

CERNUNNOS FOUNDATION / BRIGHT MEADOW GROUP

Systems Analysis and Solutions Consulting

Designing an Aquaponic Food Production System

A Permaculture-Based Approach to Closed-Loop Water and Nutrient Management

Appendix — Aquaponic Design Reference | 31 May 2026

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Abstract *This document describes a permaculture-based approach to designing a closed-loop aquaponic food production system. It is structured around the movement of water through four functional zones — fish room, refugium, greenhouse, and cistern — and treats each zone as a defined stage with measurable inputs and outputs. The design philosophy prioritizes accessibility, resilience, and biological integrity over equipment complexity, and is intended to serve both first-time builders and experienced practitioners seeking to improve system efficiency. This document functions as a standalone reference and as a foundational appendix to the River Refugium Project document series, Version 3.0.*

Section I

Reading the Land Before Drawing the Lines

Permaculture design begins not with a pencil but with patience. Before a single pipe is laid or a single bed is framed, the skilled designer observes. Where does the sun track across the site? Where does water naturally move when it rains? Where are the warm pockets and the cold drafts? Where is access easiest, and where will you actually walk when your hands are full? These questions are not preliminary to design — they are the first acts of it. Every answer shapes what comes next, and a system built on honest observation will outperform one built on optimistic assumptions every single time.

The advantage of aquaponic systems is that this principle scales with remarkable fidelity. The same observational logic that governs the placement of a ten-gallon guppy tank and a tray of lettuce on a windowsill governs the placement of a watershed-scale intervention like the River Refugium Project. The inputs change, the outputs change, the stakes change — but the method does not. Observe correctly, and the system tells you where it wants to go.

For our purposes we are designing a greenhouse-based aquaponic food production system, and observation gives us three functional zones. I prefer these to be separate rooms. Separate rooms mean controlled inputs: controlled light, controlled temperature, controlled access. Simpler systems collapse all three zones into a single greenhouse space and that works — but understanding the zones as distinct functional units is what allows a builder to push any system toward higher efficiency, regardless of how the walls are drawn. So we define them as rooms, and we design accordingly.

The Three Zones

The Fish Room receives fully conditioned water from the cistern. At that entry point the water is as clean and oxygenated as it will be anywhere in the cycle — refreshed, temperature-stabilized, carrying the lowest nutrient load of any point in the loop. The fish change that. They consume oxygen, they produce ammonia through respiration and waste, and they generate solids. By the time water leaves the fish room it is warm, oxygen-depleted relative to entry, loaded with ammonia and suspended solids, and carrying the full biological output of the fish population. Light is excluded entirely from the fish room. Algae in a fish tank competes for oxygen at night, introduces uncontrolled biological variables, and creates maintenance burdens that serve no productive purpose in this design. Thermal mass — stone, water volume, insulated construction — is used here to buffer temperature swings, because fish are acutely sensitive to thermal fluctuation and a stable environment reduces stress, improves feed conversion, and keeps immune function strong.

The Refugium receives that biologically rich but unbalanced water directly from the fish room. Its job is transformation. Mechanical filtration pulls suspended solids from the water column. Biological filtration — the bacterial colonies at the heart of the nitrogen cycle — converts ammonia first to nitrite and then to nitrate, the form of nitrogen plants can actually use. Gas exchange works in the other direction, driving off excess carbon dioxide and reintroducing oxygen. By the time water leaves the refugium it has shed its solids, completed its nitrogen conversion, and is approaching the chemical balance that makes it genuinely productive rather than merely biologically active. Light is excluded here as well, for the same reasons as the fish room — algal growth in the refugium introduces competition and instability into a system that depends on controlled bacterial populations doing predictable work.

The Greenhouse receives that conditioned, nutrient-rich water and puts it to work. This is where photosynthesis happens, where nutrient uptake happens, where the biological load the fish generated becomes food. Plants strip nitrates, consume phosphorus, take up micronutrients, and return cleaner, somewhat cooled, oxygen-enriched water toward the cistern. Light here is not excluded but managed — optimized for growing conditions, for the specific crops in production, for the season. Thermal mass in the greenhouse moderates the swings between day and night temperatures that would otherwise stress plants and destabilize water chemistry.

The Cistern sits at the return point of the greenhouse and the entry point of the fish room, and it performs a function that is easy to underestimate. It is buffer, reservoir, and conditioning station. It holds volume enough to absorb variability in the system — a heavy harvest day, a hot afternoon, a fish feeding surge. And critically, it is where fresh water enters. Rainwater collected from the roof is diverted into the cistern on a continuous basis, with overflow managed so that when the cistern approaches capacity the diversion redirects rather than floods. This means the system is never operating on fully static water. Fresh inputs dilute accumulated mineral loads, replace what evapotranspiration removes, and keep the chemistry from drifting in the directions that closed recirculating systems tend to drift when left entirely to themselves. The cistern is where the sky participates in the design.

Section II**The Water Cycle as Design Backbone**

Every aquaponic system has a neutral point — a place in the cycle where the water is as close to ideal as it is going to get before the biology takes over. In this system that point is the cistern-to-fish-tank transition. The water entering the fish tank is the product of everything the system has done right. It arrives as a blend: nutrient-depleted but oxygen-rich and mineral-balanced water returning from the greenhouse, combined with whatever the sky contributed the last time the cistern needed refreshing. In a healthy system that should be most rains — the cistern drawing down steadily enough through evapotranspiration and fish respiration that incoming rainwater is a regular event rather than an occasional one.

What enters the fish tank must meet a narrow set of conditions. The fish are livestock. They have no ability to seek better water, no way to compensate for a chemical environment that is working against them, and no margin for extended exposure to conditions outside their tolerance. The water must carry sufficient dissolved oxygen to support respiration under full feeding load. Toxicity — ammonia, nitrite, accumulated nitrate beyond threshold, chlorine if municipal top-off water ever enters the system — must be at or near zero. pH must fall within the range the selected species can tolerate, which in practice means the range where they thrive rather than merely survive, because stressed fish are inefficient fish and inefficient fish are expensive fish.

Measuring water quality at this entry point is therefore two things simultaneously. It is basic animal husbandry — the minimum responsible standard for anyone keeping fish as productive livestock. And it is a system health indicator at the highest level of abstraction. A single test at the cistern-to-tank transition tells you whether the loop is functioning. If the numbers are good, the system is working. If they are drifting, something somewhere in the loop is underperforming.

What it will not tell you is where. For that you have to walk the system. Each zone begins with a known water condition and does specific work to change it. The story of system health is written in the delta between what enters each zone and what leaves it. A reading at the fish tank entry gives you the headline. The sections give you the reporting behind it.

So we follow the water where it goes next: into the fish room, where the neutral point ends and the biology begins.

Section III**The Fish Tank — From Neutral Water to Nutrient Load**

The fish tank receives neutral water. Everything that happens from this point forward is the system earning its keep.

The first design decision is species selection, and it is genuinely open. Any fish that consumes feed and converts it to waste is a candidate. The constraint is not biology but intent. Are you producing fish for the table? Choose accordingly — yellow perch, tilapia, catfish, trout depending on your climate and water temperature range. Are you primarily interested in nutrient generation with minimal management overhead? A chronically overpopulated guppy tank will outperform almost any elaborate setup on a cost-per-nutrient basis, and there is no shame in that. For this design we are optimizing for food production, and that means selecting species with an eye toward both the table and the tank.

Schooling fish like yellow perch and social fish like catfish are well suited to intensive aquaponic production for a practical reason: their stress threshold is spatial rather than strictly numerical. As long as they can move, they are not stressed. Pump enough oxygen into the column and maintain enough water volume for physical movement, and you can stock right up to that threshold. The system rewards pushing those two variables — stocking density and oxygenation — upward together.

Tank sizing follows from grow space, not the other way around. The rule of thumb that experience gives us: roughly 25 tilapia on a standard feeding regimen can support a 10x20 greenhouse stocked wall to

wall with tomatoes, peppers, and whatever fills the gaps between them. That relationship — fish population to plant canopy — is the sizing equation. Build or select your tank to match the nutrient demand your greenhouse will generate, and then stock to match the tank. A system that produces more nutrient than the plants can consume is a system accumulating problems. A system that produces less is leaving productivity on the table. The goal is balance, and balance starts with intentional sizing.

The substrate is not optional in this design. The base is sand, covered with piles of river rock arranged deliberately around the pump intake — protecting it, keeping it clear, and distributing flow. This is not merely housekeeping. Sand and river rock together contribute to mineral balance throughout the system, introducing trace elements slowly and consistently the way a natural streambed does. More importantly, they provide surface area. Bacterial colonies — the nitrifying organisms that make the entire nitrogen cycle function — need surface area to colonize, and they will colonize every square inch you give them. Mass and bacterial surface area are critical parameters in every living system we design, and the substrate in the fish tank is one of the primary places we build both deliberately.

Airstones are placed throughout the tank and covered by the river rock piles, protected from fish disturbance and positioned for maximum distribution through the water column. We use them liberally — closer to excess than to sufficiency. The airline feeding them runs from the greenhouse, and that direction is intentional. The greenhouse air is being pulled through the system anyway; routing it to feed the airstones means the fish are breathing air that has already passed through a living plant environment, and the oxygen-rich exhaust of active photosynthesis is exactly what you want entering a tank under heavy biological load.

Dissolved oxygen at the fish tank is not a comfort parameter — it is the primary limiter of how hard you can push the system. Fish respiration, bacterial activity in the substrate, and the decomposition of organic waste all compete for the same dissolved oxygen budget. The airstones address all three simultaneously. They replenish what the fish consume, they support the nitrifying bacteria working through the substrate, and they drive the gas exchange that keeps carbon dioxide from accumulating in the water column to levels that suppress respiration. This is why we err toward excess. An over-aerated tank costs you a little electricity. An under-aerated tank costs you fish.

The CO₂ that fish respiration produces in volume goes somewhere useful — directly into the greenhouse through the room ventilation — but that exchange is the greenhouse's gain, not the fish room's concern. The fish room's job is oxygen in and waste out. The airstones are how we guarantee the first half of that equation.

A note on fish welfare that is also a note on system economics: tanks will tolerate overcrowding, but they will not reward it. The easiest disease prevention in aquaponics is a fish that is not stressed. Good substrate, reasonable stocking for movement, a sound diet — these are not indulgences. Stressed fish eat poorly, convert feed inefficiently, suppress immune function, and become vectors for pathogens that can collapse a tank faster than almost any other system failure. The space allowance pays for itself many times over in feed conversion ratio and disease-free production runs.

By the time water leaves the fish room it has been transformed. It carries a broad nutrient load — ammonia, dissolved organics, suspended solids from waste and uneaten feed — mineral content shaped by the substrate, and an aeration profile that reflects the intensity of biological activity in the tank. It is rich, it is complex, and it is not yet ready for the plants. That is the refugium's job.

Section IV The Refugium — From Nutrient Load to Plant-Ready Water

The refugium is the stage that separates a functional aquaponic system from an optimized one. The concept is straightforward: add water column, add bacterial surface area, add controlled conditions, and let biology finish the work the fish room started. The implementation described here prioritizes broad accessibility — a version that can be built, understood, and maintained by anyone willing to learn the underlying biology.

The refugium needs to exist for two reasons: to add water column to the system, and to provide the bacterial filtration that converts raw fish room output into something plants can actually use. The room itself runs heavy with CO₂ and nitrogen compounds as a direct consequence of the bacterial processing happening inside it. Like the fish room, it is ventilated into the greenhouse — specifically into the finishing area — where that CO₂-rich, biologically warm air becomes an input to plant production rather than exhaust. Light is excluded completely.

Water entering the refugium arrives directly from the fish room. It is warm, oxygen-depleted relative to its condition at the cistern, loaded with ammonia and dissolved organics, carrying suspended solids, and mineral-rich from the sand and river rock substrate. Ammonia at this concentration is not yet a plant nutrient. It needs to move through the nitrogen cycle — ammonia to nitrite to nitrate — before the greenhouse can use it productively.

The refugium is a multi-tank sequence. Multiple tanks allow for bacterial diversity across different oxygen levels, temperatures, and media conditions. A single tank can run the nitrogen cycle. Multiple tanks run it better, and the differences between them encourage populations that would not thrive if the whole refugium were homogeneous. The specific tank configuration used here reflects years of iteration toward something that works reliably and can be built and understood by anyone.

Bacterial seeding is simpler than most new builders expect. Commercial products sold under names like Stress Zyme and similar aquarium store offerings will establish the colonies you need and they work fine. The faster and more reliable method is to find someone with a healthy established aquarium and offer to do a water change for them. Take their waste water and put it directly into your first refugium tank. A single gallon from a mature healthy aquarium carries a bacterial population dense enough to seed the entire refugium and begin establishing the nitrogen cycle immediately. Water from a healthy established pond works equally well. What you are looking for is a living system that has already done the work of selecting for the organisms you need. Nature has been running this experiment for a long time. You do not need a laboratory to access the results. A nose test and a quick basic aquarium water test will tell you everything you need to know about whether your bacterial population is healthy and working. If it smells like a healthy pond and the ammonia and nitrite numbers are moving in the right direction, you are on track.

Water leaving the refugium and entering the greenhouse is a fundamentally different product than what arrived from the fish room. Suspended solids have been reduced. Ammonia has been converted through the nitrogen cycle to nitrate — the form plants take up directly through their roots. The mineral profile has been processed across distinct biological environments. Dissolved oxygen is high. The water is not sterile — it is alive with the bacterial diversity that processed it — but it is balanced, plant-ready, and carrying the full nutrient value of everything the fish produced.

The refugium does not add nutrients to the system. It transforms the ones that are already there into a form the greenhouse can use. That distinction defines what can go wrong at this stage and how to read it. A refugium that is underperforming will show elevated ammonia and nitrite at the output. A refugium working correctly will show low ammonia, low nitrite, and nitrate levels that reflect the fish load upstream. When those numbers drift, the sequence tells you where to look.

Section V The Greenhouse — From Plant-Ready Water to Nutrient Cycling

This design will get you argued with by at least half of any room full of aquaponic practitioners, regardless of their discipline. It borrows from deep water culture, from soil growing, from Will Allen's foundational work on living soil systems, and from the practical reality that a system nobody can keep running is not actually a system. What follows is one of the easiest ways to guarantee a successful aquaponic greenhouse, and it works precisely because it refuses to be precious about methodology.

The primary grow system is deep flow beds, run deep. Eight inches of water column is the minimum. A foot is preferred. That water mass does more to regulate greenhouse temperature than almost any other single design decision — the thermal mass of a foot of water across a full greenhouse floor is substantial, and it moderates the swings between day and night that stress plants and destabilize chemistry. It is passive, it is free once built, and it works continuously without any management attention.

All but the top five inches of that water column is filled with river rock. Across the entire bed, layered just below the surface and concealed by the top rock layers, airstones are spaced on a six inch grid. Every square foot of bed has aeration directly beneath it. The water column is heavily oxygenated throughout, bacterial surface area is maximized by the rock, and the thermal mass of the combined water and rock volume gives the greenhouse a stability that no heating or cooling system alone can match.

The top four to five inches of open water column is where the crop lives. Here is where this design parts ways with conventional deep water culture, and where Will Allen's influence is direct: we use soil. Planters with perforated bottoms sit in the open water column. Each planter is based with two inches of river rock for drainage and weight, then filled with six inches of living soil. The soil is made from compost generated by the system itself — fish waste solids, plant material, the biological output of a closed loop that produces its own fertility. The planters sit in the aerated, nutrient-rich water. Roots grow through the perforated bottoms into the water column. The soil above provides biological complexity, moisture buffering, and a growing environment that most crops recognize as home.

This configuration has consequences that matter for anyone running a production system. Crop separation is built in — each planter is its own unit. Harvesting is simplified. Variety selection and market sorting happen at the planter level rather than the bed level. And the system carries a resilience that purely hydroponic designs cannot match: if you experience a complete fish kill, the soil biology in the planters continues to support plant growth while you diagnose and solve the problem upstream. The beds do not crash. Production continues. You fix the fish room on your own timeline rather than in a panic.

Any other hydroponic grow format operates directly off this system without modification. Drip lines drop a pump feed into the water column. NFT channels, vertical towers, additional grow tables — all of them draw from the same source. The deep flow bed is the backbone, and everything else hangs off it.

Aeration in the greenhouse draws from three sources simultaneously: pumps within the greenhouse itself, and the ventilation fed directly from both the fish room and the refugium. This is the convergence point of all the gas exchange design decisions made upstream. The CO₂-rich air from the fish room and the nitrogen-heavy air from the refugium enter the greenhouse and feed the plant canopy directly. The airstones in the beds drive dissolved oxygen into the water column from below. Gas exchange is maximized at every surface and in every direction.

The last corner of the greenhouse is a finishing area: a small duckweed and algae production zone fed directly by the gas lines from the fish room and refugium. Duckweed and algae are among the most efficient biological filters available — they strip residual nutrients from water that has already been through the main grow beds, they produce harvestable biomass that feeds back to the fish as a feed supplement, and they close the loop on nutrients that would otherwise accumulate in the system over time. Adjacent to this is a small testing tank that measures water quality at the end of the greenhouse cycle before it returns to the cistern. This is the final checkpoint — the last place to read the system before the water completes its circuit and begins again.

Section VI**Closing the Loop — The System as a Whole**

The water leaves the greenhouse testing tank and returns to the cistern. The cistern blends it with whatever the sky contributed since the last refresh. The fish room pump draws it up and delivers it to the tank, clean and oxygenated, and the fish begin converting it again. The refugium receives that output and transforms it. The greenhouse receives that transformation and turns it into food. The water returns to the cistern. This is the loop, and once you can hold the whole circuit in your head you can read any problem in the system by asking one question: where in the loop did the water change in a way it was not supposed to?

Each zone starts with a known water condition and does specific work to change it. The fish tank receives neutral water and loads it with biological output. The refugium receives that load and converts it through the nitrogen cycle into plant-available nutrients. The greenhouse receives those nutrients and strips them into food while returning cleaner, oxygenated water downstream. The cistern receives that return and conditions it for another pass. Every stage has a measurable input and a measurable output. When you know what those numbers should look like, the system tells you what it needs.

Hands-on monitoring will outperform equipment redundancy every time. A builder who walks the system daily, runs a basic water test at each checkpoint, uses their nose, watches the fish, and reads the plants will catch problems earlier and solve them faster than any automated sensor array. Sensors fail. Automated systems fail in ways that are sometimes harder to diagnose than the original problem. The person who knows their system intimately — who knows what healthy smells like, what stressed fish look like, what a plant showing nitrogen deficiency looks like versus one showing pH drift — that person is the most reliable instrument in the building.

Equipment redundancy is best applied not within a single large system but across multiple smaller ones. This is where the economics of aquaponics diverge from conventional agricultural logic. Economies of scale work against animal husbandry. A single very large system concentrates risk — one pump failure, one disease event, one chemistry crash affects everything simultaneously. Three modest systems running in parallel means that a failure in one is a problem to solve, not a catastrophe. Production continues. The fish in the other systems are fine. You have time to think.

The real failure points in this system are electromechanical. Air pumps and water pumps — and the sensors and controls that govern them — are where the system is genuinely vulnerable. If the air moves and the water moves, everything else has the conditions it needs to function. Water chemistry can drift and be corrected. A disease event in the fish room can be isolated and addressed. A crop failure in the greenhouse is a loss but not a system failure. All of these are phenomena separate from the mechanical operation of the loop. Keep the pumps running and you have time to solve everything else.

And the barrier to entry is lower than most people assume. If you can keep fish alive and manage a garden, you can run this system. Those two skills are the entire knowledge base. The biology does the rest.

The permaculture dimension of this design runs deeper than the ODI methodology used to develop it. This is a true closed system. The only nutrient input is fish feed. Buy it or grow it — that is the one external dependency. The sun drives photosynthesis. The biology drives the nitrogen cycle. The water carries everything from where it is produced to where it is needed and back again. The soil in the planters is made from what the system generates. The duckweed that finishes the water feeds back to the fish. Nothing leaves the loop except the food you harvest, and everything the system needs to keep running it produces itself.

That is the design. Observe the site, define the zones, follow the water, and let the biology work.

Document Information

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This document will be incorporated into River Refugium Project v3.0 and the Aquaponic Food Production System book (Relevant Irreverence).
