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RIVER REFUGIUM PROJECT Cernunnos Foundation Bright Meadow Group	**Appendix H — Metal and Micropollutant Sequestration Pathway** Document No: RRP0002-AppH │ Version: 1.0 │ 04 AUG 2026 0001 Status: Published — New document, issued against Series Version 2.0 │ Supersedes: None *Contact: robert@brightmeadowgroup.com │ www.cernunnosfoundation.com*

Abstract

Appendix H defines the metal and micropollutant sequestration pathway — an RRP deployment mode designed from the outset to remove trace metals, pharmaceutical residues, and organic micropollutants from water, rather than encountering them as a constraint on some other crop. It is the first pathway in the series whose product is the removal itself. Deployment is as a biosecure enclosed station: fully covered, wildlife-excluded, containment-designed, with planting prescribed from a site contaminant assay and every harvest routed by measured uptake. The appendix specifies the accumulator species set, a redox-sequenced treatment train that removes different contaminants by different mechanisms, a regenerable biosorption branch that elutes metals rather than burning them, the pharmaceutical and micropollutant capture case — the one contaminant class the framework can truly destroy — and the mercury, selenium, and PFAS exceptions that must be screened before a station is built. All uptake, sizing, and recovery figures are provisional literature proxies pending RRP pilot data per RRP8.

1. Position Within the RRP Framework

1.1 The Inversion

In Appendices E, F, and G, contamination is a constraint. Feed is disqualified by metals in tissue. Coppice accumulates them in recycled media and carries them into wood. Fiber tolerates them in the crop and inherits them in the char.

This pathway inverts that relationship. Contaminant capture is not a side effect to be managed — it is the product, and the biomass is the instrument.

Every design decision follows from that inversion. Species are selected for uptake rather than for yield. Planting is prescribed from a contaminant assay rather than from a market. Harvest timing is set by tissue loading rather than by maturity. And the station is enclosed, because concentrating contaminants in open water is a hazard rather than an achievement.

1.2 Four Pathways Compared

	E — Feed	F — Coppice	G — Fiber	H — Sequestration
Product	Protein	Durable wood	Fiber	The removal itself
Contamination is	Disqualifying	Accumulating	Tolerated	The objective
Siting driver	Clean water near livestock	Nutrient load	Worst tolerable water	Known contaminant artifact
Enclosure	Optional	Optional	Climate-driven	Mandatory (§2)
Revenue basis	Layer 1 + 5	Layer 1 + 4	Layer 1 + 5	Layer 5 + 7 — paid to

				exist (§12)

Table H-1. *The sequestration pathway is the first in the series whose revenue does not depend on selling the biomass.*

1.3 Relationship to Existing Series Documents

Document	Relationship to Appendix H
RRP3	Biofiltration train. The redox train in Section 6 is a parallel branch, not an extension — sulfate reduction and nitrification cannot share a vessel. See §6.6.
RRP5	Thermochemical processing. Destroys the organic micropollutants of Section 8 and concentrates the metals of Section 6. Two opposite outcomes in one reactor.
RRP7	Governance. This pathway introduces residual waste classification and wildlife protection obligations not present elsewhere in the series.
RRP8	Governing document for measurement. Contaminant assay and tissue loading verification in Section 4 are additive to Axis 2 and Axis 3.
Appendix A	Site Selection Matrix. The Trace Metal Review proposed in Appendix E §8.5 becomes the primary siting instrument for this pathway rather than a supplement.
Appendix E §8	Dispersal-is-the-damage framework and the six recovery review criteria. Apply without modification.
Appendix G §8	Metals do not burn. Governing statement for all char and ash disposition in this pathway.

2. The Biosecure Station

A metal sequestration deployment is not a pond. It is an enclosed, access-controlled treatment station built with intent, and the enclosure is a design requirement rather than a refinement.

Why Enclosure Is Not Optional

In the early 1980s, agricultural drainage in California's San Joaquin Valley was routed to evaporation ponds at Kesterson Reservoir. The drainage carried selenium. The ponds concentrated it, aquatic vegetation and invertebrates accumulated it, and waterfowl fed on them. The result was mass mortality and embryo deformity, a federal intervention, and a precedent that anyone evaluating this pathway will reach for immediately.

An open pond of metal-laden floating plants is a feeding station that concentrates contaminants precisely where wildlife will encounter them. Any deployment that does not exclude wildlife is not a remediation facility. It is a delivery mechanism.

2.1 Mandatory Design Elements

- Full enclosure or exclusion netting over every open water surface. No exceptions for temporary or pilot installations.
- Physical containment of all plant material, with attention to fragment escape. Several accumulator species propagate from fragments carried on equipment, boots, or waterfowl.
- Access control and signage. Harvested biomass in this pathway is a contaminated material and should be handled as one.

- Contained drainage and secondary containment. A station holding concentrated metals must not discharge on failure.
- Separate handling, storage, and equipment from any food, feed, or textile pathway operating on the same site. Cross-contact between an H station and an E pathway is a categorical failure.

2.2 Species Exclusions on Regulatory Grounds

Several of the strongest documented aquatic accumulators are listed noxious weeds under federal or state law. Water hyacinth, salvinia, water lettuce, and the invasive haplotype of common reed are excluded from this framework entirely, regardless of measured performance.

The reasoning is not that containment could not be engineered. It is that a pathway whose regulatory case depends on containing a listed noxious weed has imported a permitting and liability problem large enough to consume the project. The species set in Section 5 is deliberately limited to material that can be cultivated without that argument.

3. Assay Before Planting

Planting is prescribed, not chosen. The site contaminant assay determines the species set, the train configuration, the harvest schedule, and the disposition route before anything is planted.

3.1 The Prescription Sequence

- Characterize the artifact. What is actually in the water, at what concentration, in what chemical form, and with what seasonal variation. Speciation matters as much as concentration — arsenite and arsenate behave differently, and hexavalent chromium is not trivalent chromium.
- Identify the source. A smelter fallout signature, a mine drainage signature, an urban stormwater signature, and a wastewater outfall signature call for different trains and different species.
- Screen the exceptions. Mercury and selenium require the special handling in Section 9 and can change the entire design. PFAS changes the disposition case entirely per §8.4.
- Set the objective. Remediation to a target concentration, or recovery of a specific element, or both. These produce different harvest schedules — see §3.2.
- Prescribe the planting and the train. Species by contaminant affinity, cells by removal mechanism, harvest interval by expected tissue loading.

3.2 Two Harvest Objectives, Two Schedules

	Remediation Objective	Recovery Objective
Goal	Maximum mass removed from water per unit time	Maximum concentration in harvested material
Harvest timing	Frequent — crop held in rapid growth phase, where uptake rate is highest	Delayed — crop held to tissue saturation, accepting slower growth for higher grade
Output character	High volume, low grade. Disposition cost dominates.	Low volume, high grade. Recovery value may be realizable.
Typical driver	Regulatory target, permit condition, or public remediation contract	Recovery-interest metal identified under Appendix E §8.3

Table H-2. *The two objectives conflict. A station must be operated to one or the other in a given cell, and a site running both must zone for it.*

The conflict is real and is stated here rather than elided. Rapid uptake and high tissue concentration are not achieved by the same operating regime, and a station attempting both in one cell will do neither well.

4. Verification

Additive to RRP8 Axis 2 and Axis 3. Three measurement layers are required and none substitutes for another.

- Water, at station inlet and outlet, per contaminant of concern with speciation where relevant. This is the removal claim.
- Tissue, at every harvest event, by species and by cell. This is the uptake record and it drives disposition routing. Water data does not predict tissue loading — the enrichment factor is the unknown the pathway exists to measure.
- Residual, on char, ash, sludge, or eluate. This is the disposition determination and the regulatory classification per Section 11.

Mass balance across the three layers is the integrity check. Contaminant that leaves the water and does not appear in tissue or residual has gone somewhere unaccounted for, and in the case of selenium and mercury the unaccounted destination may be the atmosphere. See Section 9.

5. Accumulator Species

5.1 Azolla

Azolla filiculoides, A. caroliniana, A. pinnata. A floating aquatic fern in obligate symbiosis with a nitrogen-fixing cyanobacterium housed in its leaf cavities. It doubles biomass in a matter of days under warm conditions and has documented uptake across cadmium, chromium, copper, nickel, lead, zinc, and uranium. ⚑ PROVISIONAL

Two properties make it the lead species for this pathway. The growth rate delivers rapid, repeated harvest cycles, which suits the remediation objective in §3.2. And the nitrogen-fixing symbiosis means it does not require the nutrient load the rest of the framework is built around — it performs on water that is contaminated but not especially fertile, which is common in mine-influenced and industrial reaches.

That second property is also the same irony noted for black locust in Appendix F §3.2 and stated plainly here: the best metal worker in the set has the least appetite for the nutrient. Azolla cells should not be relied on to carry a Layer 5 nutrient removal claim.

5.2 Lemna and Wolffia

Common duckweed and watermeal, defined as Class F-1 in Appendix E §3.1 and used there for protein. In this pathway they are used for the property that disqualifies them there — aggressive accumulation of cadmium, lead, arsenic, chromium, copper, and zinc from dilute solution.

They bring high nutrient appetite, which makes them the species of choice where the contaminated water is also nutrient-loaded, and they permit a station to carry both a metal removal claim and a nutrient removal claim from the same cell.

Absolute rule: Lemna or Wolffia harvested from an H station never enters an E pathway. Not as feed, not as compost, not as a stocking source. The species is identical and the material is not. Physical separation of stock, equipment, and handling between pathways is required per §2.1.

5.3 Vetiver

Chrysopogon zizanioides. A perennial bunch grass with an exceptionally deep and dense root system, extensively used worldwide for erosion control, mine site rehabilitation, and phytoremediation. It tolerates extreme pH, high metal loading, and prolonged saturation, and it can be grown in floating or hydroponic configuration rather than in soil.

Its decisive advantage in this framework is regulatory rather than botanical. The cultivars used in commercial phytoremediation are sterile — they do not set viable seed and propagate only by root division. That solves the invasiveness problem in Section 2.2 by genetics rather than by containment engineering, which is a materially stronger position in front of a permitting authority.

Vetiver's root mass also makes it the structural species of the set. Where azolla and duckweed are surface films harvested by skimming, vetiver builds a persistent root volume that functions as both uptake surface and physical substrate. It is the species that anchors a long-duration cell.

Sterile cultivar identity must be verified at purchase and documented at the site level. ⚑ PROVISIONAL — vetiver performance under RRP culture is unmeasured.

5.4 Submerged Species

Coontail (Ceratophyllum demersum) is a rootless submerged macrophyte and therefore a pure water-column accumulator — everything it takes up comes from the water rather than from sediment. Elodea, Vallisneria, and Potamogeton species serve similar roles. These species extend uptake into the water column beneath a surface film crop and are useful where contaminant concentration is low and residence time is long.

5.5 Species Reference

Species	Position	Documented Affinity	Nutrient Appetite	Harvest Method
Azolla	Floating film	Cd, Cr, Cu, Ni, Pb, Zn, U ⚑	Low — fixes its own nitrogen	Skim; days to weeks
Lemna / Wolffia	Floating film	Cd, Pb, As, Cr, Cu, Zn ⚑	High — carries Layer 5 claim	Skim; days to weeks
Vetiver	Rooted / floating raft	Broad tolerance; Pb, Zn, Cu, Cd, As ⚑	Moderate	Cut and root division; months
Coontail and submerged spp.	Water column	Broad cationic uptake ⚑	Moderate	Rake or net; weeks
Aquatic moss and filamentous algae	Biosorption bed — §7	Very high; used as metal biomonitors ⚑	Low	Bed regeneration rather than harvest
⚑ **PROVISIONAL:** *Affinity listings indicate documented uptake in published literature, not measured RRP performance, and do not imply comparable efficiency across metals or conditions. Enrichment factors are species-, metal-, pH-, and competing-ion dependent and are the primary measurement target of this pathway per Section 4.*				

Table H-3. *Accumulator species set. Selection is prescribed from the site assay per Section 3, not chosen from this table directly.*

6. The Redox Train

Plants are one removal mechanism among several, and for some contaminants they are not the important one. A station designed only as a planting will underperform badly on arsenic and on the classic mine-drainage metal suite.

The train below sequences cells by redox condition, because each condition removes a different set of contaminants by a different mechanism.

Cell	Condition	Mechanism	Targets
M-1	Aerobic — iron oxidation	Dissolved iron oxidizes to ferric oxyhydroxide, which adsorbs and co-precipitates other species onto the floc as it forms	Arsenic principally — this is how arsenic is actually removed, not by plant uptake. Also phosphorus and several co-precipitating metals.
M-2	Aerobic — planted	Biological uptake into harvestable tissue per Section 5	Cationic metals; nutrient load; organic micropollutants per Section 8
M-3	Anoxic — sulfate reducing	Sulfate-reducing bacteria in an organic substrate generate sulfide; metal sulfides are extremely insoluble and drop out as a stable sludge	Cd, Cu, Zn, Pb, Ni. The heavyweight cell for mine-influenced water. ⚠️ Mercury exception — see §9.1.
M-4	Alkalinity and pH	Carbonate dissolution raises pH; most metals precipitate as hydroxides and carbonates as pH rises	Broad. Also restores alkalinity consumed upstream. See §6.2.
M-5	Aerobic — polishing	Re-aeration, residual uptake, biosorption bed per Section 7	Residual metals; dissolved sulfide removal before discharge
⚑ **PROVISIONAL:** *Cell sizing, retention times, substrate composition, and sequencing for RRP deployment are unestablished. The mechanisms are drawn from passive mine drainage treatment and constructed wetland practice, where they are well demonstrated at field scale but not in combination with the RRP nutrient train.*			

Table H-4. *Redox-sequenced treatment train. Cells may be omitted where the site assay does not warrant them, but sequence is not arbitrary.*

6.1 Sequence Matters

Iron oxidation precedes sulfate reduction because iron floc removed early does not later armor the alkalinity media. Polishing follows sulfate reduction because an M-3 cell effluent carries residual dissolved sulfide that must not reach discharge. Planted cells sit where the water is aerobic and the contaminant is in a plant-available form.

6.2 A Direct Contradiction With Appendix F, Stated Deliberately

Appendix F §4.2 prohibits limestone and carbonate media in the coppice channel. Cell M-4 specifies carbonate media on purpose. Both are correct.

In a nitrifying channel, carbonate dissolution buffers pH upward in an uncontrolled way and fights the alkalinity chemistry the biofilter depends on. In a metals cell, that same upward pH shift is the removal mechanism. The specification is opposite because the objective is opposite.

This is why the metals train is a physically separate branch and not an addition to the refugium. A reader encountering the two specifications without this note would reasonably conclude the series contradicts itself.

6.3 Separation From the Nutrient Train

Sulfate reduction is obligately anaerobic. Nitrification is obligately aerobic. Denitrification in an anoxic cell consumes the nitrate the rest of the framework exists to capture and sell.

The metals train is therefore a parallel branch with its own redox regime. Water is routed through it or bypasses it as a routing decision, and the two trains do not share vessels. A site running both is running two systems that happen to share an intake.

7. Biosorption — The Regenerable Branch

Biosorption is metal binding to functional groups on cell wall material — carboxyl, hydroxyl, and amine sites. It is a physicochemical process rather than a metabolic one, which produces a property with significant consequences for this pathway.

Dead biomass works. Biosorption does not require the organism to be alive, which means a packed bed of dried algal or moss material sorbs metals from flow with no cultivation, no light, and no nutrient demand.

7.1 Materials

- Aquatic mosses, particularly Fontinalis species, which are standard biomonitors for metals in surface water precisely because they concentrate so strongly.
- Filamentous algae — Cladophora, Spirogyra — which are frequently a nuisance crop elsewhere in the framework and a resource here.
- Surplus or off-spec biomass from any pathway, dried and packed. A biosorption bed is a terminal use for material that has no other route.

7.2 Elution and Regeneration

A loaded bed is eluted with dilute acid or a chelating solution. The metal comes off in a small volume of concentrated liquid; the bed is rinsed and returned to service for multiple cycles.

This is a fundamentally better endpoint than thermochemical processing for recovery purposes. The output is a concentrated metal solution rather than a metal-bearing ash, which is closer to a form a refiner will accept, avoids the ash classification problem in Appendix G §8.1, and does not consume the biomass.

Constraints are real. Elution generates an acidic metal-bearing liquid that must be handled and neutralized or processed. Bed capacity declines with cycling and the material eventually becomes a disposal item. Selectivity is limited, so mixed-metal water produces mixed eluate. And bed fouling by solids and biofilm is the practical failure mode. ⚑ PROVISIONAL — cycle life, capacity, and elution economics under RRP conditions are unmeasured.

7.3 Where It Fits

Biosorption suits the recovery objective in §3.2 and the M-5 polishing position, where concentrations are low, plant uptake is inefficient, and the target is a specific recovery-interest element rather than bulk removal.

8. Pharmaceutical and Organic Micropollutant Capture

The accumulator species in Section 5 do not restrict themselves to metals. The same uptake behavior draws in dissolved organic micropollutants — pharmaceutical residues, hormones, antibiotics, and personal care product compounds — which are present in exactly the water this pathway is sited on: reaches downstream of wastewater treatment outfalls, urban stormwater, and livestock operations.

Conventional wastewater treatment was not designed to remove these compounds and largely does not. They pass through to the receiving water at low concentration and persist there.

8.1 The One Class the Framework Can Actually Destroy

Appendix G §8 states that metals do not burn. The corollary is the opportunity in this section: organic molecules do.

Every other contaminant in this framework is concentrated, relocated, and eventually handed to someone as a residual. Pharmaceutical and micropollutant capture is different in kind. Hydrothermal processing operates at temperatures and residence times that break organic molecules apart, which means the capture-and-process sequence is a genuine destruction endpoint rather than a transfer.

- Accumulator biomass strips the compound from dilute water into tissue.
- Biomass routes to HTL per RRP5.
- The compound is destroyed in the reactor rather than concentrated into the residue.
- No downstream contaminated product results, and no receiving party inherits the problem.

Antibiotic resistance genes, a growing concern in these same waters, are subject to the same thermal destruction.

8.2 Why This Matters for the Pathway's Case

A metals station makes a difficult argument: it moves a contaminant from a place where it is dispersed to a place where it is concentrated, and someone must then hold it. That argument is defensible — Appendix E §8.1 makes it — but it is not clean.

The micropollutant case is clean. The compound enters the water, enters the plant, enters the reactor, and ceases to exist. There is no residual to classify, no buyer to find, and no party left holding anything. For a station sited downstream of a wastewater outfall, this may be the more valuable of the two functions and it should be measured and reported alongside the metals removal rather than treated as incidental.

8.3 Verification Requirements

Claiming destruction requires demonstrating it rather than assuming it. Three measurements, additive to Section 4:

- Compound concentration in water at inlet and outlet — the capture claim.
- Compound concentration in harvested tissue — confirms uptake rather than degradation in the water column, which would be a different and less controlled outcome.
- Compound and transformation product concentration in the HTL aqueous phase and solid residue — the destruction claim. Partial breakdown into a transformation product is not destruction, and the aqueous phase is recycled within the node, which means an incompletely destroyed compound returns to the front of the system.

8.4 PFAS Is the Exception and Must Be Screened

PFAS Does Not Follow This Logic

Per- and polyfluoroalkyl substances are organic compounds, but the carbon-fluorine bond is among the strongest in organic chemistry and PFAS compounds are not reliably destroyed at hydrothermal processing conditions. Destruction requires substantially more aggressive treatment than HTC or HTL provide.

A PFAS-bearing site therefore behaves like a metals site rather than a pharmaceutical site: the compound is concentrated into biomass and then into residue, and the residue becomes a disposal question with an evolving and increasingly stringent regulatory framework.

PFAS screening is mandatory at the assay stage per §3.1 and is a siting decision, not an operating detail. A station built on the destruction case and then found to be concentrating PFAS has inherited a liability rather than solved a problem.

9. Special Cases

9.1 Mercury — The Sulfate Reduction Conflict

The M-3 Cell Is Also an Ideal Methylation Reactor

Sulfate-reducing bacteria are the principal agents of mercury methylation in the environment. The same organisms that precipitate cadmium, copper, zinc, and lead as insoluble sulfides convert inorganic mercury into methylmercury — a compound that bioaccumulates through food chains and is far more toxic than the mercury that entered.

A sulfate-reducing cell built on mercury-bearing water is therefore capable of producing a worse contaminant than it removes. This is not a marginal risk; it is the central mechanism by which mercury becomes dangerous in aquatic systems.

Mercury screening is mandatory before any M-3 cell is designed. Where mercury is present, the correct response is to omit sulfate reduction entirely and remove the remaining metals by other cells, accepting reduced performance in exchange for not manufacturing methylmercury.

9.2 Selenium — Removal by Volatilization

Selenium behaves unlike the other elements in this pathway. Plants and associated microorganisms convert it biologically to volatile methylated forms that leave to the atmosphere. This is genuine removal rather than concentration — the selenium does not accumulate in a residual anyone must hold.

Whether that is elegant or objectionable depends entirely on who is asking. It is a real removal mechanism with a substantial literature behind it, and it is also an uncontrolled release to air from an enclosed facility, which is a category regulators are entitled to have views about.

The position taken here is disclosure. Volatilization is documented as a removal mechanism, mass balance per Section 4 will show selenium leaving the water without appearing in tissue or residual, and that gap must be reported as volatilization rather than left as an unexplained discrepancy. An enclosed station's ventilation path is the relevant emission point and should be identified as such. ⚑ PROVISIONAL — volatilization rates and any applicable air permitting threshold are unassessed.

Selenium is also the Kesterson contaminant. A selenium-bearing site is the exact scenario that produced the precedent in Section 2, and enclosure and wildlife exclusion are not negotiable on such a site under any circumstances.

10. Disposition

Three terminal routes exist for loaded biomass, and the site assay and objective determine which applies.

Route	Product	Determining Factor

H-1 Elution	Concentrated metal solution from a regenerated biosorption bed per §7.2	Recovery objective, single dominant recovery-interest metal, buyer access. The best available endpoint where it applies.
H-2 Thermochemical	Metal-bearing char or ash; organic micropollutants destroyed in the same operation	Default route for plant biomass. Char classification governs everything downstream per Appendix G §8.1.
H-3 Stabilized residual	Metal sulfide sludge from M-3, and any residual failing recovery criteria	Regulatory classification and leachate testing. This is a managed disposal item, and the cost is a line in the project, not a surprise.

Table H-5. *Disposition routes. H-3 is not a failure condition — for most remediation sites it is the expected outcome and should be budgeted as such.*

10.1 Honesty About the Endpoint

Appendix E §8.1 establishes that concentration converts an unrecoverable dispersal into a defined stream with options, and that this is worth doing whether or not a sale results. That position holds here and is the pathway's foundation.

It should not be inflated. On most sites the metals will not clear the recovery criteria in Appendix E §8.3, the residual will require managed disposal, and the value delivered is the removal rather than the material. A station financed on anticipated metal sales will disappoint. A station financed on remediation performance will not.

11. Economics

11.1 Paid to Exist

This is the first pathway in the framework whose revenue does not depend on selling the biomass. Its outputs are a measured reduction in contaminant concentration, a documented mass removed, and a published data record.

- Layer 5 — water quality credits and contract remediation payments. The primary revenue line, and unlike the other pathways it is not secondary to a product sale.
- Layer 7 — productized side-streams, where an H-1 eluate finds a buyer.
- Layer 8 — environmental data. Substantial here, because contaminant-specific removal datasets under controlled conditions barely exist and have direct research and regulatory value.
- Layer 1 — largely absent. Biomass is a residual to be managed rather than a product to be sold.

11.2 The Funding Category Is Different

E, F, and G are agricultural propositions and can be funded as such. This pathway is a remediation proposition and belongs to a different funding world — environmental remediation programs, consent decree obligations, watershed restoration funds, mine reclamation programs, and responsible-party liability. Those sources are frequently larger and less price-sensitive than agricultural funding, and they are procured differently.

Cost structure is dominated by enclosure capital, laboratory analysis, and residual disposal rather than by growing operations. Analysis in particular is a heavier and more continuous cost than in any other pathway, because the removal claim is the product.

12. Deployment Scales

12.1 Scale H-1 — Single Contaminant Station

One enclosed cell, one dominant contaminant identified by assay, one or two species, planted cells only with no redox train. Suits a defined agricultural or single-source contaminant on a small flow. This is the entry configuration and the one that will generate the first enrichment factor data.

12.2 Scale H-2 — Full Redox Train

Sequenced M-1 through M-5 cells with planted stages and an M-4 alkalinity cell, sized to a characterized mixed-metal water such as mine-influenced drainage. Adds the residual handling and classification regime in Section 10 and the mercury screening gate in §9.1.

12.3 Scale H-3 — Outfall Micropollutant Station

Sited downstream of a wastewater treatment outfall and operated primarily for the Section 8 destruction case, with metals capture secondary. Planted cells and biosorption polishing, biomass routed directly to HTL. Requires the verification regime in §8.3 and PFAS screening per §8.4. This is the configuration with the cleanest environmental argument in the entire framework.

12.4 Scale H-4 — Recovery Station

Operated to the recovery objective in §3.2 with biosorption and elution as the primary route, on a site where the assay identifies a single dominant recovery-interest element at sufficient throughput. The least likely configuration and the one that must clear every criterion in Appendix E §8.3 before it is proposed.

13. What the Pilot Must Prove

- Enrichment factors by species, metal, pH, and competing ion load under RRP conditions — the central unknown of the entire pathway.
- Whether tissue loading tracks water concentration predictably enough to schedule harvest, or whether direct tissue measurement is required at every event.
- The remediation-versus-recovery trade-off curve in §3.2 — how much grade is lost per unit of uptake rate gained.
- Azolla performance on low-nutrient contaminated water, where its nitrogen fixation should be decisive.
- Vetiver performance in floating and hydroponic configuration, and sterile cultivar behavior over multiple seasons.
- M-3 sulfate-reducing cell substrate composition, sizing, and longevity before substrate replacement is required.
- Biosorption bed capacity, cycle life, elution efficiency, and fouling behavior.
- Pharmaceutical uptake rates into tissue by compound class, and confirmed destruction — not merely disappearance — in the HTL solid and aqueous phases.
- Transformation product formation in HTL processing of micropollutant-loaded biomass, and aqueous phase recycling behavior.
- Selenium volatilization rates and whether any air permitting threshold is engaged.

- Residual leachate classification across representative site types — the number that determines disposal cost and therefore project viability.

14. Provisional Status

⚑ **PROVISIONAL —** All uptake figures, enrichment factors, cell sizing, retention times, biosorption capacities, and destruction efficiencies in this appendix are drawn from published literature in phytoremediation, passive mine drainage treatment, and constructed wetland practice, or are unestablished. None has been measured under RRP conditions. This pathway makes claims about contaminant removal that carry regulatory and public health consequences, and no figure in this document should be relied upon for a permit application, a remediation performance commitment, a disposal classification, or a public health determination without site-specific measurement.

Closing Note

The other pathways in this framework grow something and remove contaminants while they do it. This one removes contaminants and grows something because that is how the removal happens.

It is the pathway with the least appealing product and the most defensible purpose. Most of what it produces is a residual somebody has to hold, and the honest version of the argument is that holding a defined, assayed, contained residual is better than leaving the same material dispersed through a watershed where nothing can recover it and everything is exposed to it.

The exception is Section 8, and it may be the most important paragraph in the series. Pharmaceutical and micropollutant capture is the one place where the framework does not relocate a problem. The compound enters the water, enters the plant, enters the reactor, and is gone. Nobody inherits it. That is worth building a station for on its own.

Notes

Citations follow Chicago Notes-Bibliography style. Internal Bright Meadow Group / Cernunnos Foundation documents are cited by document title and year. Figures marked ⚑ are provisional proxies pending replacement by RRP pilot data per RRP8. Regulatory and public health references are provided for orientation and do not constitute legal, permitting, or public health advice.

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