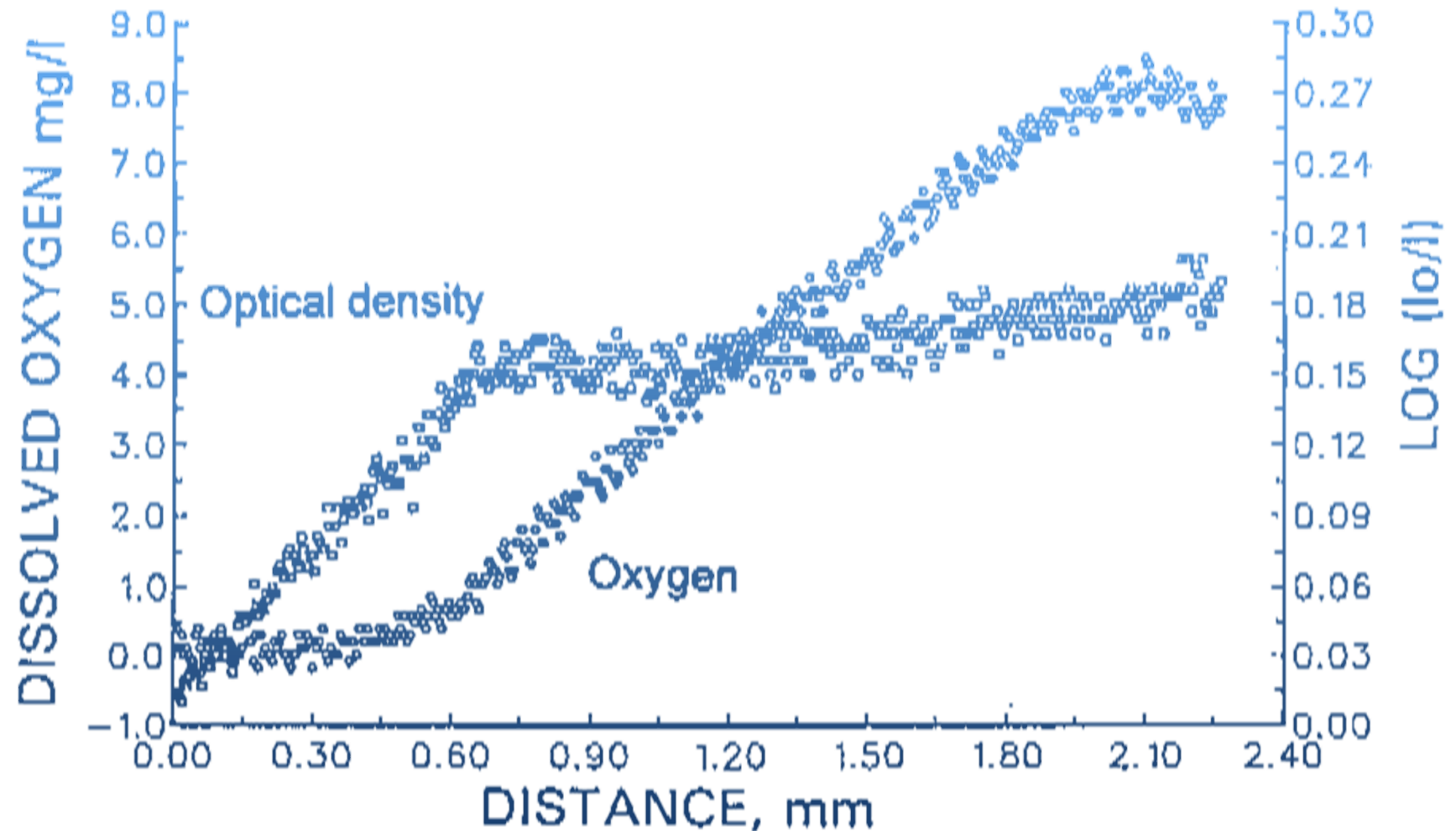
Parameter	Value
D_N	$1.71 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$
D_O	$2.0 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$
K_N	2.5 mg L^{-1}
T	$20 \text{ }^\circ\text{C}$
X	40 g-VSS L^{-1}
$Y_{O/N}$	$4.33 \text{ mg-O}_2 / \text{ mg-NH}_3$
$Y_{X/N}$	$4.33 \text{ mg-VSS} / \text{ mg-NH}_3$
$\mu_{\max}$	0.77 d^{-1}

NTF Model Simulations: Oxygen Profiles in WW

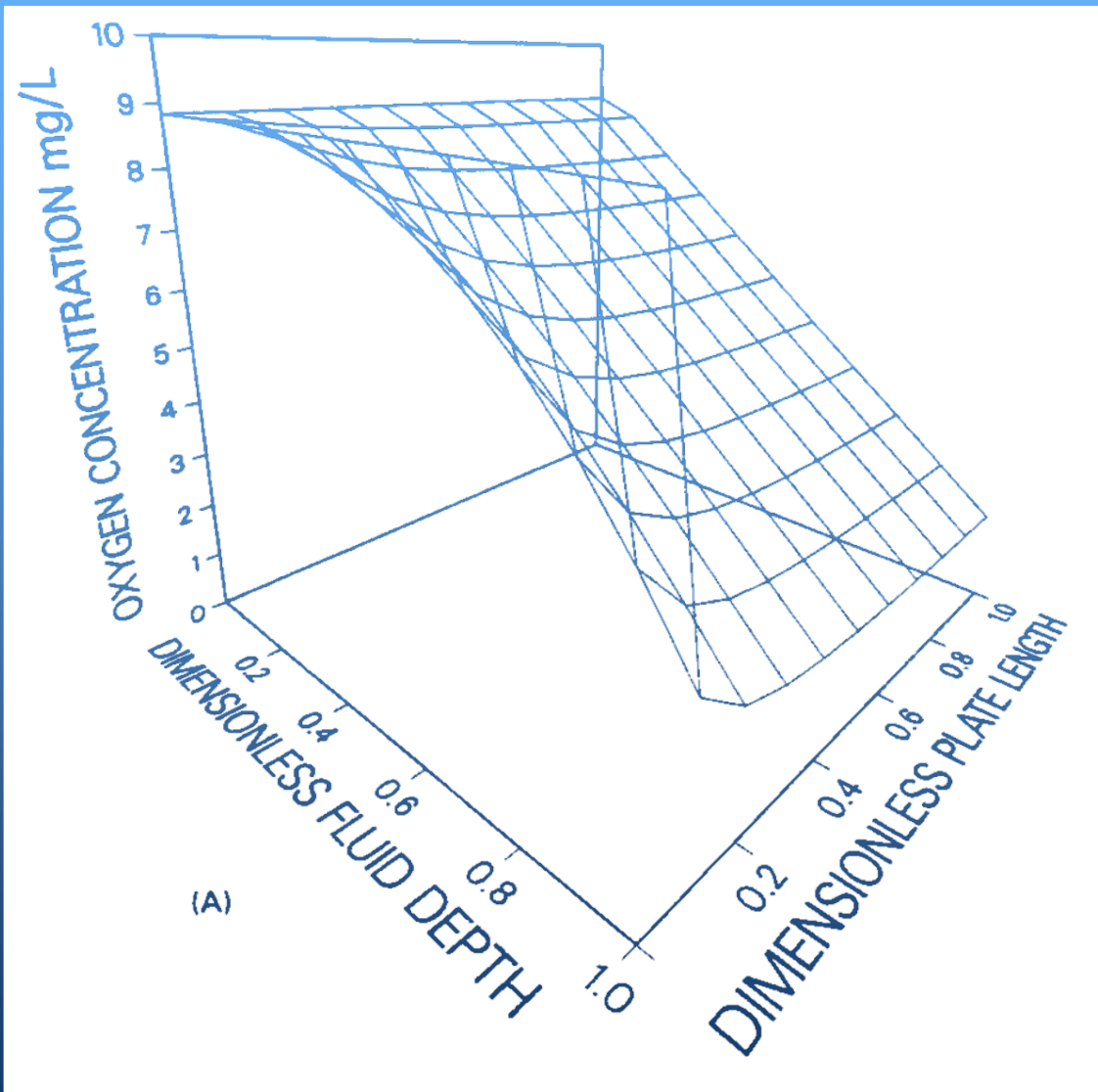


EXPERIMENTS:

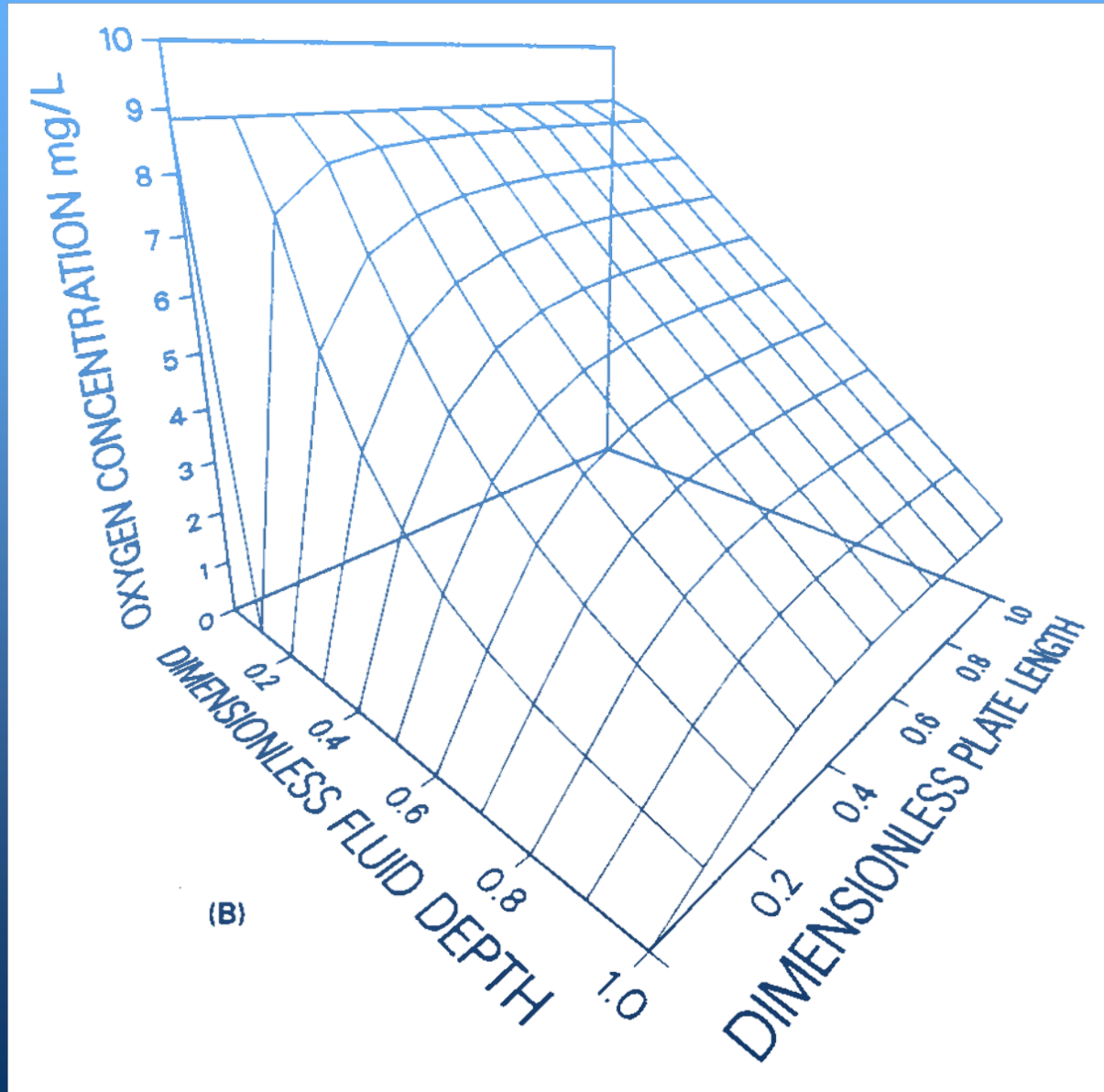
Measured oxygen profiles in WW and biofilm



NTF Model: 3-D Profiles

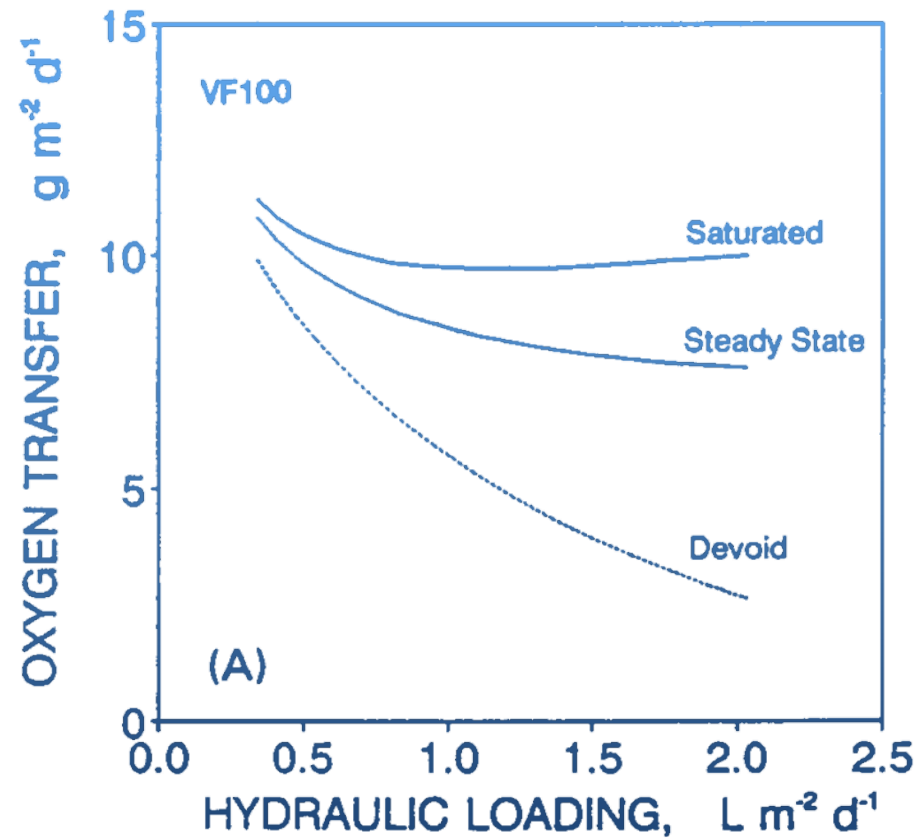
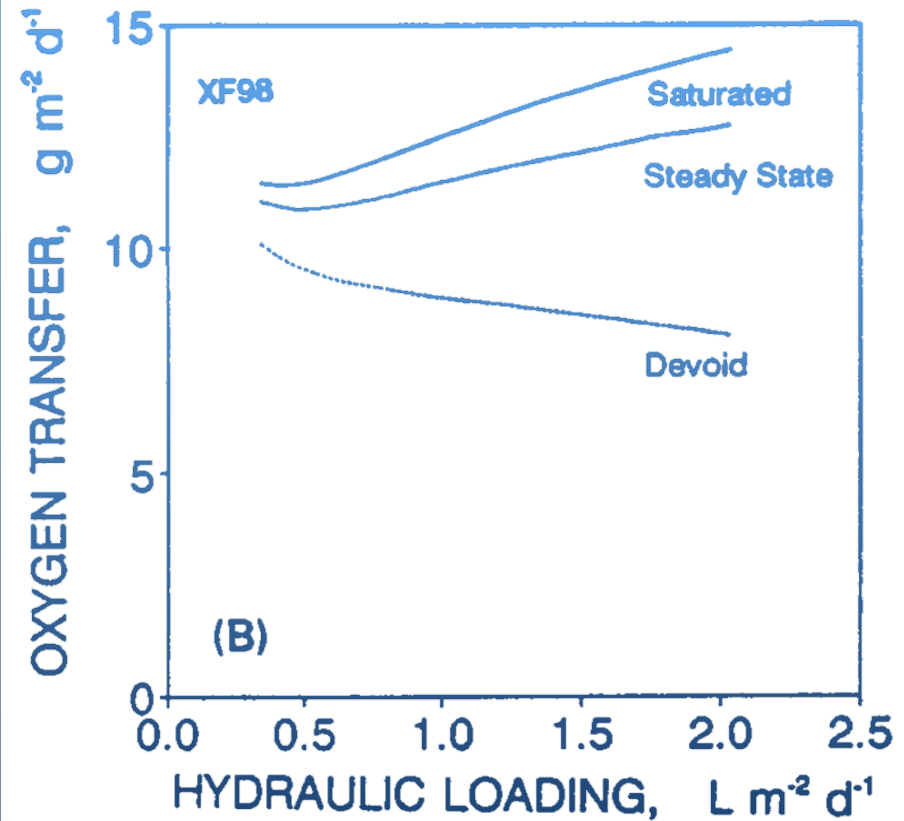


NTF Model: 3-D Profiles



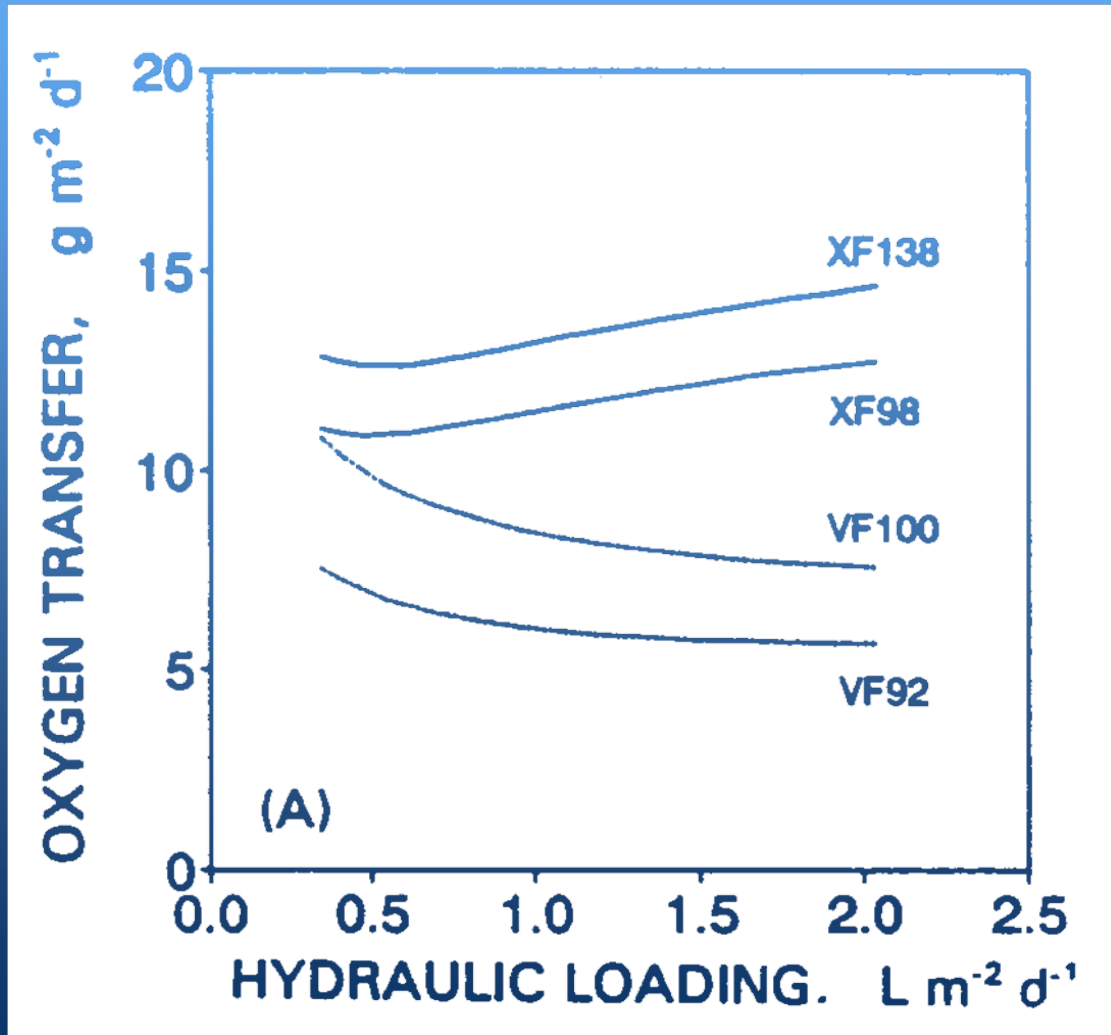
From: Logan (1993) Fig. 3

NTF Simulation of Single Module Oxygen Uptake: Effect of Initial DO on total oxygen transport rate



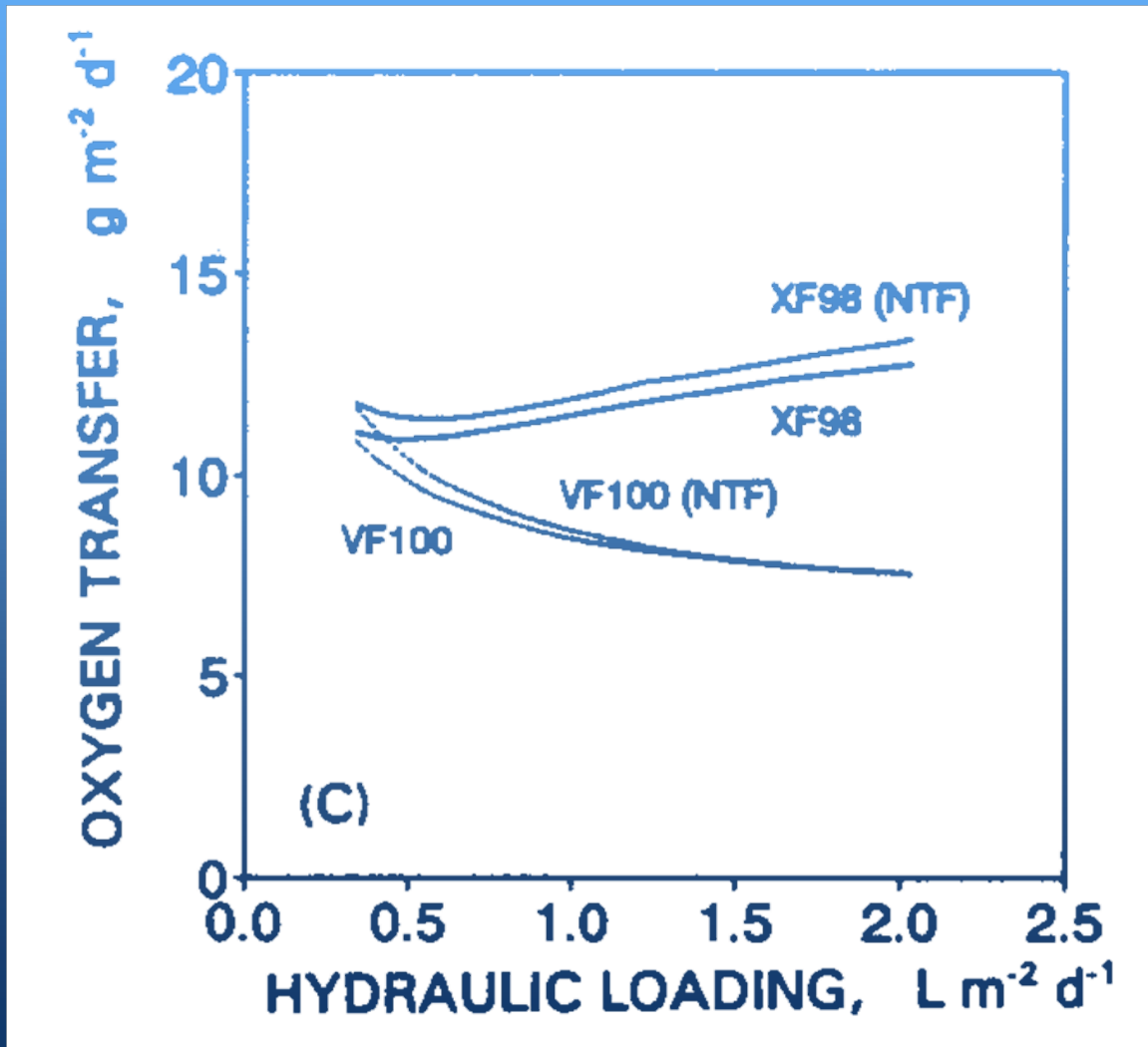
NTF Simulations:

Total Oxygen transport rates in cross-flow (XF) and vertical-flow (VF) media

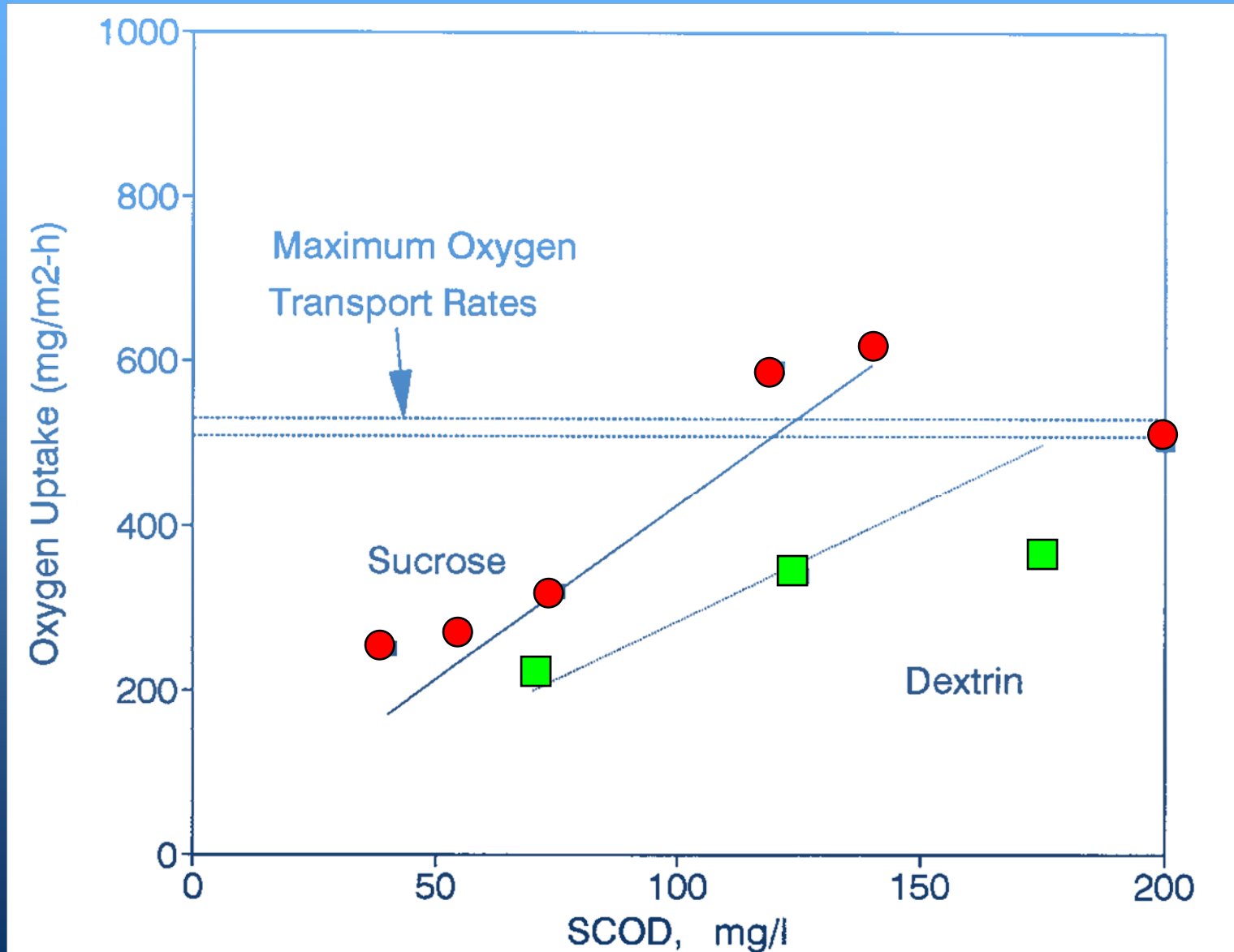


From: Logan (1993) Fig. 2

NTF Simulations: Maximum oxygen transport rates predicted by **NTF** (ammonia biofilm kinetics) versus **TFO** model (sBOD biofilm reaction kinetics)



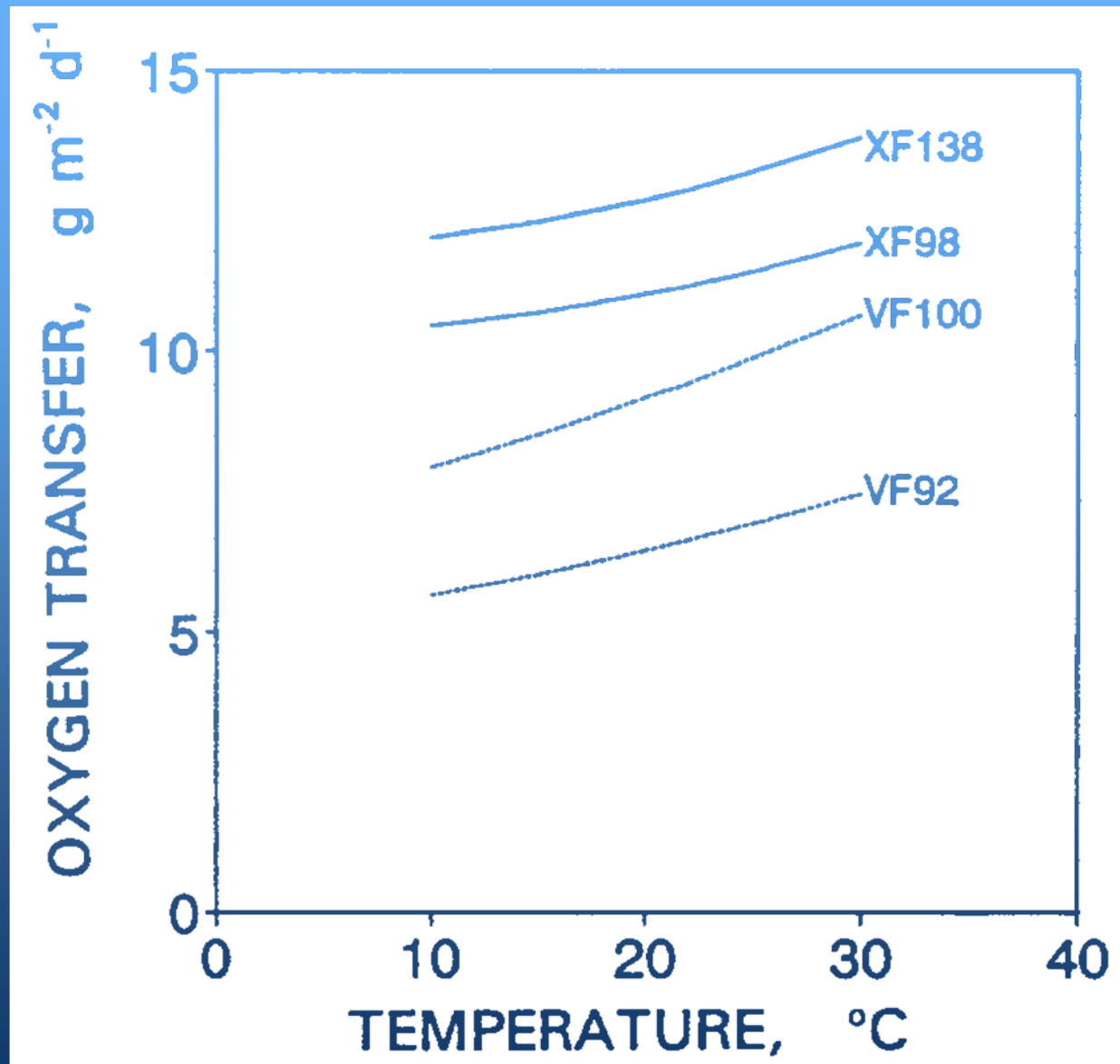
NTF Model vs Data: Maximum predicted vs measured oxygen transport rate (synthetic wastewater)



Data from Hinton and Stensel (1994)

Figure from Logan (1996)

NTF Model: Effect of Temperature



How well does NTF model work to predict maximum oxygen transfer rates?

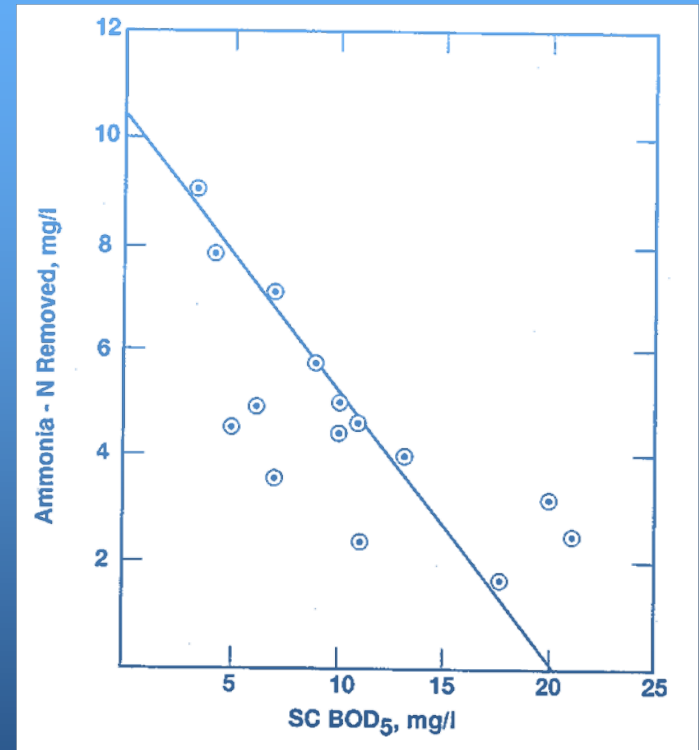
Plant (scale)	Media	Rate (g-N/md)	Temp (oC)	E
Central Valley, UT	XFa-140	1.4	16	0.66
		2.6	20	0.89
		2.3	22	0.83
		3.2	18	0.99
		1.6	15	0.71
		1.7	12	0.72
		2.1	11	0.81
Malmo, Sweeden	XFa-140	2.5	15	0.78
		2.8	16	0.87
		2.0	13	0.64
		2.2	13	0.71

How well does NTF model work to predict maximum oxygen transfer rates?– cont'd

Plant (scale)	Media	Rate (g-N/md)	Temp (oC)	E
Bloom Township, IL	VFc-89	1.2	20	0.88
		1.1	17	0.82
Midland, MI	VFc-89	1.2	13	0.86
		0.93	7	0.74
Lima, OH	VFc-89	1.2	18	0.88
		1.8	21	1.30
		1.5	22	1.10
		1.2	22	0.76
Average at all sites				0.81 ±0.11

SBOD in Wastewater Reduces Nitrification Rates

Measurements of nitrification rates in NTFs demonstrate that sBOD in the wastewater reduces nitrification rates

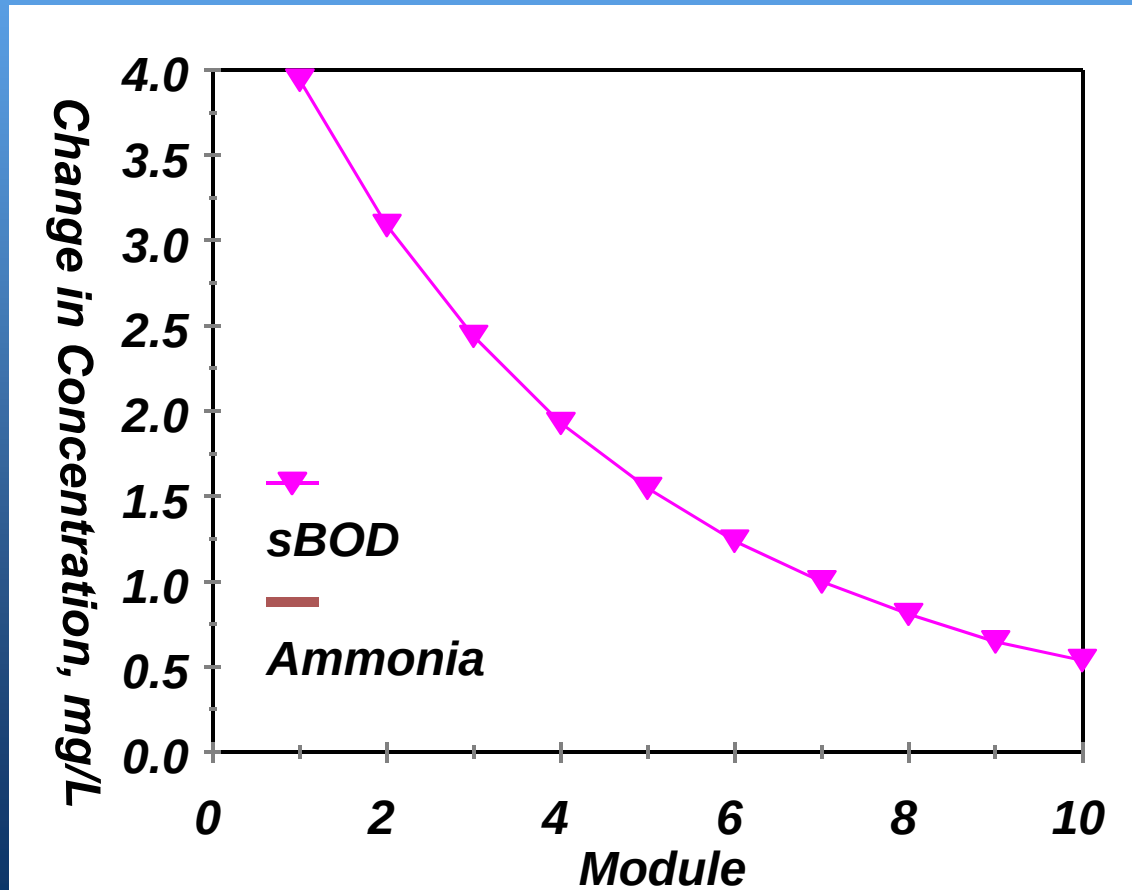


Reduction of nitrification rate is due to competition of heterotrophic bacteria with nitrifying bacteria for oxygen

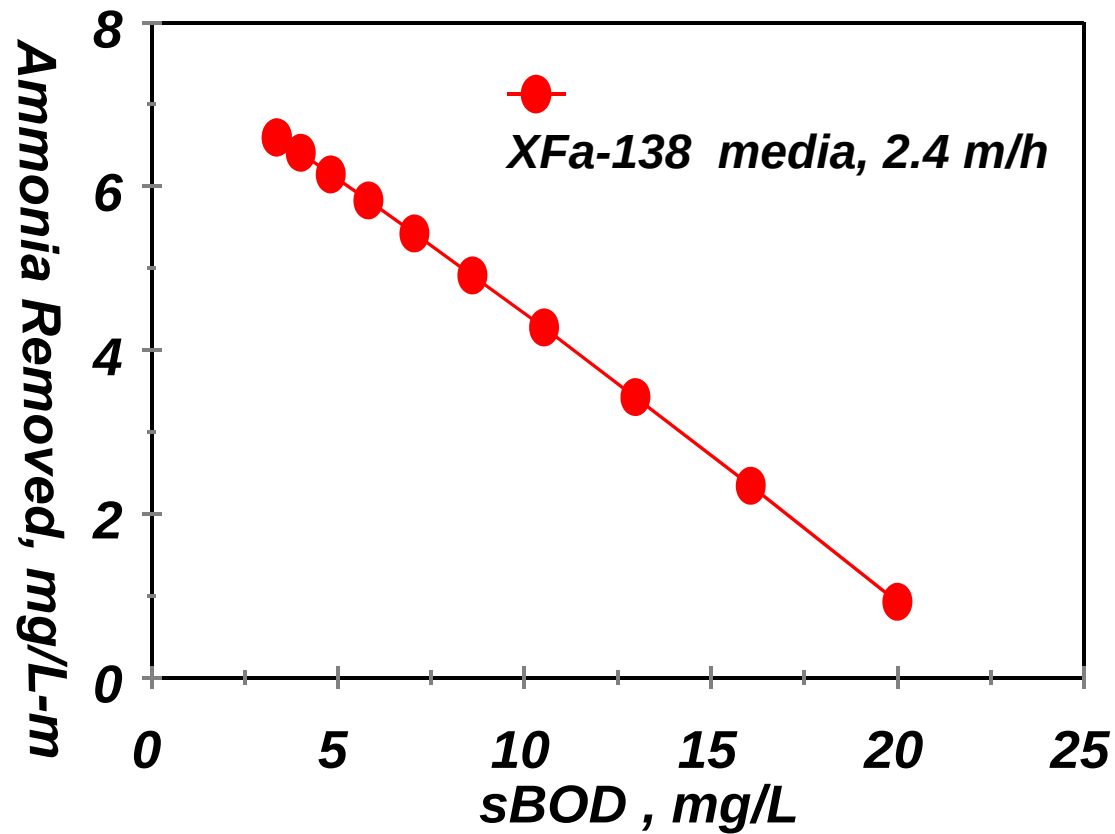
Figure from
Parker et al.
(1998)

Maximum nitrification rate versus sBOD removal in TF

Xfa-138 media, 1 gpm/sf (2.4 m/h)
sBOD_{in}=20 mg/L (20 C)



Predicted ammonia removals



Nitrifying Trickling Filter Design

NTF DESIGN STEPS:

make sure the TF works!

- ! Remove sBOD in upstream process to at least 20 mg/L (preferably below 5 mg/L)
- ! For Trickling filters-- If possible-- check performance of system using LTF or TRIFIL2 models.
 -  Add on Solids Contact Process if necessary

sBOD Profiles in TF

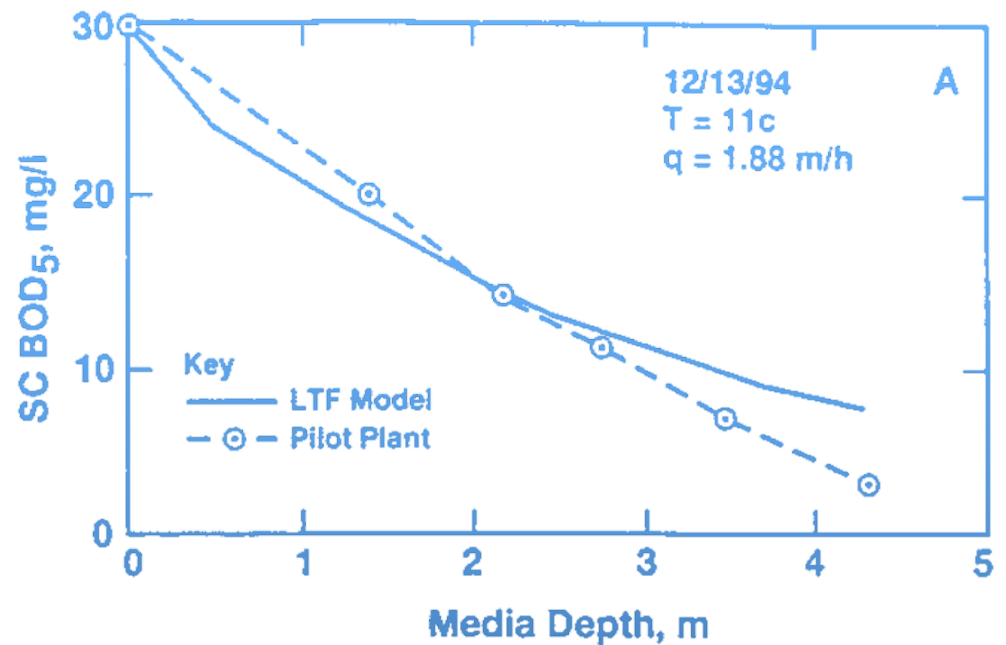
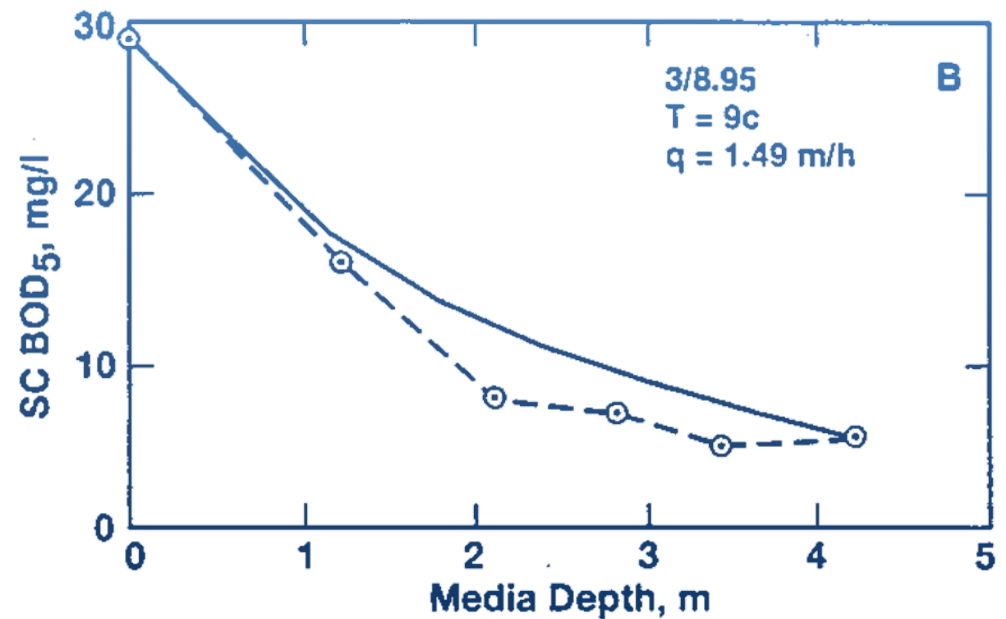


Figure 3 from
Parker et al.
(1998)

NTF DESIGN STEPS: Top of Tower

In top of tower:
Design system for
80% of maximum
ammonia removal
using NTF2 model
(2KN or $\sim \text{CN} > 5$
mg/L ammonia-N)

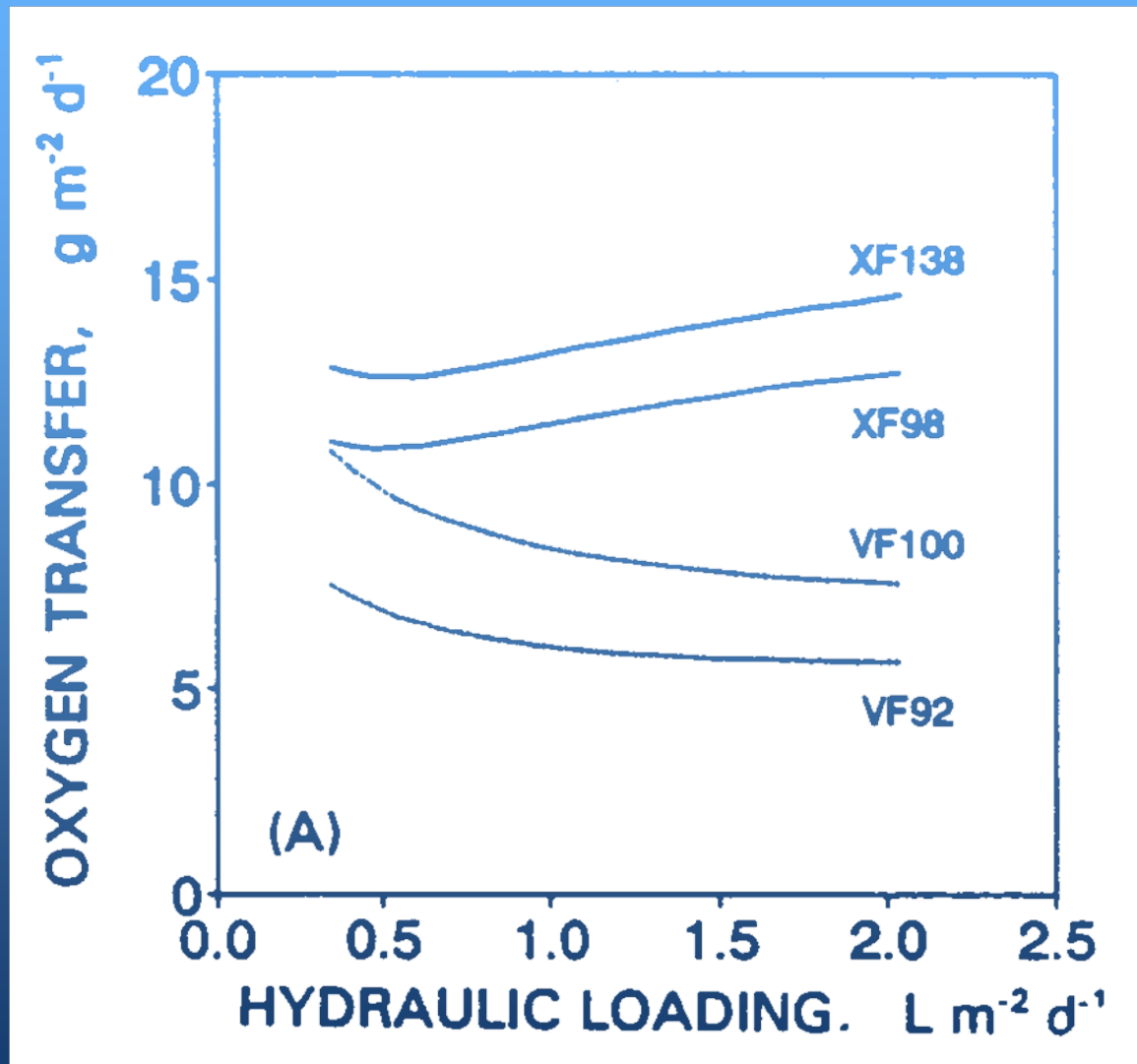


Figure 3 from
Logan (1993)

NTF DESIGN STEPS:

Lower Parts of Tower

In the lower parts of tower, when oxygen may not limit ammonia removal, the ammonia removal can be calculated using different approaches.

- Flux based on kinetic approximation:
- Empirical data (may have higher efficiencies)
- Reduction in Efficiency based on maximum oxygen transfer

Flux based on kinetic approximation

When dissolved oxygen does NOT LIMIT ammonia flux, the ammonia flux is based on its concentration at the biofilm surface

For $c_{Ni} < 2K_N$

$$x = \delta \quad J_N = \left(\frac{\mu_{\max} X}{K_N Y_{X/N}} \right)^{1/2} D_N^{1/2} c_{Ni}$$

For $c_{Ni} \geq 2K_N$

$$x = \delta \quad J_N = \left(\frac{2\mu_{\max} X}{Y_{X/N}} \right)^{1/2} (D_N c_{Ni})^{1/2}$$

When dissolved oxygen LIMITS ammonia flux, the ammonia flux is proportional to the maximum oxygen flux

Empirical Approach: Reduction of Nitrification Flux

Ammonia Flux = $\text{O}_2 \text{ Flux} / \text{Conv. factor}$

× Reduction due to non-saturation kinetics

× Reduction due to wetting/biofilm factors

Empirical Approach: Reduction of Nitrification Flux

$$J_N = \frac{J_{O,\max}}{4.33} \left(\frac{c_N}{K_N + c_N} \right) E_0 e^{-k_N L}$$

J_N = Ammonia flux into biofilm [g/m²d]

$J_{O,\max}$ = Oxygen flux into biofilm [g/m²d]

c_N = NH₃ concentration in ww [mg/L]

K_N = half saturation constant for NH₃ [mg/L]

E_0 = Efficiency factor []

k_N = empirical rate constant [m⁻¹]

L = Reactor height [m]

From: Parker et al. (1998)

Empirical Approach: Rate Constants

$$J_N = \frac{J_{O,\max}}{4.33} \left(\frac{c_N}{K_N + c_N} \right) E_0 e^{-k_N L}$$

$J_{O,\max}$ = XF-138: 12 g/m²d

VF-90: 8 g/m²d

K_N = 1 – 2 mg/L

E_0 = 0.81

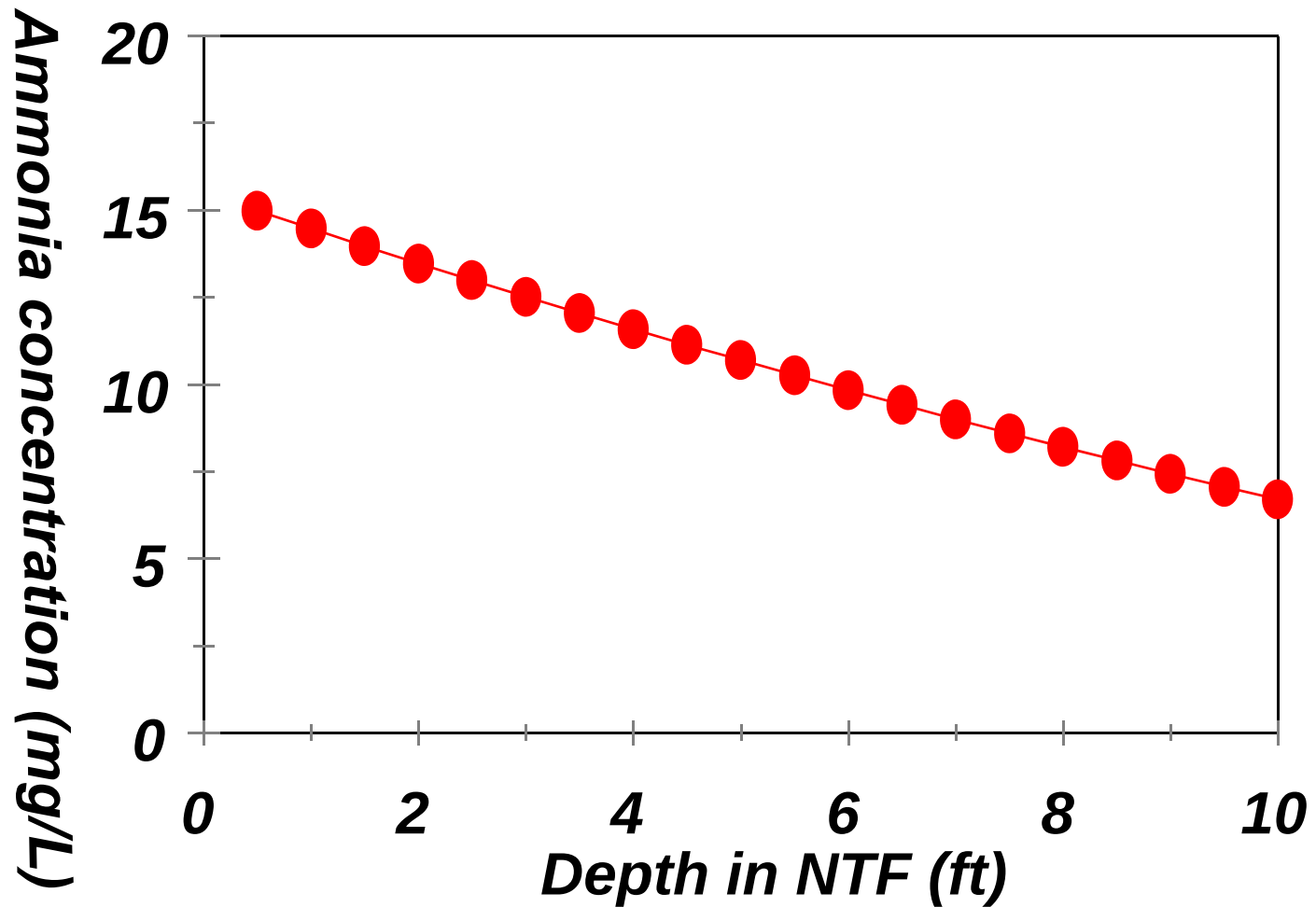
k_N = 0 – 0.16 m⁻¹

...Finally, we calculate the change in ammonia concentration as a function of distance

$$\frac{\Delta c_N}{\Delta L} = \frac{b_u J_N A_s}{Q}$$

Δc_N =	change in ammonia concentration [mg/L]
b_u =	unit conversion constant [0.056 mg/L-m]
A_s =	media specific surface area [ft ² /ft ³]
Q =	hydraulic loading rate [gpm/ft ²]

Model calculations of ammonia concentrations in NTF



Empirical data (may have higher efficiencies)

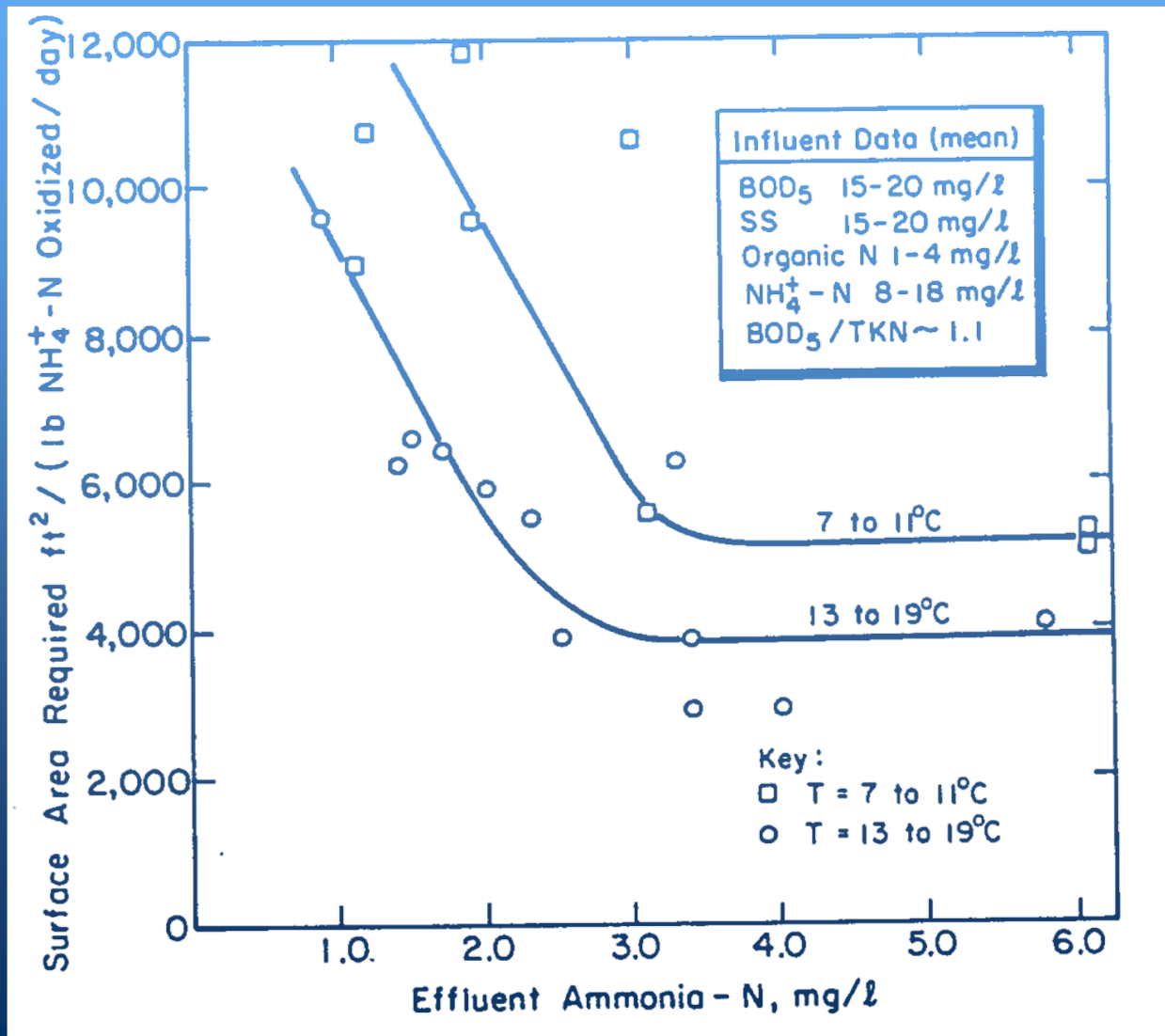


Figure 20.11
from Grady and
Lim (1980)

Reduction in efficiency: regression correlation

$$E = 0.114 + 0.217 T - 0.00841 SS + 0.838 U$$

where:

T= Temperature (C)

SS= Suspended solids mg/L)

U= Hydraulic loading (m/h)

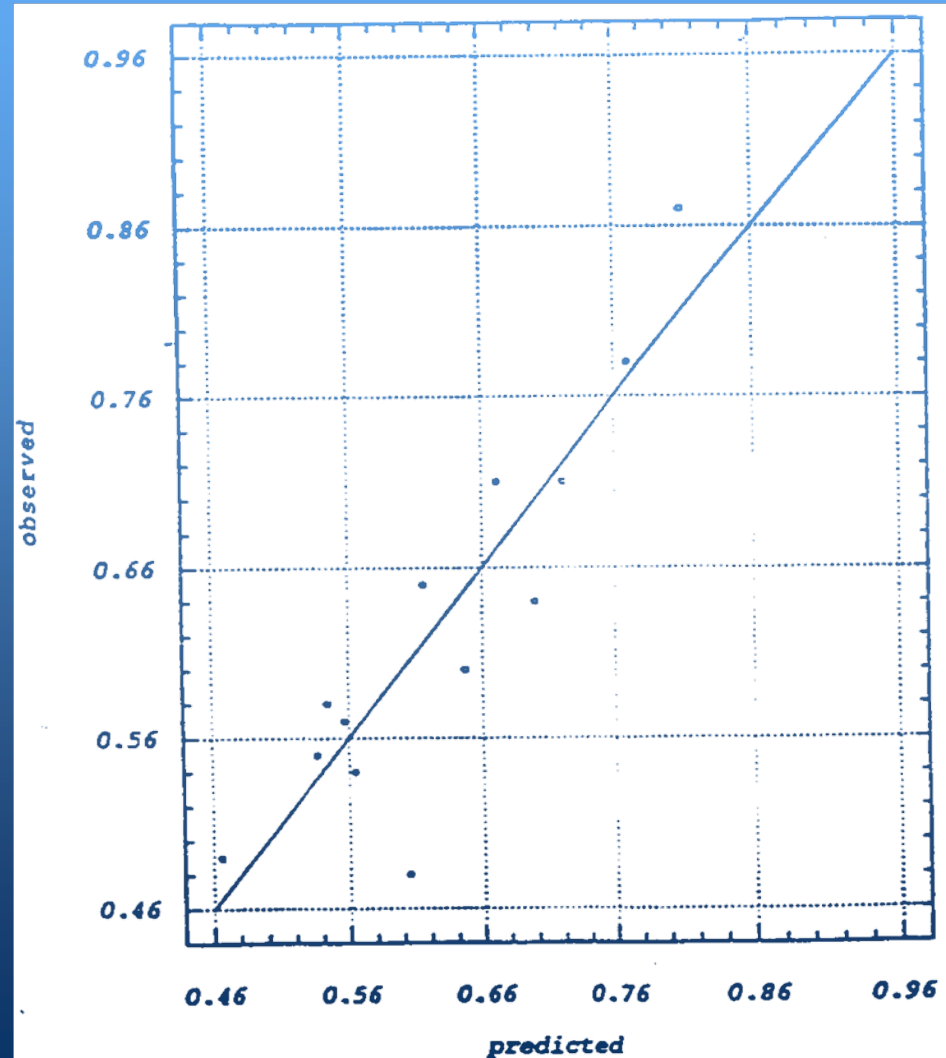


Figure 2 and Equation 2 in
Parker et al. (1995)

NTF DESIGN: Keeping the System Working!

Have a method of maintaining a thick biofilm. Options include:

- Dual System
- Flooding
- Alkaline wash

Dual systems:

City of Malmö study (Parker et al. 1995)

- Alternate flow into 2 NTFs
- Found that two-unit alternating system provided higher nitrification rates than single stage system

Flooding

- Periodic flooding (BCNTF) process was developed to control fly larvae and worms
- Operation of BCNTF in Central Valley increased nitrification rates and controlled fly problems.
- Flooding of Malm media did not increase nitrification rates, but flies were not a problem at this site.

Alkaline Wash

- Nitrification at the Littleton/Englewood WWTP were unacceptably low.
- Alkaline wash of pH=9 was used (three times in one year) to control predators (Parker et al. 1996).
- Performance following the alkaline wash was consistent with regression formula of Parker et al. (1995)

Other methods to improve NTF performance

- Recent WEF design manual recommends motorized distributor speed (SK) control to improve performance.
- SK control was *not* found to improve performance during Malm study (Parker et al. (1995)).

CONCLUSIONS

- NTFs can be used to remove ammonia from wastewater.
- Successful design requires removal of sBOD at the existing plant, and addition of an NTF that has a method for biofilm control.
- Nitrification rates achieved in NTFs (designed to maximize rates) can be larger than those historically obtained for NTFs

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