SSRZD PBL Final Report: Lake Erie Eutrophication Solution

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Problem

In the late 1960s, high volumes of toxic algal blooms earned Lake Erie its infamous title: “the dead lake,” (Rotman 2022) becoming the poster child for ecological collapse. These conditions were triggered by eutrophication—dangerously high levels of particulate phosphorus (P)—from untreated wastewater and industrial discharge, absorbing into sediment particles (Carlson & Simpson 1996). Despite multiple legislative binational attempts following its first collapse, Lake Erie has reclaimed its reputation; largely due to today’s agricultural practices that now deliver increased amounts of soluble reactive P (SRPs) to the lake (Michalak et al. 2013).

Today, harmful algae blooms (HABs) in Lake Erie are overwhelmingly composed of toxin-producing cyanobacteria that prefer warmer waters and feed off SRPs. Modern agriculture has boosted SRP runoff via tile drainage systems—underground pipes that rapidly extract excess water from fields but bypass natural soil filtering—thus delivering the most readily usable form of P directly to cyanobacteria (Watson et al. 2016). Spring rains and snowmelt then deliver a major surge of SRPs preceding the onset of summer season, allowing Lake Erie to enter warm months already primed for extensive blooming.

As blooms overpopulate and die, the sinking organic matter is decomposed by bacteria; an oxygen-consuming process that triggers hypoxia (lack of usable oxygen) (Pennuto et al. 2014). Low oxygen converts iron (III) in sediment—which normally binds phosphorus—to iron (II) which cannot do the same; this leads to internal loading—the release of internally-stored phosphorus back into the water. A reinforcing feedback loop is thereby created where hypoxia fuels further phosphorus release, sustaining blooms even when external inputs are reduced.

When oxygen levels crash, aquatic organisms are severely stressed and many ultimately suffocate, triggering cascading population declines throughout the ecosystem. Meanwhile, toxins released by cyanobacterial blooms can contaminate drinking water and overwhelm water treatment systems with algal clogs—thus posing health risks to anyone consuming Erie's drinking water (Scavia et al. 2014).

Comparable examples of Lake Erie's conditions include Lake Winnipeg (Government of Canada 2013) and the Baltic Sea region (Kleinman et al. 2015). Implementation of Best Management Practices (BMPs) were used, i.e. incorporation of buffer strips, wastewater treatment, cover crops—and success varied. This led to two important discoveries: BMPs work best for particulate—not soluble—P and even critical improvements in wastewater treatment cannot meaningfully reduce cyanobacteria blooms, because sewage was never the main driver—agricultural runoff was. Overall, these outcomes show that traditional BMPs, while valuable, cannot fully address today's SRPs-driven blooms—meaning that Lake Erie, like these regions, will require solutions that move beyond conventional methods to tackle today's eutrophication.

Solution

While legislation was an effective solution, it could not sustain the indirect P agricultural runoff that would follow in the 1980s (Scavia et al. 2014). Given these limitations, addressing re-eutrophication will require a more evidence-based and biologically grounded intervention able to target ~~soluble~~ SRPs directly. One such approach is the development of faux wetlands (Figure B1) combined with the use of specifically selected bacteria capable of outcompeting the cyanobacteria.

Faux wetlands are made to imitate the benefits that natural wetlands provide in large bodies of water. In essence, wetlands are patches of land between terrestrial and aquatic systems that provide flood attenuation, pollutant reduction, carbon storage, and wildlife refuge (Abouali et al. 2017). Additionally, these ecosystems are particularly useful for their ability to remove P from water through peat accretion, adsorption, and plant-microbial uptake (Vymazal 2007). Peat accretion begins with the accumulation of partially decomposed organic material, or peat, which drives carbon sequestration by capturing and storing atmospheric CO_2 for long-term storage. Consequently, this develops layers of soil that P from nearby water binds to, effectively burying it (Craft & Richardson 2022). This accounts for the adsorption stage in the cycle. Moreover, some P remains dissolved and is used by the wetland's vegetation (Bhomia 2018). This uptake supports plant growth and the general health of the wetland, which could be harvested for other industrial applications to restart the cycle and enable additional P removal.

Overall, the reliability of faux wetlands is supported by their growing popularity. Currently, faux wetlands are operating successfully in regions such as the Everglades, which have faced eutrophication under circumstances like Lake Erie's (Zhao & Piccone 2020; Craft & Richardson 1993). By showing high P retention after two decades of continuous P loading (Karjalainen 2018), these structures prove to be a long-term solution to eutrophication. However, while faux wetlands effectively remove particulate P through precipitation and uptake, they display clear limits in their ability to remove SRP under Lake Erie's loads (Kadlec 2016). Because SRPs oversee cyanobacteria growth, this limitation creates the need for a complimentary solution—one which targets the algae itself.

Currie and Kalff (1984) show that bacteria are remarkably superior at sequestering P, a function that is particularly relevant to the *Bacillus* genus. These are extremely resilient, rod-shaped aerobic bacteria capable of living in diverse environments (Turnbull 1996), making them excellent candidates for targeted P removal. Interestingly, many of these bacteria strains, such as *Bacillus subtilis*, also secrete biodegradable polymers (Salepe & Maliehe 2024) that due to their safety and effectiveness have been identified as flocculant alternatives (Maliehe et al. 2019). This positions bio flocculants as superior to both organic and inorganic flocculants, which—although effective—have been linked to dangerous neurotoxic effects (Okaiyeto et al. 2016). Moreover, since bio flocculants work well across 5–40°C (Shahadat et al. 2017) they could be deployed in spring to help curb the extensive summer blooms.

With functional groups such as amines, hydroxyls and carboxyls, algae and SRP molecules chemically bind to the bio flocculants during charge neutralization interactions (Kurniawan 2022). These interactions create larger aggregates of particles called flocs (Figure B2), which then settle and can be physically removed from the water (Madkour et al. 2017). Thus, by increasing the lake's *Bacillus* concentration within the controlled faux wetland systems, it is posed that the cyanobacteria's food source would be substantially compromised without other species being impacted.

In conclusion, combining faux wetlands and bioflocculant-producing *Bacillus* creates an innovative and biologically grounded solution that addresses both particulate and dissolved P. Together, these interventions could limit nutrient abundance to restrict HABs, supporting the long-term restoration of Lake Erie.

Implementation of Solution

Engineered wetlands of approximately 20,000 hectares will be constructed along the Maumee River and other major western-basin tributaries, making up Lake Erie's most eutrophic region (Kadlec 2016). They will be built on clay-rich floodplain soils, retaining large water volumes and promoting high cation exchange capacity, leading to permanent P burial (Abouali et al. 2017). Moreover, emergent vegetation, particularly *Typha latifolia* macrophytes, will be used for their high-performance during P removal (Maucieri et al. 2020).

Construction in the first three years will be managed by the U.S. Army Corps of Engineers, along with Ontario conservation authorities, using the existing Great Lakes Restoration Initiative (GLRI) and Canada-Ontario Lake Erie Action Plan funds. Land will be acquired through voluntary farmer easements, agreements where farmers keep ownership, yet allow wetland restorations, following similar steps to those successfully implemented in the Everglades model (Zhao & Piccone 2020).

Bacillus subtilis strains will be added seasonally using biodegradable capsules containing the bacteria. These will be sprayed onto the wetland surface starting the second year, which slowly dissolve and release bacteria over time (Maliehe et al. 2019).

Based on Kadlec's research (2016), the total capital cost approximates $1.2-1.8 billion, which will be funded by existing budgets over the first six years, supplemented by a small fertilizer fee imposed on commercial fertilizer distributors and large agricultural suppliers. Annual operating costs after the sixth year are estimated to be less than $40 million and will be largely offset by avoided water-treatment costs. This long-term solution will continuously remove approximately 40-70% of incoming SRPs for decades, ending the internal loading cycle and future eutrophication.

Effectiveness Assessment

A concrete way to measure the success of the plan is to compare it with the solution implemented during the 1970s, the Great Lakes Water Quality Agreement, and analyze the similarities and differences. To ensure that the solution is effective and successful, it must have an equal or increased beneficial result relative to the Great Lakes Water Quality Agreement.

To best assess the faux wetlands' productivity, Abouali et al. (2017) bolsters a Total Phosphorous (TP) and Total Nitrogen (TN) concentration (mg/L) evaluation to be conducted by examining the initial TP inflow and the final TP outflow. This will allow calculation of the phosphorus being captured in the instituted faux wetlands.

The success of the implementation of the *Bacillus subtilis* will be based on the magnitude of algae removed from the lake. This should be a similar amount of removal in comparison to the extraction of the 1970s. Flocculation will be more direct and fast-acting, while also remaining sustainable and cheap, as Tripathi et al. (2024) found that algae harvesting through centrifugation (1970s) utilizes 3.3 Kilowatt hours per cubic meters whereas bio-flocculation requires zero power to function.

The interval of when to analyze the TP essential in concluding how effective the solution is in the short term, while also ensuring that it has greater longevity than the Great Lakes Water Quality Agreement. It is essential to take an initial measurement of the TP within Lake Erie for frame of reference to compare with the final dissolved concentration that remains in the lake after the *Bacillus subtilis* implementation. Regarding the faux wetlands, the ability to contain TP runoff should be assessed on an annual basis, as the wetlands' capacity will gradually decrease as greater amounts of P seep into its' soil. It is critical to note that potential natural disasters, i.e. floods and mudslides, will give substantial reason for a re-assessment due to their damaging effects on the constructed wetlands.

Biological Ramifications

While the proposed solution aptly targets P removal, dramatically increasing one microbe's concentration presents serious ecological consequences within the faux wetlands. As existing bacteria within the wetland ecosystem neutralize individual efforts through competition for nutrients and space, the current solution can potentially disrupt this balance. By aggressively outcompeting other species, the ecosystem is prone to ecological disruption due to reduced diversity. Destabilizing the wetland's microbial ecosystem could result in weakened resilience to stress, such as pollutants or temperature changes (Wang et al. 2022), due to loss of functional redundancy—when one bacterium fails, another can step in to sustain the ecosystem function.

Appendix A: The Problem – A Cycle of Eutrophication

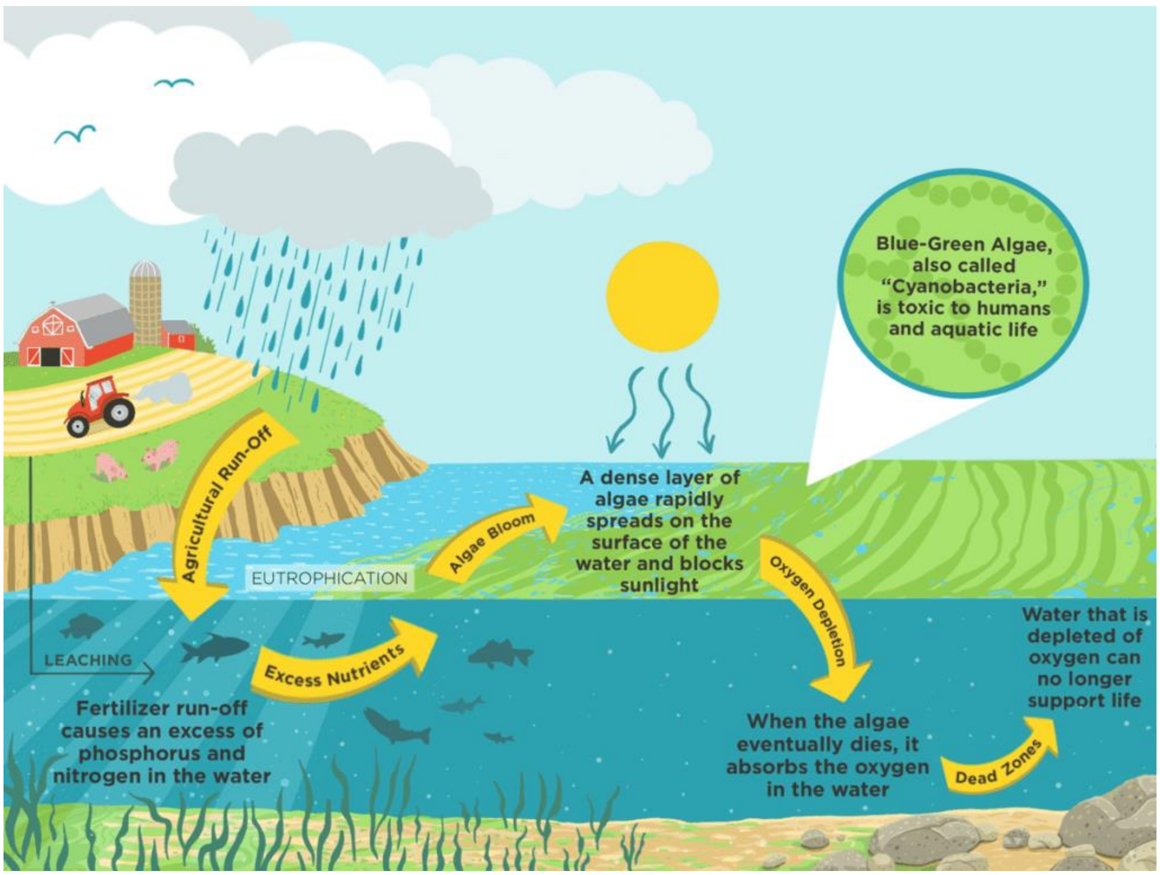

Figure A1

Comprehensive diagram reveals how excess growth of algae leads to eutrophication and death of aquatic organisms (Woodhouse 2023).

Appendix B: The Solution

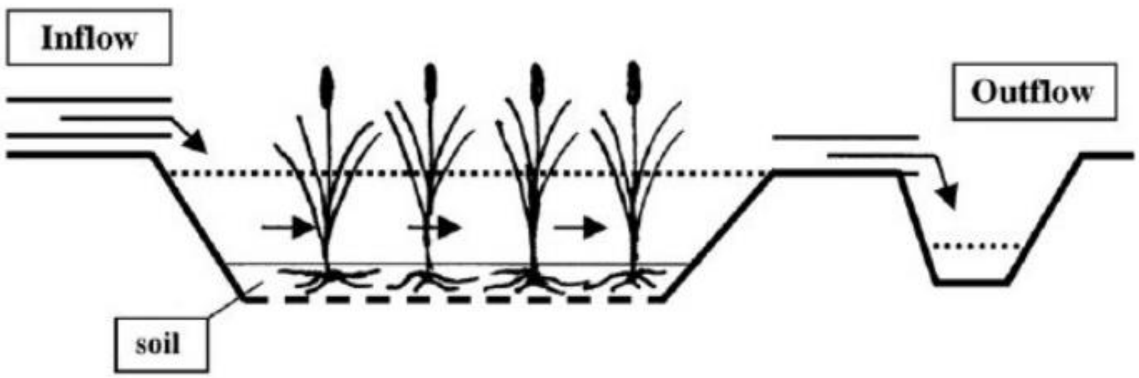

Figure B1

Diagram of faux wetland with free-water surface and emergent macrophytes as their primary vegetal species. Courtesy of Jan Vymazal (August, 2007).

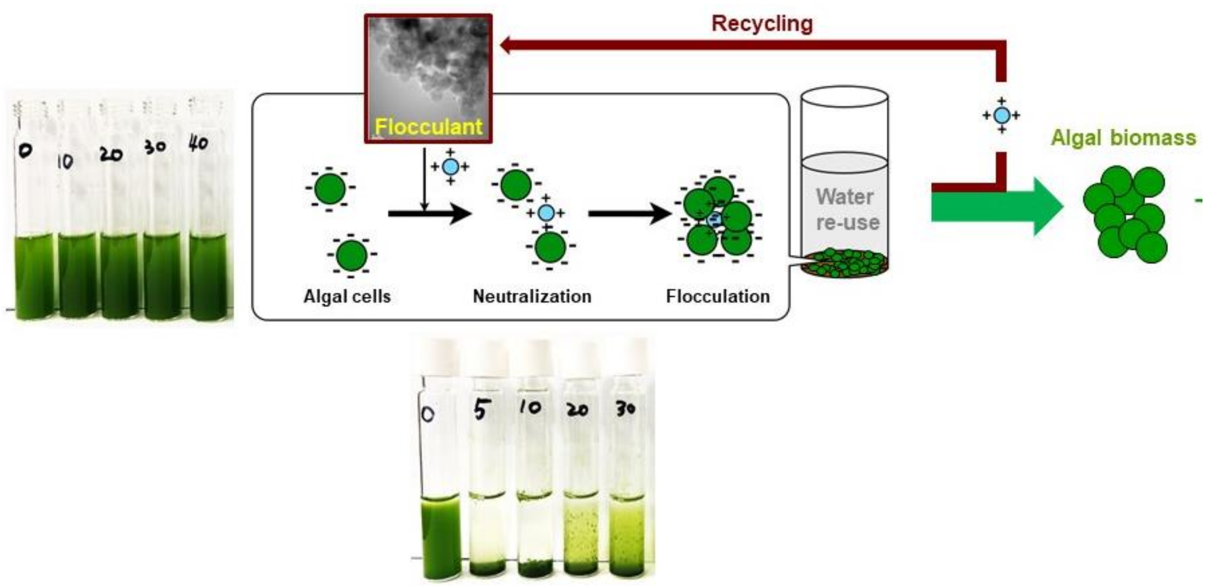

Figure B2

Diagram of flocculant being utilized to precipitate algal biomass, creating a floc. Courtesy of Matter et al. (15 July, 2019).

Appendix C: Implementation of Solution

Figure C1
Typha latifolia in a wetland, which is proposed for Lake Erie's restoration (Aline 2024).

Appendix E: Competing Bacteria to *Bacillus subtilis* (Biological Ramifications)

Function	Phyla	Genera (Notes)	Morphology of the removed phosphorus	References
PAO	*Proteobacteria*	*Rhodobacteraceae* (family), *Rhizobiaceae* (family) (Belongs to *Alphaproteobacteria*)	Phosphate	Lv et al., 2021
		Candidatus Accumulibacter, *Dechloromonas*, *Rhodocyclus* (Belongs to *Betaproteobacteria*)		Li et al., 2017; Huang et al., 2019a, 2020a; Zheng et al., 2021a
		Pseudomonas, *Klebsiella*, *Acinetobacter* (Belongs to *Gammaproteobacteria*)		Du et al., 2017; Tian et al., 2017; Huang et al., 2020a; Zheng et al., 2021a
	Chloroflexi, Gemmatimonadetes	*Rhodocyclaceae* (family), *Gemmatimonadacea* (family), *Gemmatimonas*		Wei et al., 2020; Wang et al., 2021b
PSB	*Actinobacteria, Proteobacteria*	*Corynebacterium*, *Enterobacter*	Convert insoluble phosphorus into soluble phosphorus	Wang et al., 2021b
DNPAO	*Proteobacteria*	*Paracoccus* (Belongs to *Alphaproteobacteria*), *Pseudomonadaceae* (family), Pseudomonas, Dechloromonas	Polyphosphate	Huang et al., 2019a; Lv et al., 2021; Wang et al., 2021b
	Chloroflexi	*Anaerolineae* (class)		Lv et al., 2021
Solubilize vast tricalcium phosphate through secreting organic acids	*Proteobacteria*	*Delftia* (Belongs to *Betaproteobacteria*)	Phosphate	Li et al., 2020b
Associated with the P element cycle	*Proteobacteria*	*Brevundimonas*, *Pseudorhodoferax*, *Variovorax*, *Panacagrimonas*	Organic phosphoric acid esters/ Insoluble phosphate	Wu et al., 2020
	Chlorobi, Firmicutes, Spirochaetes	*Chlorobaculum*, *Bacillus*, *Leptospira*		Wu et al., 2020

Figure E1

Bacteria found in constructed wetlands that aid in phosphorus removal (Wang et al. 2022).

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