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CHAPTER 12

Recirculating Fish Farm Simulator Where Nitrite Answers the Feed Days Later

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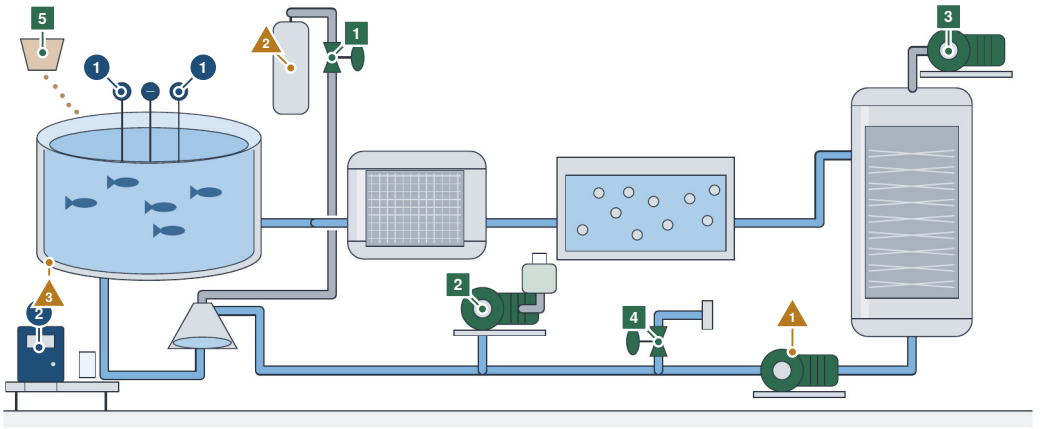
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CHAPTER 12

Recirculating Fish Farm Simulator Where Nitrite Answers the Feed Days Later



The controller moves 1 oxygen gas valve 2 bicarbonate dosing 3 degasser blower 4 makeup water valve 5 feeder, the daily ration

The controller reads 1 tank probes: oxygen, pH, carbon dioxide 2 sampled nitrogen analyzer

What disturbs it 1 power failure at the pump 2 oxygen supply sag 3 warmer surroundings

Notice that the probes read the tank's oxygen at once, while the nitrogen the biofilter must remove reaches the controller only through a sample tested every few hours. Illustration, not to scale.

IN PLAIN TERMS **Feeding Fish Faster Than Their Filter Can Grow**

The main idea. A fish farm that reuses its water needs a filter full of living bacteria to clean out the fish waste. Two kinds of bacteria do the job in turn, and each kind grows only on the food it gets.

The challenge. When the farm feeds more, the first kind keeps up within a day. The second kind needs days to grow, so a poison builds up in between, and the water is tested only every few hours.

Why it matters. Feeding faster than the bacteria can grow kills fish instead of growing them.

THREE WAYS TO READ THIS CHAPTER

Explore	12 min	the first page, the fact on world fish farming (Section 12.1), the two history segments (Section 12.2), the two try-it segments (Section 12.4), the fact of Section 12.6, and the key points
Study	45 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	15 min	the first page, the measured cases (Section 12.6), Technology in Practice (Section 12.7), Limitations (Section 12.8) and the open challenge

The control question A recirculating farm removes its fish's ammonia with a biofilter of two nitrifier populations that grow only on the load they carry, so a larger ration returns as nitrite days after the feed changes. How can a farm that measures its water every four hours and weighs its fish every two weeks feed for growth without poisoning the fish?

Learning objectives

- Explain why a feed step or a new biofilter shows an ammonia peak first and a nitrite peak days later.
- Compute the un-ionized share of the total ammonia from pH and temperature, and the total ammonia that reaches its limit.
- Estimate the minutes of oxygen reserve after a power failure from the tank volume and the fish's uptake.
- Describe what a feed governor on a sampled analyzer can and cannot prevent, and how a soft sensor infers biomass from the oxygen balance.
- Compare rations by feed conversion and margin, and recognize a stocking plan that no ration makes feasible.

Prerequisites Sections 1.4.3 (populations that grow on their load), 1.4.5 (sparse and late samples, bias update), 1.4.6 (overrides on limits) and 1.6.2 (velocity form). Chapter 11 for a culture that is the actuator.

The app https://apmonitor.com/apps/aquaculture-ras/

See also Volume 3, Chapter 2 and Volume 3, Chapter 3 for cascade structure and the speed an oxygen inner loop needs. Volume 5, Chapter 3 for control through a slow analyzer and Volume 5, Chapter 10 for a soft sensor whose bias a delayed laboratory corrects.

12.1 Introduction

Ten thousand rainbow trout of 150 g eat four meals a day in a 50 m^3 tank, and the oxygen they draw from a fixed gas flow of 0.50 kg/h falls after each meal to a lower low than the one before, from 9.99 mg/L at 11:00 to 7.63 mg/L at 21:40, two hours and ten minutes after the last meal ends. That is the fast half of the farm. The slow half is the biofilter. When the same farm triples a ration that its biofilter had grown to carry, the total ammonia peaks at 4.34 mg/L that midnight, but the nitrite peaks at 3.07 mg N/L 1.35 days after the step and stays above its 0.5 mg N/L teaching limit for 57.0 h. The nitrite comes late because the bacteria that remove it must first grow on it.

Recirculating systems dissolve pure oxygen, strip carbon dioxide and convert ammonia in a biological filter so that the same water can carry fish many times a day, and control of the dissolved gases is an essential part of such systems [1]. The water quality a reuse system must hold has been set out for each constituent [2], the nitrifying filters that remove the ammonia have been reviewed for their design and operation [3], and flows and filters are sized by mass balances on the feed [4]. Dynamic models that couple the fish to the water treatment have been written for recirculating systems [5], and precision fish farming proposes to apply control-engineering principles to fish production [6]. The broader class is any plant whose actuator is a culture with its own growth rate, so that the capacity to act is itself a slow state. The wastewater treatment that integrated recirculating models couple to the fish [5] and anaerobic digestion have that shape. Volume 9, Chapter 10 treats the nitrifiers of a wastewater works as the plant, and Chapter 11 treats a digester's methanogens as a culture that can be lost.

> ✦ DID YOU KNOW? **Farmed Fish Overtook the Catch**
>
> In 2022, for the first time, aquaculture produced more aquatic animals than capture fisheries: 94.4 million tonnes, 51 % of the world total. Inland farms, the setting of this chapter's freshwater tank, gave 62.6 % of the farmed animals [7].

A common belief, and the one this plant is meant to unsettle, holds that a biofilter is a treatment unit with a capacity fixed at design, so that the farm can feed what the fish will eat and leave the water to the equipment. In this model a mature film carries the load it was grown on and little more, a

new film takes weeks to grow from a trace, and the nitrite that a ration beyond the film's capacity makes acts on the fish. However, the sources a student is likely to read describe each piece on its own. Toxicity is reported as lethal concentrations from separate tests [8, 9], filter sizing is a steady balance [4], and growth is a curve against degree days [10]. This chapter works with a recirculating farm, simulated in a browser, in which the meal, the biofilter's growth, the fish's response to nitrite and the farm's sampled measurements are integrated together, and it measures what a cascade, a governor, a soft sensor and a daily economic ration achieve on the same plant. The growth law, the nitrification kinetics, the carbonate chemistry, the proportional integral loops and the golden-section search are established methods. The simulator built from them is a 41-state teaching model whose nitrogen and oxygen ledgers close to round-off, with an observer that follows each nitrifier population from the laboratory's conversion and a strict separation in which no controller or estimator reads a simulated truth. The app carries ten graded cases running from a day of meals to an infeasible stocking plan and a ninety-day challenge.

Section 12.2 follows the domain, from the first reuse farms to the toxicity data behind the limits. Section 12.3 sets out the farm as modeled: the cohort and its ration, the water's action on the fish, the balances in two volumes, the two nitrifier populations, the cone, the degasser, the chemistry and the instruments. Section 12.4 shows the farm's two clocks, the meal in hours and the biofilter in weeks, and the chemistry that sets how much of the ammonia is toxic. Section 12.5 describes the oxygen cascade, the pH, carbon dioxide and nitrate loops, the feed governor, the economic ration, the two estimators and the startup sequence. Section 12.6 measures the cases and the challenge and verifies the code, Section 12.7 sets the loops beside the devices a real farm installs, Section 12.8 states the limitations and Section 12.9 concludes.

12.2 Reused Water and the Farms Built Around It

Intensive fish culture that reconditions its water instead of discharging it was described in 1974 as a way to combine production with pollution abatement [11]. The engineering that followed treated each constituent the fish add to the water as a separate unit operation. Oxygen is dissolved from pure gas in a cone or a column, carbon dioxide is stripped in a packed degasser for which design procedures have been published [1], solids leave in a drum or a settler, and ammonia is oxidized in a biofilter. By 2000 the flow and filter sizes of such a farm were routine mass balances on the daily feed, written in spreadsheets [4], and the same volume of the journal that published those balances reviewed process control and artificial intelligence software for aquaculture [12]. Design reviews of nitrifying filters for recirculating systems [3] and of the water quality reuse systems must hold [2] appeared in 2006, and new European systems were reviewed from the perspective of environmental sustainability in 2010 [13].

> **HISTORY** **Oxygen Pushed Into Water by Depth (1969)**
>
> In 1969 a federal fish hatchery had run a U-tube oxygenator continuously for over a year. The water is directed down a chamber about forty feet deep, under a baffle and back up, and air bubbles injected just below the surface are dragged down with it. The hydrostatic head pressurizes the bubbles, so one pass can saturate or supersaturate the water. A free fall of three feet entrained enough air to saturate 300 gallons per minute with no external power [14]. Farms today reach the pressure with a pump instead: an oxygen cone mixes water and pure oxygen at typically around 1.4 bar and supersaturates part of the circulating flow [15].

The toxicity data behind the limits came from fisheries research. Ninety-six-hour tests on rainbow trout in soft water gave median lethal concentrations of nitrite from 0.19 to 0.39 mg N/L [8]. A later review found that each milligram per liter of chloride raises the 96-hour LC50 by 0.29 to 2.0 mg N/L, that chronic effects are difficult to detect below one fifth of the 96-hour value, and that the ratio of the 24-hour to the 96-hour value has a median of 2.0 [9]. Nitrite accumulates in fish over 24 to 48 hours, and a tenth of the 96-hour LC50 caused neither growth suppression nor tissue damage

in long exposures [16]. Ammonia is toxic mainly as its un-ionized form, whose share follows the ammonium dissociation constant as a function of temperature [17, 18], and the national freshwater criteria tabulate rainbow trout among the acute data [18]. Growth on the farm was reduced to a single coefficient when the cube root of weight was found to rise linearly with degree days in hatcheries [10].

> ⧖ HISTORY **Salt Against Nitrite (1977 to 1984)**
>
> Since 1977 nitrite toxicity has been known to depend greatly on the salinity of the water: fish in seawater died at nitrite concentrations 50 to 100 times higher than in fresh water. The effect of chloride is so large that a test which does not report its chloride cannot be meaningfully compared with others. A recommendation of 1984 asked aquaculture to monitor the ratio of chloride to nitrite nitrogen, 17 for salmon and 8 for rough fish [16]. Farm guidance still adds a little salt to the water to take the toxicity out of the nitrite peak of a new biofilter [15].

What these sources do not give is the time course. A balance sizes the filter for a steady load and a lethal concentration describes a test at fixed exposure, while the farm changes its ration every day and its bacteria take weeks to follow. Integrated dynamic models of the fish and the treatment answer that question for a designed plant [5], and the precision farming program asks for the measurement, estimation and feedback that would act on it [6]. The simulator described next is a teaching plant of that kind.

12.3 The Farm as Modeled

The simulated farm is a generic land-based unit with no proprietary source, drawn in Figure 12.1 in the order the water travels. Water leaves an oxygen cone, passes the fish tank of volume $V_t = 50\,\mathrm{m}^3$, a drum filter that removes solids, a moving-bed biofilter of water volume $V_b = 10\,\mathrm{m}^3$ and a degasser over its sump, and a pump returns it to the cone at $Q_r = 100\,\mathrm{m}^3/\mathrm{h}$, so the tank turns over every 30 min. Makeup water Q_{ex} enters the tank and the same flow leaves with the solids. Sodium bicarbonate is dosed into the tank, and an oxygen gas valve of opening u feeds the cone from a supply at relative pressure P_s. The cohort is N fish of mean weight W and biomass B, fed by a feeder that runs four 30 min meals at 07:00, 11:00, 15:00 and 19:00. The model integrates in days with a step of 60 s, so every meal edge falls on a step.

Table 12.1 classifies the variables. Forty-one quantities are integrated: the biomass and count, two gut stages, oxygen, total ammonia nitrogen, nitrite, nitrate, inorganic carbon C_T and alkalinity in both the tank and the biofilter, the two populations, the gas flow, the water temperature, the fish's toxic load E, and twenty ledgers that integrate feed, nitrogen, oxygen, gas, water, bicarbonate and the fish lost, so that every balance can be checked exactly. Concentrations are in mg/L, with ammonia, nitrite and nitrate as nitrogen, flows in m^3/d, feed in kg/d and the populations in grams of volatile solids.

12.3.1 The Cohort and Its Ration

Growth at satiation follows the thermal-growth coefficient, the slope of the cube root of weight against degree days [10], and growth below satiation follows a concave ration curve, as shown in Equation (12.1).

$$
\begin{aligned}
g_{max} &= 3W^{2/3}\,\frac{TGC}{1000}\,(T - T_0), \qquad R_{sat} = FCR_{sat}\,g_{max} \\
e(\rho) &= e_{max}(1 - c\rho), \qquad M = \rho_m R_{sat}\,e_{max}(1 - c\rho_m) \\
\frac{\mathrm{d}B}{\mathrm{d}t} &= q_f\,e(\rho)\,p - \frac{NM}{1000} - (m+h)B \\
\frac{\mathrm{d}N}{\mathrm{d}t} &= -(m+h)N
\end{aligned}
\tag{12.1}
$$

where g_{max} and R_{sat} are per fish in grams per day, $\rho = \min(a, R/R_{sat,C})$ is the day's ration over the cohort's satiation $R_{sat,C} = NR_{sat}/1000$, capped by the appetite a, p is the feed processed, M the

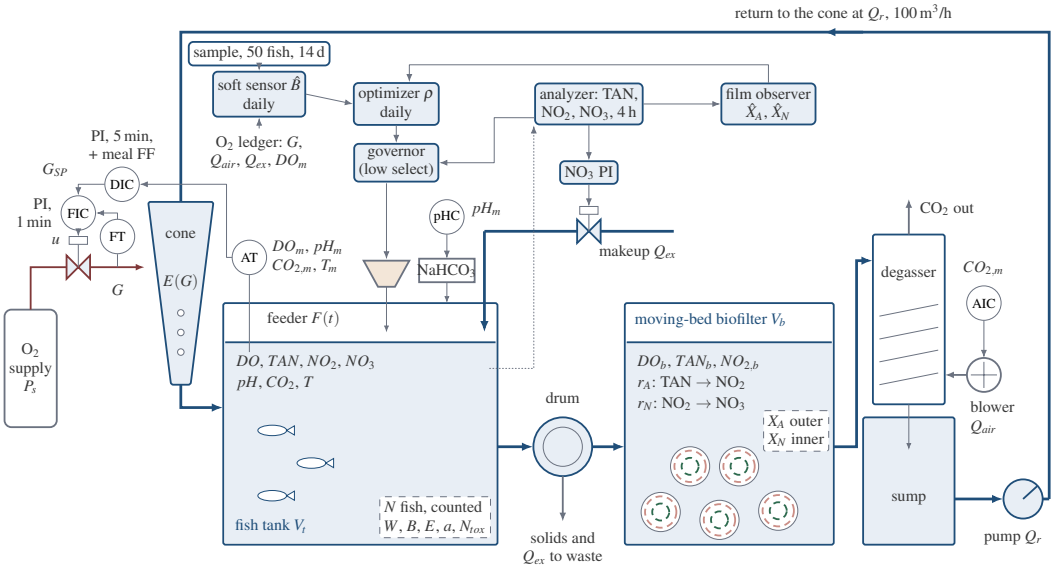


Figure 12.1 The recirculating farm as modeled, in the order of the app's Farm view. Gas at G through the valve u dissolves in the cone with absorption $E(G)$, the tank holds the cohort (N, W, B) and its water, the drum takes the solids and Q_{ex} to waste, the moving-bed biofilter holds its own water and the two populations (ammonia oxidizers X_A outer, nitrite oxidizers X_N inner), and the degasser strips CO_2 with blower air Q_{air} before the pump returns Q_r. The DO cascade (DIC over FIC), the pH loop (pHC) and the CO_2 loop (AIC) sit beside their actuators, and the supervisory layer (analyzer, governor, optimizer, soft sensor, film observer, nitrate loop) sits above the row. Process model only, not a construction drawing. Not to scale.

Table 12.1 Variables by Role, With Their Values at $t = 0$ of the Challenge

Variable	Role	At $t = 0$	Range or limit
DO	CV, tank oxygen	9.02 mg/L	SP 9, limit ≥ 6
pH	CV, tank	7.197	SP 7.2, limits 6.8–7.8
CO_2	CV, tank	9.80 mg/L	SP 10, limit ≤ 15
NO_3	CV, laboratory	59.0 mg N/L	SP 60
NO_2	constraint	0.106 mg N/L	limit ≤ 0.5
NH_3	constraint, un-ionized	0.0030 mg N/L	limit ≤ 0.025
u, G	MV, gas valve, flow	17.7 %, 0.286 kg/h	0–1.6 kg/h
u_{bic}	MV, bicarbonate	2.90 kg/d	0–150
Q_{air}	MV, blower	3.07 m³/min	1–20
Q_{ex}	MV, makeup	8.39 m³/d	2–60
R	MV, daily ration	13.44 kg/d	0–100
T_{env}, P_s	DV, surroundings, supply	15 °C, 1	8–20, 0.5–1.1
B, N, W	states, cohort	500 kg, 10,000, 50 g	truth (count known)
X_A, X_N	states, populations	481.9, 160.6 g	truth
TAN	state, tank	0.704 mg N/L	—
E, a	toxic load, appetite	0, 1	truth

maintenance, q_f the feed quality, m the background mortality and h the mortality the water causes. The constant $e_{max} = 1/\{FCR_{sat}[(1-c)-\rho_m(1-c\rho_m)]\}$ makes $\rho = 1$ grow exactly on the coefficient curve and convert at FCR_{sat}, and growth stops at ρ_m. With $c = 0.3$ the lowest conversion, 1.0068, comes at $\rho = 0.569$, which is 8.47 % better than satiation. Eaten feed F_{eat} passes two gut stages of $\tau_g = 3$ h, $\dot{g}_1 = F_{eat} - g_1/\tau_g$ and $\dot{g}_2 = (g_1 - g_2)/\tau_g$ with $p = g_2/\tau_g$, and the feed offered beyond the

appetite is wasted. After the 07:00 meal the processed feed peaks 2.93 h after the meal starts.

12.3.2 The Water Acting on the Fish

Nitrite and un-ionized ammonia act on the fish through one internal load, as shown in Equation (12.2).

$$\begin{aligned} x &= \max\Big(\frac{NO_2}{LC50_{NO_2}},\ \frac{NH_3}{LC50_{NH_3}}\Big), \qquad \tau_E \frac{\mathrm{d}E}{\mathrm{d}t} = x - E \\ s &= \max\Big(0,\ \frac{E - a_0}{1 - a_0}\Big), \qquad a = \max(0,\ 1 - s) \\ h &= s\,\frac{\ln 2}{4\,\mathrm{d}} \end{aligned} \tag{12.2}$$

where x is the water's toxicity in units of each toxicant's 96-hour LC50, $\tau_E = 1\,\mathrm{d}$ and $a_0 = 0.1$. The limits are a tenth of the LC50s, the no-effect level of [16], and τ_E gives 63 % of the load in a day and 86 % in two, in the range over which nitrite accumulates [16]. The larger toxic unit counts rather than the sum, because nitrite acts on the blood and ammonia on the gills and nerves [16, 18]. The LC50s, 5 and 0.25 mg N/L, are teaching values ten times the limits. The nitrite value is the trout LC50 of [8] raised by 0.29 mg N/L per mg/L of chloride [9] at about 16 mg/L of chloride, which the model assumes. The ammonia value is near the rainbow trout species mean of the national criteria, 82.88 mg TAN/L at pH 7, which is 0.226 mg N/L as un-ionized nitrogen at 15 °C [18]. Because the load takes a day to build, water held at one LC50 from clean kills 39.7 % of the fish in 96 h, so the law's own 96-hour LC50 is 1.324 times the declared one, and its 24-hour to 96-hour ratio of 7.60 is steeper than the median of 2.0.

12.3.3 Nitrogen, Oxygen and Carbon in Two Volumes

The ammonia excreted is the absorbed feed nitrogen less the nitrogen retained in the net growth of Equation (12.1), $\dot{n} = pN_f(1 - f_{fec}) - n_f\,(q_f e(\rho)p - NM/1000)$ with $N_f = 0.16\,PC$, and a share λ of the fecal and uneaten nitrogen leaches from the solids. At a ration of 0.9 of satiation and 150 g this is 0.0360 kg of ammonia nitrogen per kilogram of feed. The tank and the biofilter are each well mixed, as shown in Equation (12.3) for the ammonia, with nitrite, nitrate, oxygen, C_T and alkalinity balanced the same way.

$$\begin{aligned} V_t \frac{\mathrm{d}TAN}{\mathrm{d}t} &= Q_r(TAN_b - TAN) - Q_{ex}TAN \\ &\quad + \dot{n} + \lambda \dot{n}_s \\ V_b \frac{\mathrm{d}TAN_b}{\mathrm{d}t} &= Q_r(TAN - TAN_b) - r_A \\ V_b \frac{\mathrm{d}NO_{2,b}}{\mathrm{d}t} &= Q_r(NO_2 - NO_{2,b}) + r_A - r_N \\ V_t \frac{\mathrm{d}DO}{\mathrm{d}t} &= Q_r(DO_{ret} - DO) + Q_{ex}(DO_{mk} - DO) \\ &\quad - \dot{O}_f \end{aligned} \tag{12.3}$$

where r_A and r_N are the two oxidation rates in the biofilter's own water, $\dot{n}_s$ the nitrogen in feces and uneaten feed, and $\dot{O}_f$ the fish's oxygen uptake. During a startup the dosed ammonium chloride enters the tank with $\dot{n}$. The uptake is routine respiration plus the post-meal demand, $\dot{O}_f = \phi(DO)\,[Bs_0(W/100)^{bo}\,\theta_O^{T-15} \cdot 0.024 + 1000\,k_{SDA}\,p]$ in grams per day, with $\phi(DO) = 1 - e^{-DO/0.8}$ so that uptake falls only near anoxia. The filter's water loses $3.43r_A + 1.14r_N$ of oxygen and the heterotrophs on the fines $k_{het}\,p$, nitrification removes two equivalents of alkalinity per mole of nitrogen, excreted ammonia adds one, and the fish add carbon at a respiratory quotient of 0.9.

12.3.4 Two Nitrifier Populations

The biofilter's capacity is the two populations of Equation (12.4), with Monod terms in the filter's own substrate and oxygen, the uptake that grows with its population of Section 1.4.3.

$$\begin{aligned} r_A &= \frac{\mu_A}{Y_A}\,\frac{X_A}{1+X_A/X_{h,A}}\,\frac{TAN_b}{K_A+TAN_b}\,\frac{DO_b}{K_{OA}+DO_b} \\ r_N &= \frac{\mu_N}{Y_N}\,\frac{X_N}{1+X_N/X_{h,N}}\,\frac{NO_{2,b}}{K_N+NO_{2,b}} \\ &\quad\times\frac{DO_b}{K_{ON}+DO_b}\,\frac{K_I}{K_I+FA} \\ \frac{\mathrm{d}X_A}{\mathrm{d}t} &= Y_A r_A-(b_A+k_{det})X_A \\ \frac{\mathrm{d}X_N}{\mathrm{d}t} &= Y_N r_N-(b_N+k_{det})X_N \end{aligned} \tag{12.4}$$

where $\mu=\mu_{20}\theta^{T-20}$, $b=b_{20}\theta_b^{T-20}$, FA is the free ammonia in the filter, and X_h is the biomass at which a thickening film on a fixed carrier area is half active. At steady state $X=Yr/(b+k_{det})$, so a film is sized by its load, 1461 g of ammonia oxidizers and 487 g of nitrite oxidizers for 1.5 kg N/d at 15 °C. The nitrite oxidizers are slow and of high affinity ($\mu_N=0.6$ against $\mu_A=0.9$ per day, $K_N=0.08$ against $K_A=0.7$ mg N/L), the choice that leaves them less reserve than the first population and delays the nitrite.

12.3.5 Cone, Degasser and Chemistry

The cone and the degasser act on the returning water without holdup, as shown in Equation (12.5).

$$\begin{aligned} E(G) &= \max(0.2,\ E_0-E_1 G/G_{max}) \\ \tau_G\frac{\mathrm{d}G}{\mathrm{d}t} &= G_{max}\,u\sqrt{P_s}-G \\ \eta_k &= 1-e^{-k_k GL},\quad GL=1440\,Q_{air}/Q_r+GL_0 \\ DO_{ret} &= C_s+(DO_b-C_s)(1-\eta_O) \\ &\quad+24000\,E(G)\,G/Q_r \\ C_{T,ret} &= C_{T,b}-\eta_C\,(CO_{2,b}-CO_{2,eq})/44.01 \end{aligned} \tag{12.5}$$

where G is in kg/h, C_s is oxygen saturation in fresh water [19], 10.08 mg/L at 15 °C, and $CO_{2,eq}=1.204$ mg/L is carbon dioxide in equilibrium with air at 600 ppm. The absorption falls from 0.92 with a nearly closed valve to 0.70 fully open, and the blower's 1 to 20 m^3/min moves the stripping efficiency η_C from 0.185 to 0.883. The pH follows from the charge balance $ALK=C_T(\alpha_1+2\alpha_2)+K_w/[H^+]-[H^+]$ solved by eight Newton steps on $\ln[H^+]$, with the carbonic acid constants of [20] and the water and carbon dioxide constants as the PHREEQC database carries them, and the unionized share of the ammonia is $f_{NH_3}=1/(1+10^{pK_a-pH})$ with $pK_a=0.09018+2729.92/T$, 9.564 at 15 °C [17]. At pH 7.2 and 15 °C the share is 0.43 %, and at 7.8 it is 1.69 %, so the total ammonia that reaches the 0.025 mg N/L limit falls from 5.81 to 1.48 mg/L. The water temperature follows its surroundings, $\tau_T\dot{T}=T_{env}-T$ with $\tau_T=1.5$ d. A power failure stops the pump, the cone, the blower, the feeder and the makeup, while the fish keep breathing.

12.3.6 Measurements

The controllers read only declared instruments. The tank oxygen probe, the gas flow meter, the pH probe, a membrane carbon dioxide probe behind a 10 min lag and a temperature probe carry first-order colored noise of 0.05 mg/L, 1 %, 0.01, 0.2 mg/L and 0.05 °C. An analyzer draws a tank sample every 4 h and reports total ammonia, nitrite and nitrate 20 min later with errors of 0.03, 0.01

Table 12.2 Model Parameters. Hidden Ones Are Marked h, the Rest Are in the Parameters Panel

Symbol	Meaning	Value	Unit
TGC, T_0 (h)	growth coefficient, zero	2.0, 0	—, °C
FCR_{sat}, c, ρ_m	conversion, ration curve	1.1, 0.3, 0.1	—
m	background mortality	0.02	%/d
τ_g, k_{SDA}	gut stage, post-meal O_2	3, 0.12	h, kg/kg
s_0 (h), b_O (h), θ_O	routine O_2 at 100 g	150, −0.2, 1.07	mg/kg/h, —, —
PC, f_{fec} (h), n_f (h), λ (h)	feed N, retention	0.45, 0.15, 0.028, 0.1	—
RQ (h), DO_{mk} (h)	quotient, makeup O_2	0.9, 0.95	—, of C_s
$LC50_{NO_2}$, $LC50_{NH_3}$	96-h LC50s	5, 0.25	mg N/L
a_0 (h), τ_E (h)	no-effect share, load lag	0.1, 1	—, d
V_t, V_b, Q_r	volumes, recirculation	50, 10, 100	m^3, m^3/h
G_{max}, E_0, E_1, τ_G (h)	cone	1.6, 0.92, 0.22, 2	kg/h, —, —, min
k_C, k_O (h), GL_0 (h)	degasser	0.17, 0.17, 0.6	—
μ_A, K_A, Y_A (h), b_A	ammonia oxidizers	0.9, 0.7, 0.15, 0.12	1/d, mg N/L
μ_N, K_N, Y_N (h), b_N	nitrite oxidizers	0.6, 0.08, 0.05, 0.12	1/d, mg N/L
K_{OA}, K_{ON} (h)	oxygen half-saturation	0.6, 1.2	mg/L
θ_A, θ_N, θ_b, all (h)	temperature factors	1.072, 1.06, 1.029	—
k_{det}, K_I (h), X_h	detachment, FA, carrier	0.05, 0.5, 4000	1/d, mg N/L, g
k_{het}, K_{OH} (h)	heterotrophs	0.10, 0.5	kg/kg, mg/L
x_0	natural seed of new media	0.1	% of mature
ALK_{mk}, pH_{mk}, $NO_{3,mk}$ (h)	makeup water	100, 7.6, 1	mg/L $CaCO_3$, —, mg N/L
τ_T (h), p_{CO_2}	temperature lag, air	1.5, 600	d, ppm
$\hat{s}_0$, FCR_{book}	farm's respiration, book	165, 1.0	mg/kg/h, —
T_s, n_s, CV	sample period, size, spread	14, 50, 18	d, fish, %
ΔT, t_{out}	warming, power failure	4, 20	°C, min
κ_A, κ_N	disinfectant kills	60, 75	%
c_{fish}, c_{feed}, c_{O_2}	prices	3.3, 1.6, 0.2	$/kg
c_w, c_{bic}	makeup, bicarbonate	0.5, 0.5	$/$m^3$, $/kg

and 0.5 mg N/L, holding each report until the next. A daily test kit, drawn at 09:00 and read an hour later, is the alternative. Section 1.4.5 treats such sparse and late samples. Dead fish are counted, so N is known, while the biomass is measured only by netting 50 fish every 14 d, whose mean carries the spread of individual weights, 18 %, over $\sqrt{50}$, about 2.5 %. The populations, the biofilter's water, W, B, E, a and the count killed N_{tox} are truth, drawn dashed in the scene and prefixed in the export.

12.3.7 Parameters, Initialization and Numerics

Table 12.2 lists the parameters. All are teaching values chosen to make a consistent design point, except the chemistry and saturation constants, which are published, and the toxicity constants, which are teaching values checked against the trout data above. Each case starts at a midnight of a lined-out plant. The cohort is placed as stocked, the film is either the steady film for the starting load or, on new media, a thousandth of the film a 0.5 kg N/d load grows, and the water is then settled over three days of the case's feeding (one without feed for new media) with the cohort and the film held. At $t = 0$ of the challenge the tank holds 500 kg of 50-gram fish fed 13.44 kg/d, a load of 494.8 g N/d on a film of 481.9 and 160.6 g, and the fish use 3.89 kg/d of oxygen against 4.40 kg/d in the biofilter. Integration uses fourth-order Runge–Kutta steps of 60 s, the controller runs every minute, and a row is logged every 15 min, on the engine of Section 1.6.1. Ninety simulated days take 45.0 s in a browser at the fastest setting, 2 d/s.

12.3.8 Assumptions

One cohort of one species lives in one well-mixed tank, with no size spread, grading, disease or behavior, and the coefficient model is a fit over a size range rather than a bioenergetic model. The tank and the biofilter are two well-mixed volumes and the cone and degasser act without holdup, so the model says nothing about where in a tall column the oxygen dissolves. Nitrification is two populations with Monod kinetics and a carrier-area limit, with no diffusion inside the film, no denitrification and no heterotrophic growth, so a thick film's response is approximate. The solids leave at once, and the

leached ammonia brings no alkalinity, so nitrification removes 1.023 rather than 1.000 equivalents per equivalent excreted. The chemistry is fresh water with unit activity coefficients. The temperature follows its surroundings with no heat balance. The toxicity law is linear between the no-effect level and the LC50, which no single law can match against tests of differing duration, and oxygen and carbon dioxide act on the fish only through the uptake's fall near anoxia. The water-quality limits are teaching values for a salmonid. Real ones come from water-quality criteria for reuse systems [2], national criteria [18] and a species' own toxicity data, and a simulated pass is not a welfare or compliance assessment.

12.4 Two Clocks in One Tank

12.4.1 The Meal, in Hours

The fast clock is the meal. In case 1 the oxygen station is held at 0.50 kg/h, the settled daily mean of 0.492 kg/h. Each meal's digestion overlaps the next, so the lows fall through the day, 9.99, 8.38, 7.75 and 7.63 mg/L at 11:00, 14:28, 18:05 and 21:40, and overnight the oxygen climbs to 12.50 mg/L by 07:35. The total ammonia follows the same digestion, from 1.09 at midnight to 1.30 mg/L at 22:03. A fixed gas flow is right only on average.

> **TRY IT IN THE APP** **1 · The Meal: Oxygen Dips and Ammonia Climbs**
>
> Load the case and press run. Watch the tank oxygen trend through the day. After each of the four meals the oxygen dips, and each low sits below the one before, down to 7.63 mg/L after the last meal ends. Overnight, with no meal to digest and the gas flow unchanged, the oxygen climbs back to 12.50 mg/L.

12.4.2 The Biofilter, in Weeks

The slow clock is the film. On new media in case 2, dosed with ammonium chloride and no fish, the total ammonia rises to 8.09 mg N/L on day 8.8 before the ammonia oxidizers catch up, and the nitrite they make rises to 10.78 mg N/L on day 18.9, a lag of 10.1 days, as shown in Figure 12.2a. Figure 12.4 shows the app's Water view on day 30 of this case. The nitrite oxidizers start from the same trace but have nothing to eat until nitrite appears, and in the first days free ammonia of up to 0.313 mg N/L also slows them. The lag is not an artifact of one parameter set. Run on the plant equations alone with the dose at 0.12 kg N/d and 6 m^3/d of makeup, the declared values give 13.25 days, and a tenfold smaller seed, no free-ammonia inhibition, a slower first population, no detachment, and equal activated-sludge-like kinetics without the carrier limit give lags from 8.7 to 22.1 days, with the nitrite peak second in every run.

> **TRY IT IN THE APP** **2 · Starting the Biofilter on New Media: The Ammonia Hump, Then the Nitrite Spike**
>
> Load the case and press run. Watch the ammonia and nitrite trend: the ammonia hump comes first and tops out on day 8.8, and the nitrite that the ammonia oxidizers make reaches its own peak about ten days later, on day 18.9. The startup sequence stays in its dose stage until the laboratory reads both low for three days.

A mature film shows the same physics after a feed step. Case 3 feeds a third of the table for weeks, so both populations have grown to that load, and then returns to the full table on day 1. A step from a third to the full table in one day would not happen on a well-run farm, but it separates the biofilter's delay from everything else. The total ammonia peaks at 4.34 mg/L at midnight, while the nitrite passes its limit at 15:38 on day 1.65 and stays above it after the meals until day 7.05. With the fish's response switched off the nitrite peak, 4.69 mg N/L, comes 2.19 days after the step and the limit is broken for 84.6 h. As shipped, the fish that take up the nitrite eat less (an appetite of 64 % on day 3.22), which ends the peak sooner at 3.07 mg N/L, 1.35 days after the step, at a cost of

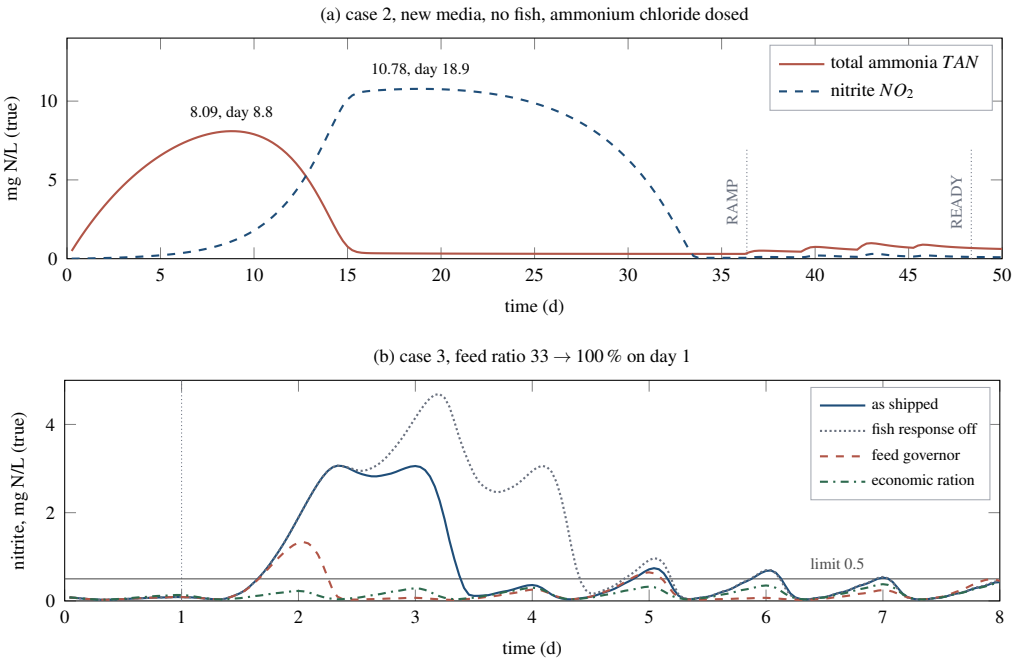


Figure 12.2 Nitrite after the ammonia, from the simulator's truth. (a) Case 2's startup on new media, total ammonia solid and nitrite dashed, with the sequence's RAMP and READY marked by dotted verticals. (b) Case 3's tripled ration on day 1 under four policies: as shipped solid, fish response off dotted, feed governor dashed and economic ration dash-dotted, against the 0.5 mg N/L teaching limit drawn as a thin line. Without the fish's response the peak comes 2.19 days after the step.

873 fish and 57.0 h over the limit, as shown in Figure 12.2b. The consequence for control is that a measurement of nitrite reports a decision made a day or more earlier.

Pause. Try Exercise 12.1 before reading on.

12.4.3 The Chemistry, in Units of pH

Case 4 holds a tank of 250-gram fish at pH 7.2, where the total ammonia ranges from 0.32 to 1.70 mg/L through day 0 and the un-ionized ammonia peaks at 0.0073 mg N/L. Raising the pH setpoint to 7.75 on day 1 barely moves the total, a daily high of 1.76 mg/L on day 2, but the un-ionized peak rises 3.73 times to 0.0273 mg N/L and first crosses the limit at 20:56 on day 1.87. The filter is unchanged and the toxicity is not.

Pause. Try Exercise 12.2 before reading on.

12.5 The Control Layers as Implemented

All five loops use the framework's velocity-form proportional integral algorithm of Section 1.6.2, Equations (1.12) to (1.15), run on measured values with no derivative term. This chapter writes the action $\alpha = \pm 1$ in place of Chapter 1's a, so $\alpha = +1$ is reverse acting and $\alpha = -1$ direct acting. Windup is prevented by back-calculation from the clamped output, with τ_I as the tracking time. A loop resting on a lower limit reports its request to the station floored at that limit.

12.5.1 The Oxygen Cascade

The outer loop runs every 5 min on the measured tank oxygen, reverse acting ($\alpha = +1$), with $K_c = 0.25$ kg/h per mg/L and $\tau_I = 30$ min, and its output plus a meal feedforward is the gas flow

setpoint,

$$G_{SP} = \mathrm{clip}_{[0,\,G_{max}]}\left(\mathrm{PI}_{DO} + \frac{k_{SDA}\,\hat{p}}{24\,E(G_m)}\right) \tag{12.6}$$

where $\hat{p}$ is the processed feed of the controller's own two-stage gut model driven by the feed it delivered, and $E(G_m)$ is the declared absorption at the metered flow. The inner loop runs every minute on the flow meter, reverse acting, with $K_c = 0.6$ per kg/h and $\tau_I = 2$ min and moves the valve between 0 and 100 %. Both loops track while the pumps are stopped. In case 1 switched to Auto on the second morning, the next day's oxygen stays between 8.88 and 9.10 mg/L, against 8.76 to 9.15 mg/L without the feedforward. The inner loop earns its place on the supply side. A sag to 60 % of the supply pressure for six hours takes the tank to 8.87 mg/L with the inner loop in Auto and 8.44 mg/L with it in Manual. Volume 3, Chapter 3 measures how fast such an inner loop has to be in a fermenter's oxygen cascade.

12.5.2 pH, Carbon Dioxide and Nitrate

Bicarbonate is dosed between 0 and 150 kg/d by the pH loop every 5 min, reverse acting, with $K_c = 200\,\mathrm{kg/d}$ per pH unit and $\tau_I = 2$ d. The carbon dioxide loop moves the blower between 1 and 20 $\mathrm{m^3/min}$ every 5 min, direct acting ($\alpha = -1$), since more air lowers the carbon dioxide, with $K_c = 1.5$ per mg/L and $\tau_I = 1$ h, toward a setpoint of 10 mg/L. The nitrate loop sets the makeup between 2 and 60 $\mathrm{m^3/d}$, direct acting ($\alpha = -1$), since more makeup dilutes the nitrate, with $K_c = 0.5$ per mg N/L and $\tau_I = 2$ d, and executes only when an analyzer report arrives, toward 60 mg N/L. A schedule replaces it when the switch is set.

12.5.3 Feeding: Table, Book, Governor and Optimizer

The feed table gives the daily ration in percent of body weight by weight class and temperature, printed once from the declared model at satiation, and the farm multiplies it by the biomass it believes, either the feed book (the stocking weight plus the feed fed over an assumed conversion of 1.0, reset at each sample) or the soft sensor. The feed governor is an override with a low select, of the kind Section 1.4.6 describes for limits approached through another variable. Each limit gives a fraction x of its limit, from the laboratory's total ammonia at the measured pH and temperature, from the nitrite, from the carbon dioxide probe, and for oxygen from the fall below its setpoint toward 6 mg/L. For ammonia and nitrite the governor reads the larger of the last report and the next one projected from the last two. Each limit cuts the ration as $f = 1 - (1 - f_{min})\,\mathrm{clip}_{[0,1]}((x-a)/(1-a))$ with $a = 0.7$ (0.5 for oxygen) and $f_{min} = 0.25$, the lowest cut wins, and the cut in force falls at once and rises by at most a quarter of the ration a day. It acts on a four-hourly analyzer, the slow measurement whose cost to a composition loop Volume 5, Chapter 3 measures.

The economic optimizer chooses the day's ration at midnight as a fraction ρ of the table ration R_{tab}, as shown in Equation (12.7).

$$\begin{aligned} \max_{0\le\rho\le 1}\ & c_{fish}\,\frac{\hat{N}\,g(\rho)}{1000} \\ & - \left(c_{feed} + c_{O_2}\tfrac{o_f}{E} + c_w w_f + c_{bic} b_f\right)\rho R_{tab} \\ \text{s.t. } & \dot{O}_r + 1.5\,o_f\,\rho R_{tab} \le 0.9\,O_{cap} \\ & 1.2\,y\,\rho R_{tab} \le \min(\hat{C}_A, \hat{C}_N) \\ & \dot{C}_0 + \dot{C}_1\,\rho R_{tab} \le \dot{C}_{cap}, \quad \rho R_{tab} \le 1.25\,R_{k-1} \end{aligned} \tag{12.7}$$

where $g(\rho)$ is the farm's growth model at the believed weight and the measured temperature, o_f, w_f and b_f are the oxygen, makeup water and bicarbonate per kilogram of feed, y the ammonia yield, $\dot{O}_r$ the routine oxygen, O_{cap} the cone and degasser capacity at full valve and full air, 1.5 and 1.2 declared peak factors on the oxygen and nitrogen loads, $\hat{C}_A$ and $\hat{C}_N$ the film observer's capacities at 60 % of each limit, the carbon dioxide row the degasser's capacity scaled from yesterday's operating

point, and the last row a ramp of 25 % a day. Every constraint is affine in ρ, so the feasible interval is exact, and golden section on the concave objective stops at 10^{-4} of the table or 40 iterations. With no feasible ration the fish fast for a day.

12.5.4 Two Estimators and a Sequence

The soft sensor closes a daily oxygen ledger from measurements and declared values only. The fish's oxygen is the cone's dissolved gas, $\sum E(G_m)G_m$, plus the degasser's transfer and the makeup's oxygen, less the accumulation in the tank and the biofilter's oxygen from the measured conversion, and the post-meal oxygen of the processed feed is then removed. The remaining routine respiration, divided by the declared per-kilogram rate at $\hat{s}_0 = 165\,\mathrm{mg/kg/h}$, gives a weight and with the count a biomass measurement $z = \hat{N}\hat{W}/1000 \cdot e^{\beta}$. The update is a fixed-gain observer,

$$\begin{aligned} \hat{B}^{-} &= \hat{B} + \frac{\hat{N} g(\hat{\rho})}{1000}, \qquad \hat{B} = \hat{B}^{-} + w(z - \hat{B}^{-}) \\ \beta &\leftarrow \beta + \lambda(\ln B_s - \ln z_{raw} - \beta) \end{aligned} \tag{12.8}$$

with $w = 0.3$, the sample B_s correcting the bias β with $\lambda = 0.8$ through the framework's bias updater (clamped to ± 0.5), the logarithmic update of Equation (1.8), and the estimate itself by 0.8 of the residual. Volume 5, Chapter 10 corrects a moisture soft sensor's bias the same way from a sampled and delayed laboratory. The cohort's own coefficient, 150, is hidden, so the sensor starts biased.

The film observer follows each population once a day. The ammonia made is the farm's yield times the processed feed plus any ammonium chloride the controller dosed, and the conversion $\hat{r}_A$ is that less the accumulation and the makeup's loss of total ammonia, and $\hat{r}_N$ the same on nitrite. Each estimate grows by $Y\hat{r} - (b + k_{det})\hat{X}$, and when the filter's water was above half-saturation but the film converted less than 85 % of what the estimate predicts, the estimate is scaled down by the shortfall, which is how a kill shows. The capacity it reports is what the estimated film converts at 60 % of each limit. A startup sequence on the shared stage sequencer doses 0.12 kg N/d of ammonium chloride until the laboratory reads total ammonia under 1 and nitrite under 0.5 mg N/L for three days, raises the dose by half every three days while the readings hold up to the 0.5 kg N/d that 10,000 fingerlings of 50 g make, and then reads READY.

12.5.5 Three Models

The plant is Section 12.3. The farm's model, used by the feedforward, the soft sensor, the film observer and the optimizer, is a copy of the declared values with the respiration coefficient set to 165 against the cohort's hidden 150, and it never reads the populations, the biofilter's water, the true pH or the weight. A grep-level test in the application fails if a controller or estimator file reads a truth field. A third, identified model exists only when a learner fits one to a case's trends.

12.6 Ten Cases, Measured

The cases appear in Table 12.3, and Section 1.6.4 describes how a case is run, scored and exported. The numbers below come from the engine run headless at each case's seed and advanced with the same calls the browser makes, with any setting a sentence names entered as that sentence says. Opening a case first, choosing it after another one, or restarting it with Reset produces identical runs. The shared defaults are the tunings above, the feed table on the feed book with no governor, the analyzer, and the mature film for the starting ration.

12.6.1 The Governor on a Sampled Analyzer

The governor can prevent what it sees coming. On a step from 55 to 100 % of the table it holds the nitrite under its limit, where the step without it breaks the limit for 26.5 h. On case 3's tripled ration it cuts the time over from 57.0 to 20.7 h with a peak of 1.34 mg N/L and one fish lost, because the analyzer reports every four hours, after the meals that make the nitrite have been eaten. The economic

Table 12.3 The Cases

#	Case and events	Teaching point
1	150-g fish, Manual gas flow, 3 d	the meal
2	New media, no fish, startup sequence, 50 d	ammonia, then nitrite
3	Feed ratio 33 to 100 % on day 1, 10 d	nitrite days later
4	250-g fish, pH setpoint to 7.75 on day 1	pH sets the toxicity
5	Soft sensor feeding, new feed lot on day 21, 60 d	a biomass from oxygen
6	Power failure at 12:00 for 20 min, 1 d	minutes of reserve
7	Governor and soft sensor, 30 d	the ration as economics
8	Disinfectant kills 60 and 75 % on day 1, 14 d	a film regrown
9	Challenge: 90 d, warming on day 40, upset on day 62	the whole farm
10	10,000 fish stocked on new media, 21 d	infeasible

ration under its ramp raises the feed 4.8 to 12.6 % a day, from 14.4 to 25.1 kg/d over nine days, and never breaks the limit, as shown in Figure 12.2b. The biofilter, not the fish, sets how fast the ration may rise.

12.6.2 Weighing Fish by Their Oxygen

In case 5 the table feeds on the soft sensor. Before the first sample the estimate reads up to 18.5 % low, because the farm's coefficient is 10 % above the cohort's, and on day 14 the table feeds 14.4 kg/d against the 16.4 kg/d the fish would eat. The sample on day 14.4 reads 674 kg, 0.6 % below the truth, and moves the bias. From day 15 the estimate stays within 5.5 % of the truth between midnights and within 4.1 % after the second sample. A new feed lot that grows 15 % less per kilogram arrives on day 21. The feed book cannot see it and is 8.2 % high on day 42 (10.2 % at its worst), while the soft sensor, which reads what the fish breathe, is 2.0 % high.

Pause. Try Exercise 12.3 before reading on.

12.6.3 Minutes, Margin and a Lost Film

In case 6 the oxygen above the 6 mg/L limit in the tank is about 149 g against an uptake of 0.529 kg/h at noon, and the oxygen reaches the limit 16.7 min after the power fails, falling to 5.34 mg/L. With 20,000 fish (4.98 t) it takes 8.7 min, 1.92 times faster, and falls to 2.15 mg/L, while 300-gram fish (3.01 t) take 14.6 min and 150-gram fish (1.51 t) stay above the limit with a low of 6.41 mg/L. Doubling the count halves the reserve time, and weight shortens it more slowly because heavier fish use less per kilogram.

Case 7 prices the ration over 30 days in Table 12.4. Feeding 80 % of the table converts better than the full table, 1.05 against 1.09, and earns less, $764 against $847, and the fish reach the full table's 234 g only on day 35.5. The optimizer feeds 0.95 of the table and earns $837, within 1.1 % of the full table on 45 kg less feed. It earns slightly less because it maximizes each day's margin and does not value that a heavier fish grows more tomorrow. Its value appears where a limit binds. In case 8 a disinfectant kills 60 % of the ammonia oxidizers and 75 % of the nitrite oxidizers on day 1 while 10,000 fish of 200 g keep eating. Without the governor the nitrite reaches 6.49 mg N/L on day 2.22, the appetite falls to 33 % and 1,843 fish die. The governor holds the peak to 1.09 mg N/L with no fish lost, and the optimizer with the soft sensor to 0.91 mg N/L, 2.5 h of the 6.4 h over the limit coming before the first report after the upset.

> **DID YOU KNOW? Better Conversion, Smaller Margin**
>
> From the simulator: over the 30 days of case 7, feeding 80 % of the table gains 677 kg and earns $764, against 824 kg and $847 on the full table (Table 12.4). Fish sold by weight pay for growth, not for a good conversion.

Table 12.4 Measured Results. Hours Over Any Limit, Nitrite Peak, Fish Killed by the Water, Biomass Gained and Margin

Case	Policy	Over (h)	NO_2 peak (mg N/L)	Killed	Result
3, 10 d	as shipped	57.0	3.07	873	—
	fish response off	84.6	4.69	0	—
	governor	20.7	1.34	1	—
	economic ration	0.0	0.41	0	—
7, 30 d	table 100 %	—	—	—	824 kg, $847
	table 80 %	—	—	—	677 kg, $764
	table 60 %	—	—	—	506 kg, $581
	economic, $\rho = 0.95$	—	—	—	793 kg, $837
8, 14 d	as shipped	84.1	6.49	1,843	1974 kg
	governor	13.4	1.09	0	2237 kg
	economic, soft sensor	6.4	0.91	0	2241 kg

Case 3's economic row is that run's peak over 8 days. Case 7's results are biomass gained and margin, case 8's the biomass on day 14.

12.6.4 The Infeasible Variant

Case 10 stocks 10,000 fingerlings directly on new media with the governor on. The nitrite passes its limit on day 5.8, the total ammonia reaches 14.8 mg/L on day 8.0 and the nitrite 15.8 mg N/L on day 14.4, and the fish go off their feed and die, half of them by day 9.2 and 9,937 of the 10,000 by day 21. A logged sweep of feed ratios from 10 to 100 % with makeup from 10 to 60 m^3/d, the governor off and on, breaks the limit in every run. The lowest peak, 0.517 mg N/L at 10 % of the table and 60 m^3/d, comes from the maintenance ration, on which the biomass falls from 500 to 490.1 kg in three weeks, and at 20 %, where the fish just hold their weight, the peak is 0.632 mg N/L. A lower pH through a higher carbon dioxide setpoint and the daily test kit do not change that. The economic feeding stays under, at 0.345 mg N/L, only by starving the cohort to 471.0 kg, and colder water at 12 °C would allow it. At the case's 15 °C no ration that grows the fish keeps nitrite under its limit, and the answer is case 2's sequence, which carries the stocking load by day 48.3.

12.6.5 The Challenge

The challenge grows 10,000 fingerlings of 50 g for 90 days through a 4 °C warming of the surroundings from day 40 and a disinfectant upset on day 62. It is judged on the truth at day 90: a harvest of at least 2.40 t, any water-quality limit broken for at most 8 h in total, and a feed conversion of at most 1.10, with every parameter and the stocking as shipped. Table 12.5 gives five policies at the case's seed and over eleven seeds. As shipped the nitrite after the upset peaks at 6.85 mg N/L on day 63.1 and stays over the limit for 69.8 h, the appetite falls to 42 % and 1,359 fish die. The cohort still weighs 2.58 t, in larger fish, on 2664 kg of feed, a conversion of 1.28 and a margin of $1,326. The suggested soft sensor, governor and economic ration harvest 2.54 t in 1,352 more fish on 2199 kg of feed, at 1.08 and $2,148, with 6.6 h over a limit and none lost. Of those hours, 2.8 h come before the first report that shows the upset and 3.8 h from meals already eaten passing through the weakened filter. Feeding past what the biofilter can carry does not buy fish. Figure 12.3 draws the five policies of Table 12.5 side by side.

12.6.6 Verification

Code verification, agreement with published relations and educational use are kept apart in this section. On the code side the nitrogen inventory over the shipped challenge, 191.8 kg of nitrogen in through feed and 132.8 kg out, closes to 3.6×10^{-12} kg, and the oxygen over its 795.8 kg of fish uptake to 9.4×10^{-13} kg. The same holds through case 10's mortality, case 2's dose and a power failure, a supply sag and a mortality event fired together, to below 3×10^{-12} kg. The one exception is case 6 with 20,000 fish, whose biofilter goes anoxic during the outage and leaves an oxygen residual of 1.05×10^{-6} kg through a round-off guard. Halving the step to 30 s with the instrument noise off

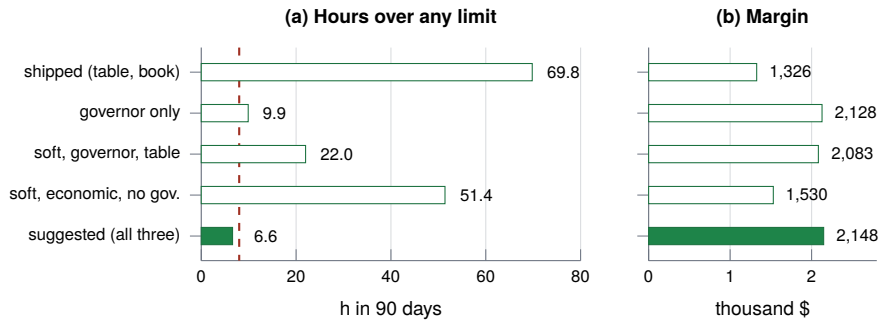


Figure 12.3 The five challenge policies of Table 12.5 at the case's seed: hours over any water-quality limit against the 8 h the challenge allows (dashed line), and the margin. The solid bar passes, white bars fail. Notice that the fewer the hours a policy spends over a limit, the larger its margin, and that the governor alone misses the allowance only narrowly.

Table 12.5 The Challenge Over 90 Days at the Case's Seed, and the Range Over Eleven Seeds

Policy	Harvest (t)	Over (h)	FCR	Killed	Margin ($)	Seeds passing
shipped (table, book)	2.58	69.8	1.28	1,359	1,326	0/11
governor only	2.55	9.9	1.08	0	2,128	2/11
soft, governor, table	2.47	22.0	1.07	0	2,083	4/11
soft, economic, no gov.	2.47	51.4	1.21	1,172	1,530	0/11
suggested (all three)	2.54	6.6	1.08	0	2,148	11/11
shipped, 11 seeds	2.57–2.58	69.6–69.9	1.28–1.30			
suggested, 11 seeds	2.45–2.54	6.0–6.9	1.07–1.08	0		

moves the shipped harvest by 0.004 % and the suggested one by 0.396 %, and case 3's nitrite peak, 3.052 mg N/L, not at all. At every midnight of the suggested challenge the optimizer's ration agrees with the closed-form maximum of its concave quadratic objective within 2.0×10^{-5}, 65 times interior, 15 times on the nitrite row and 10 on the oxygen row. The application's own suite passes 44 of 44 checks.

Against published relations, the carbonic acid, water and carbon dioxide constants equal those of the PHREEQC database, which carries the expressions of [20], to four decimals at 10, 15 and 25 °C, and three equilibria through the app's solver and an independent bisection agree to four decimals in pH. The un-ionized ammonia share is within 0.4 % of the form the national criteria print [18] at three conditions. The satiated cohort follows the declared coefficient curve, 96.3, 164.9 and 260.2 g at 30, 60 and 90 days, within 0.447 %. These checks confirm that the model is built as declared. They do not validate it against a farm, and no learning gain is claimed.

12.7 Technology in Practice

The simulated farm runs five loops, a feed governor, an economic ration and two estimators on a handful of instruments. Figure 12.5 draws the oxygen cascade and the nitrogen path with the devices a land-based farm would install.

What Measures It

The fast loops read probes in the tank for oxygen, pH, carbon dioxide and temperature, each with colored noise. The nitrogen that sets the ration is not measured in the tank at all. The chapter's analyzer draws a sample every 4 h and reports total ammonia, nitrite and nitrate 20 min later, and the

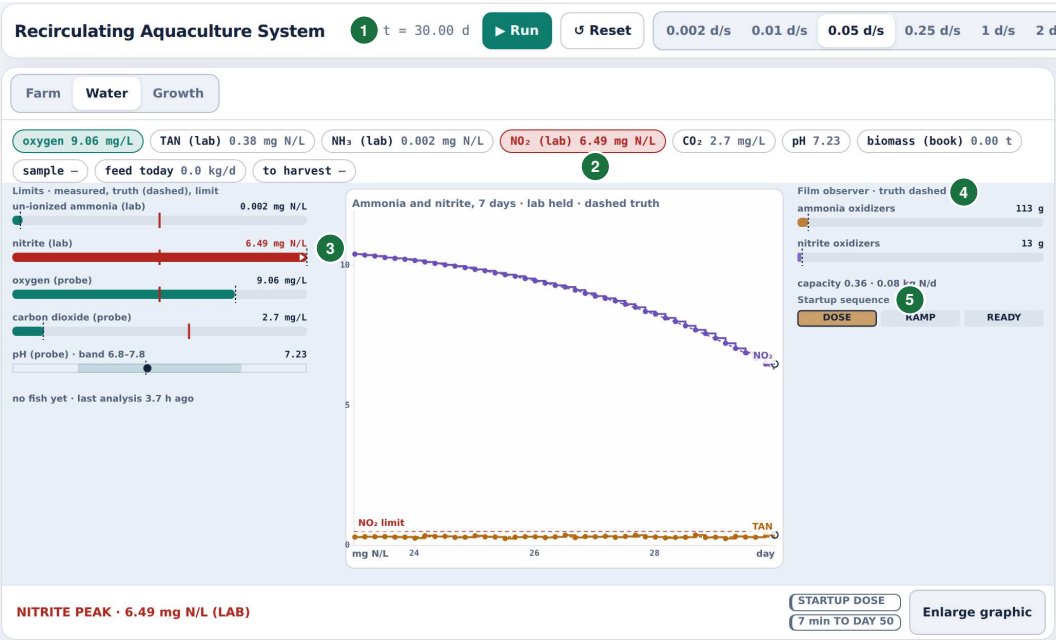


Figure 12.4 Case 2's biofilter startup on day 30 (1), on the Water view. The laboratory (2) holds total ammonia at 0.38 and nitrite at 6.49 mg N/L from a report 3.7 h old, against the dashed truth of 0.31 and 6.30 on the limit bars (3), and the status strip reads the nitrite peak. The film observer (4) believes 113 and 13 g of ammonia and nitrite oxidizers, against a truth of 112 and 16 g, and the startup sequence (5) is still dosing. The readings show tank oxygen at 9.06 mg/L, pH 7.23 and carbon dioxide at 2.7 mg/L.

biomass is known only from netting 50 fish every 14 d. No loop or estimator reads the simulated truth.

> **TECHNOLOGY** **Sensor: Optical Dissolved Oxygen Probe**
>
> Dissolved oxygen is measured mainly by two methods, the Clark electrode and fluorescence quenching [21]. In the optical probe a thin layer of material fluoresces red under green or blue light, and oxygen that reaches the layer quenches the glow, so less oxygen gives a stronger and longer fluorescence [22]. In a circular tank the probe sits near the outlet, never close to where oxygen is injected or oxygen-rich water enters, and it must be wiped clean and calibrated from time to time [15]. Water quality sensors are prone to biological growth on their surfaces, which makes online measurement less reliable [21]. The chapter's probe reads the true tank oxygen with colored noise of 0.05 mg/L.

What Moves It

The oxygen station sets the gas into the cone, a dosing pump adds bicarbonate, the blower drives air through the degasser, a valve admits the makeup water and the feeder delivers the day's ration in four meals. The ration is the actuator that matters most, because the load it puts on the biofilter returns days later as nitrite, while the other four act within minutes or hours.

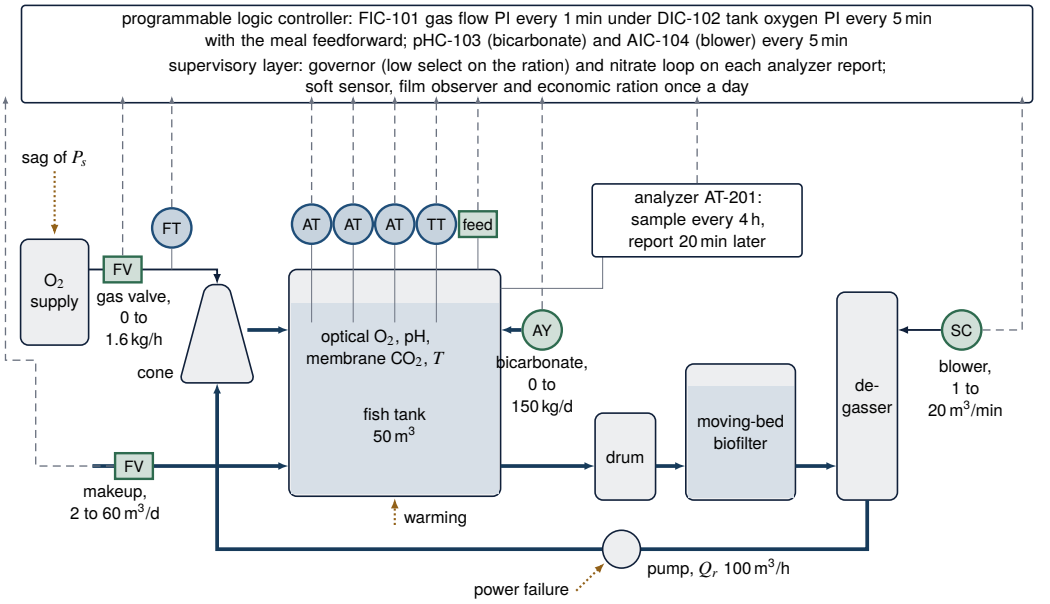


Figure 12.5 The chapter's loops with the devices a land-based farm would install. Thick blue lines carry the water, thin dark lines the oxygen and the air, dashed gray lines the signals and dotted amber arrows the disturbances. Notice that the probes on the tank are read continuously, while the nitrogen that limits the ration reaches the controller only through an analyzer sample every four hours.

TECHNOLOGY Final Element: Oxygen Cone on a Gas Valve

Pure oxygen reaches a farm as liquid in tanks or comes from an oxygen generator on site. In a cone a pump forces water and the gas together at typically around 1.4 bar, which drives the oxygen into the water, at the price of the electricity the pump uses. A cone treats only part of the circulating water, while a low-pressure oxygen platform treats the main flow. A central control system can raise the oxygen dose at each feeding as the fish's consumption rises [15]. In the chapter the valve sets a gas flow of up to 1.6 kg/h, an inner loop holds that flow, and the cone's absorption falls from 0.92 to 0.70 as the valve opens.

Where the Controller Runs

On a land-based farm a central control system monitors and controls oxygen, temperature, pH, water levels and motor functions, starts a corrective action when a value leaves its preset band, raises an alarm when that fails, and can coordinate the automatic feeding with a higher oxygen dose during the meals. Its operators set its alarms and emergency levels on programmable logic controllers and computers [15]. A programmable logic controller holds instructions for logic, timing, counting and three-mode PID control, and supervisory and lower loops run continuously with cycle times from milliseconds to minutes [23]. The chapter's inner gas-flow loop runs every minute and the outer oxygen, pH and carbon dioxide loops every 5 min, so the platform's scan is never the limit. In a function block program the oxygen cascade is two PI blocks with the meal feedforward summed into the outer block's output. The governor is a low select on the ration, and the economic ration and the two estimators run once a day in a supervisory layer above the loops.

What Is Modernizing It

Three lines of work aim at the delays this chapter measures. The first is the sensor. A review describes optical dissolved oxygen probes as needing no calibration and responding fast, and expects probes based on fluorescence without a membrane to be a focus of future research [21]. The second is

the soft sensor. Models that take online temperature, salinity, pH and oxygen as auxiliary variables have been built to estimate the ammonia nitrogen [21], as the chapter's soft sensor estimates the biomass from the oxygen balance. The third is learned feeding control. A reinforcement-learning feeding controller for recirculating systems has been compressed to run on a small edge device in real time [24], and precision fish farming sets feed delivery among the first problems that control engineering should take on [6]. None of them removes the days a nitrifier film needs to grow.

> **IN PRACTICE** **Minutes Count When the Power Fails**
>
> Technical failures can easily cause substantial losses, so the control system calls the staff when a major failure is about to occur, and a reaction time under 20 minutes is recommended even where automatic backups exist. Pure oxygen as a backup is the first safety precaution: if the electricity fails, a magnetic valve opens and stored oxygen flows to diffusers in every tank, at a flow set beforehand so that the store lasts until the failure is corrected. A fuel-driven generator should restart the main pumps within an hour or so, because the ammonia builds up when the water stops passing over the biofilter. The routine includes alarm tests and a check of the emergency oxygen in every tank [15].

12.8 Limitations

The sizes, kinetics and prices are teaching values that make one consistent farm without being fitted to any. The two-population film with a carrier limit was chosen because equal activated-sludge-like kinetics leave a mature film three to four times its load in reserve, so its delay after a feed step is a property of the chosen constants and not a prediction for a real filter, while the startup's ammonia-then-nitrite order survives every variant tried. The toxicity law is a declared teaching law whose 96-hour mortality at the LC50 is 39.7 % rather than half, and it ignores chronic effects below the limits, disease and the effect of carbon dioxide on growth. One cohort, two mixed volumes and a temperature without a heat balance leave out grading, stratification, total gas pressure and the farm's heating.

The soft sensor is a fixed-gain observer whose weights are declared rather than computed from noise statistics, and the film observer finds a film larger than it believes only by growth. The optimizer maximizes one day's margin, uses declared peak factors of 1.5 and 1.2 for the meal, and does not plan the cohort to harvest, which is why it trails the full table in case 7. The governor reads a four-hourly analyzer and cannot prevent the nitrite of meals already eaten. The disturbances arrive as scheduled steps.

> **OPEN CHALLENGE** **Measuring Nitrogen Where the Fish Are**
>
> Ammonia, nitrite and nitrate on a fish farm are usually measured only by online analyzers that move the laboratory's chemistry into a detection box. Water quality sensors suffer from biological growth on their surfaces, poor reliability and a short life, and many of the studies behind intelligent farms are still done in a laboratory [21]. Precision fish farming asks for control-engineering principles that move production from an experience-based to a knowledge-based regime, with biomass monitoring and feed delivery among its first cases [6]. Progress would look like reliable nitrogen sensing in the tank itself, so that a feed governor could act on the meal rather than on a sample hours old.

12.9 Conclusion

A recirculating farm is a plant whose most important actuator, the nitrifying film, has to be grown, and the simulator of this chapter integrates the fish, the film and the water's chemistry together with every controller restricted to the farm's own instruments. The fish answer a meal in hours, with oxygen lows falling to 7.63 mg/L under a fixed gas flow, while a new film shows its ammonia peak on day 8.8 and its nitrite peak on day 18.9, and a tripled ration returns as nitrite 1.35 days later. A governor on a four-hourly analyzer cuts case 3's hours over the nitrite limit from 57.0 to 20.7, a soft sensor on the oxygen balance follows the biomass within 5.5 % once a sample has removed its bias, and the three

together pass the ninety-day challenge on eleven of eleven seeds where the shipped table fails on all eleven. Stocking on new media is infeasible at any ration that grows the fish. The model is a declared teaching model and its film and toxicity constants are chosen, not fitted. A fuller model would add diffusion inside the film, a size-structured cohort, a heat balance and a ration planned over the whole cohort. The simulator shows that on a fish farm the ration is the load, and the biofilter decides how fast it may change.

KEY POINTS

- A recirculating farm cleans its water with bacteria that grow only on the load they carry, so a larger ration returns as nitrite days later.
- In case 3 the nitrite of a tripled ration peaks at $3.07\,\mathrm{mg\,N/L}$ 1.35 days after the step and stays above its limit for 57.0 h.
- A governor on a four-hourly analyzer cuts those hours to 20.7, and it cannot prevent the nitrite of meals already eaten.
- A soft sensor on the oxygen balance follows the biomass within 5.5 % once a sample has removed its bias, and with the governor and the economic ration it passes the challenge on eleven of eleven seeds.

Where else this applies. Volume 9, Chapter 10 treats nitrifiers as the plant, Chapter 11 a culture as the actuator, and Volume 3, Chapter 3 an oxygen cascade like this farm’s.

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12.10 Exercises

12.1 ○ Concept check · 2 min

In case 3 the feed ratio steps from 33 to 100 % on day 1. The true total ammonia peaks at 4.34 mg/L that midnight, but the true nitrite peaks only 1.35 days after the step. Why does the nitrite come so much later?

(a) The analyzer reports every four hours, so the nitrite peak shows on the trend later than it occurs

(b) Nitrite forms slowly in the tank's own water from the ammonia, away from the biofilter

(c) The fish excrete nitrite only after two gut stages of about three hours each

(d) The nitrite oxidizers have less reserve and grow more slowly, so they must grow on the new load first

12.2 ○ Concept check · 1 min

In case 4 the pH setpoint rises from 7.2 to 7.75 on day 1. The daily high of total ammonia moves only from 1.70 to 1.76 mg/L. What happens to the toxicity of the water?

(a) It rises about 3.7 times, because the un-ionized share of the same total grows with pH

(b) It falls, because the bicarbonate dosed to raise the pH binds part of the ammonia

(c) It stays the same, because the limit applies to the total ammonia and the total barely moved

(d) It rises about tenfold, because each step of the pH multiplies the un-ionized share by ten

12.3 ○ Concept check · 2 min

In case 5 the table feeds on the soft sensor, and before the first sample on day 14 the estimate of the biomass reads up to 18.5 % low. What causes the low reading?

(a) The oxygen probe's colored noise averages to a negative error over each day
(b) The farm's model gives each kilogram of fish a higher routine oxygen use than this cohort has
(c) The feed book resets the soft sensor to the stocking weight at every midnight
(d) The ledger leaves out the biofilter's oxygen, which hides part of the fish's use

12.4 Theory and calculation · 5 min

The ammonium constant is $pK_a = 0.09018 + 2729.92/T$ with T in kelvin, and the un-ionized share of the total ammonia is $f = 1/(1 + 10^{pK_a - pH})$.

(a) Compute pK_a at 15 °C. *Checkpoint:* 9.564.

(b) Compute f at pH 7.2 and 7.8, and the total ammonia at which the un-ionized ammonia reaches its limit of 0.025 mg N/L at each pH. *Checkpoint:* 0.43 % and 1.69 %; 5.81 and 1.48 mg/L.

(c) Compute the ratio of f at pH 7.75 to f at 7.2, and compare it with the 3.73-fold rise of the un-ionized peak in case 4. *Checkpoint:* 3.51; the total also rose, from 1.70 to 1.76 mg/L.

12.5 Theory and calculation · 8 min

Use the growth law of Equation (12.1) per fish, with the eaten feed equal to the ration, ρR_{sat}, and $q_f = 1$. The feed conversion is the feed over the growth.

(a) Show that the conversion is $FCR(\rho) = \rho / \{e_{max}[\rho - c\rho^2 - k]\}$ with $k = \rho_m(1 - c\rho_m)$. *Checkpoint:* Growth $= R_{sat} e_{max}(\rho - c\rho^2 - k)$.

(b) Find the ρ that minimizes the conversion for $c = 0.3$ and $\rho_m = 0.1$. *Checkpoint:* $\rho^* = \sqrt{k/c} = 0.569$.

(c) With $FCR_{sat} = 1.1$, compute e_{max}, the lowest conversion and how much better it is than the conversion at satiation. *Checkpoint:* 1.508; 1.0068; 8.47 %.

12.6 Theory and calculation · 5 min

In case 6 the power fails at 12:00. The tank holds 50 m^3 at a true oxygen of 8.98 mg/L, and the fish take up 0.529 kg/h. The pumps stop, so no water reaches the cone.

(a) Compute the oxygen in the tank above the 6 mg/L limit, in grams. *Checkpoint:* 149 g.

(b) Estimate the minutes to the limit at a constant uptake. *Checkpoint:* 16.9 min.

(c) Case 6 stocks 10,000 fish. Estimate the minutes for 20,000 fish of the same weight, starting from the same oxygen. *Checkpoint:* About 8.5 min.

12.7 App challenge · 9 min

Load case 3, The feed step: nitrite returns days later, and change no setting. Run the ten days at 0.25 d/s (40 s) with the default seed until the run stops at day 10.

(a) Read the Limits broken tile (hours and worst nitrite) and the fish killed by the water on the Harvest mass tile. *Checkpoint:* 57.0 h, 3.07 mg N/L, 873 fish, within 0.2 h, 0.02 and 2.

(b) Set Feed governor to On, press Reset and run the ten days again. Read the same values and the feed conversion (FCR) of both runs. *Checkpoint:* 20.7 h, 1.34 mg N/L, 1 fish; FCR 3.29 as shipped and 1.05 with the governor.

(c) The governor cuts the ration as the nitrite nears its limit. Explain why the limit is still broken for most of a day. *Checkpoint:* The four-hourly analyzer reports the nitrite after the meals that make it have been eaten.

12.8 App challenge · 6 min

Load case 6, Power failure: minutes to the oxygen limit, and change no setting. Run one day at 0.25 d/s with the default seed (about 4 s).

(a) Read the minutes from the failure to 6 mg/L in the note, and the worst oxygen on the Limits broken tile. *Checkpoint:* 16.7 min and 5.34 mg/L, within 0.1 and 0.02.

(b) Set Fish stocked to 20,000, press Reset and run the day again. Read the same two values, and the ratio of the two times. *Checkpoint:* 8.7 min and 2.15 mg/L; 1.92.

(c) The second run's Limits broken tile also reports about 16 h over a limit and a few hundred fish killed. Which limit caused that, and what does it say about a stocking density chosen for its oxygen reserve alone? *Checkpoint:* Nitrite after the meals; the biofilter, not only the oxygen, sets the density.

12.9 App challenge · 10 min

Load the Challenge, ninety days to harvest through a summer and an upset, and change no setting. Run at 2 d/s (45 s) with the default seed to day 90 and read the Challenge target tile.

(a) Record the harvest, the hours over a limit, the feed conversion, the fish killed and the margin. *Checkpoint:* 2.58 t, 69.8 h, 1.28, 1,359 fish, $1,326; not met.

(b) Press Reveal suggested tuning, then Reset, and run the ninety days again. Record the same five values. *Checkpoint:* 2.54 t, 6.6 h, 1.08, none, $2,148; met.

(c) The shipped run harvests more fish mass and fails. Explain both facts, and say which part of the suggested settings acts on the upset of day 62. *Checkpoint:* The shipped fish are fewer and larger; the governor and the economic ration cut the feed after the upset.

12.10 Application area · 3 min

A review of nitrite toxicity reports that each milligram per liter of chloride raises the trout's 96-hour LC50 by 0.29 to 2.0 mg N/L, and soft-water tests gave 0.19 to 0.39 mg N/L. The model assumes about 16 mg/L of chloride.

(a) Compute the LC50 range at 16 mg/L of chloride with the low slope, and with the high slope. *Checkpoint:* 4.83 to 5.03, and 32.19 to 32.39 mg N/L.

(b) The model uses an LC50 of 5 mg N/L and a limit of a tenth of it. Say why a farm adds salt, and why the limit uses the low slope. *Checkpoint:* Chloride protects against nitrite; the low slope is the cautious end.

12.11 Application area · 4 min

A farm manager asks how fast a ration may rise on a mature biofilter at 15 °C. Take the nitrite oxidizers' growth at its upper bound: substrate and oxygen saturating and no carrier limit, so the population grows at $\mu_N - (b_N + k_{det})$ with $\mu_N = 0.6 \times 1.06^{T-20}$, $b_N = 0.12 \times 1.029^{T-20}$ and $k_{det} = 0.05$ per day.

(a) Compute this net growth rate and the factor by which the population can grow in one day. *Checkpoint:* 0.294 d^{-1}; 1.34.

(b) Compute the shortest time for the population to triple, and compare it with the economic ration's ramp of at most 25 % a day. *Checkpoint:* 3.73 d; the ramp stays below the bound.

12.12 Review the agent · 5 min

A new farm runs case 2's startup on new media. On day 9 an AI assistant writes: "The total ammonia peaked at 8.09 mg N/L on day 8.8 and is now falling, so the biofilter is working. Stock the 10,000 fingerlings today and turn the feed governor on. If the water gets worse, the governor will cut the ration in time." Find the flaw and say how you would check it in the app.