

Energy Research and Development Division
FINAL PROJECT REPORT

MICROALGAE FACILITY FOR INTEGRATED TREATMENT OF DAIRY WASTEWATER

Securing Energy Efficient Water Use for California's Main Agricultural Commodity

Prepared for: California Energy Commission
Prepared by: Quantitative BioSciences, Inc.



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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Microalgae Facility for Integrated Treatment of Dairy Wastewater is the final report for the project PIR-11-032 conducted by Quantitative BioSciences, Inc. The information from this project contributes to Energy Research and Development Division's Industrial/Agricultural/Water End-Use Energy Efficiency Program.

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ABSTRACT

Quantitative Biosciences Inc. designed and constructed a fully integrated dairy wastewater solution using microalgae for improved energy efficiency and water reclamation. The Van Ommering Dairy farm in Lakeside, California served as the project demonstration location. Quantitative Biosciences Inc. and its partners designed and constructed the novel pilot scale facility and validated its operational metrics for improving water quality and energy efficiency. This project demonstrated the feasibility of using a low-cost algae-based solution to address the wastewater challenges facing California's largest agricultural sector. Overall, this algae system significantly improved effluent water quality (90.4 percent reduction in ammonia, and 41.8 percent reduction in total phosphorus) with significantly reduced operational costs (an energy savings of 2,893 kWh per million gallons per day of treated water) compared to traditional aeration-based systems. In addition, the algae biomass is used as a slow release fertilizer to enhance the growth of crops on site. If deployed on California's dairies, such a system could help reduce state-wide water and energy use.

Keywords: Algae, Microalgae, Wastewater, Dairy, Anaerobic digestion, CNG, Nutrient management, Water quality, Energy efficiency

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TABLE OF CONTENTS

Acknowledgements	i
PREFACE	ii
ABSTRACT	iii
TABLE OF CONTENTS	iv
LIST OF FIGURES	v
LIST OF TABLES	v
EXECUTIVE SUMMARY	1
Introduction	1
Project Purpose.....	1
Project Results.....	1
Project Benefits	1
CHAPTER 1: Facility Design and Site Selection	3
1.1 System Overview	3
1.2 Siting System Components on the Van Ommering Dairy	4
1.3 Process Flow in Detail	5
CHAPTER 2: Construction	12
2.1 Algae Raceway ponds	12
2.2 Algae Settling Basin	16
2.3 Solids settling pond	18
2.4 Maturation Pond	20
CHAPTER 3: Data Collection and Analysis	22
3.1 Wastewater Treatment Test Plan.....	22
3.2 Water Quality Results.....	23
3.3 Energy Savings Results	30
3.3.1 Measuring Electricity Consumption	31
3.3.2 Electricity Consumption Results.....	31
3.4 Additional Benefits	32

3.4.1	Cleaner Water	32
3.4.2	Clean Energy Production.....	32
3.4.3	Renewable Biomass Generation.....	33
3.4.4	Land Reclamation	33
3.4.5	Reduced Greenhouse Gas	33
3.4.6	Conservation of Resources.....	33
CHAPTER 4: Technology Transfer: Tailoring a System for Future Clients		34
GLOSSARY		39
APPENDIX A		A-1
APPENDIX B.....		B-1
APPENDIX C: Full Time Series Data from Ponds.....		C-1

LIST OF FIGURES

Figure 1: Components of an Integrated Algae-based Wastewater Treatment Facility	3
Figure 2: Topography Surrounding Demonstration Site at Van Ommering Dairy.....	4
Figure 3: Wastewater Treatment System Components (A through I) on the Van Ommering Dairy	5
Figure 4: The Freestall Barn and Milking Parlor Washdown Areas of Van Ommering Dairy	6
Figure 5: Existing Plug Flow Anaerobic Digester.....	7
Figure 6: New Solids Settling Pond Constructed as Part of this Project	8
Figure 7: Existing Holding Lagoon.....	8
Figure 8: New Paddlewheel-Mixed Algae Raceway Ponds.....	9
Figure 9: New Algae Settling Basin	10
Figure 10: New Maturation Pond and Existing Irrigation Field	11
Figure 11: Earthwork Pad Preparation for Algae Raceway Ponds	13
Figure 12: Concrete Curbing Work for Algae Raceway Pond Wall Construction.....	14
Figure 13: Paddlewheel Base Construction	14
Figure 14: EPDM Lining of Algae Raceway Ponds.....	15
Figure 15: Paddlewheel Assembly.....	16

Figure 16: Shaping the Algae Settling Basin to Final Dimensions and Installing Reinforcing Bar	17
Figure 17: Shotcrete Work for Algae Settling Basin	17
Figure 18: Finishing Algae Settling Basin and Installing Pump to	18
Transfer Water to Maturation Pond	18
Figure 19: Forming the cleanout for the manure settling pond.....	19
Figure 20: Deploying the Double-sided Geocomposite Liner in the Solids Settling Pond.....	19
Figure 21: Liner Deployment and Filling the Maturation Pond.....	20
Figure 22: Irrigation Using Maturation Pond Water.....	21
Figure 23: Water Testing is Carried Out on Site and in the Laboratory.....	22
Figure 24: TSS Data.....	24
Figure 25: VSS Data.....	24
Figure 26: COD Data.....	25
Figure 27: Ammonia Data.....	25
Figure 28: Nitrate Data	26
Figure 29: Nitrite Data	26
Figure 30: Total Nitrogen Data.....	27
Figure 31: Reactive Phosphorus Data.....	27
Figure 32: Total Phosphorus Data	28
Figure 33: Alkalinity Data.....	28
Figure 34: Turbidity Data.....	29
Figure 35: Conductivity Data	29
Figure 36: pH Data.....	30

LIST OF TABLES

Table 1: Waste Stream Generation at the Van Ommering Dairy	6
Table 2: Summary of QBI Process Flow Characteristics on the Van Ommering Dairy	11

EXECUTIVE SUMMARY

Introduction

California is our nation's biggest dairy state, producing over 20 percent of the country's milk supply. With more than 1.5 million cows, California's dairy farms generate over 7 million tons of manure annually, most of which is liquefied into wastewater and discarded inefficiently, without tapping into the waste's rich nutrients and high-energy content. This untreated and untapped wastewater is a valuable resource, containing almost 10 times more energy than is required to treat it. Developing a sustainable solution to wastewater treatment has the potential to improve the state's energy efficiency as well as benefit the environment. As California faces increasing strains on both its limited water supplies and finite energy resources, it is important to develop new technologies to maximize energy efficiency, water efficiency and treatment and to generate new, renewable energy sources.

Project Purpose

Quantitative Biosciences Inc. (QBI) designed and constructed a fully integrated dairy wastewater solution at the Van Ommering Dairy Farm in Lakeside, California using microalgae to improve energy efficiency of the process and reduce water use. The dairy's prior waste treatment protocol consisted of a system in which waste is stored in a large holding lagoon for at least 60 days before being applied to nearby fields for irrigation. This treatment method, while common for dairy farms, is ridden with problems that include insufficiently removing undesired organic nutrients, which then contaminate groundwater and local water bodies. QBI designed and installed this novel pilot scale facility to incorporate these nutrients into the algae biomass and improve the quality of the water effluent, while providing treatment comparable to a compliant municipal system at a reduced energy cost. An independent engineering firm used data from the operating project to validate its operational metrics for improving water quality and energy efficiency.

Project Results

Since completing construction, QBI has been regularly testing nitrogen, phosphorus, turbidity, pH, total suspended solids, volatile suspended solids, alkalinity, chemical oxygen demand, and conductivity to ensure that the system has been functioning properly. The system's energy use has also been measured to compare it to a baseline to calculate energy savings. Overall results indicate that the algae system improved effluent water quality (reducing ammonia by more than 90 percent and total phosphorus by almost 42 percent) at significantly reduced operational costs (an energy savings of 2,893 kilowatt hours [kWh] per million gallons of treated water per day [kWh/MGD]) compared to traditional aeration-based systems. In addition, the algae biomass is used as a slow release fertilizer to enhance the growth of crops on site.

Project Benefits

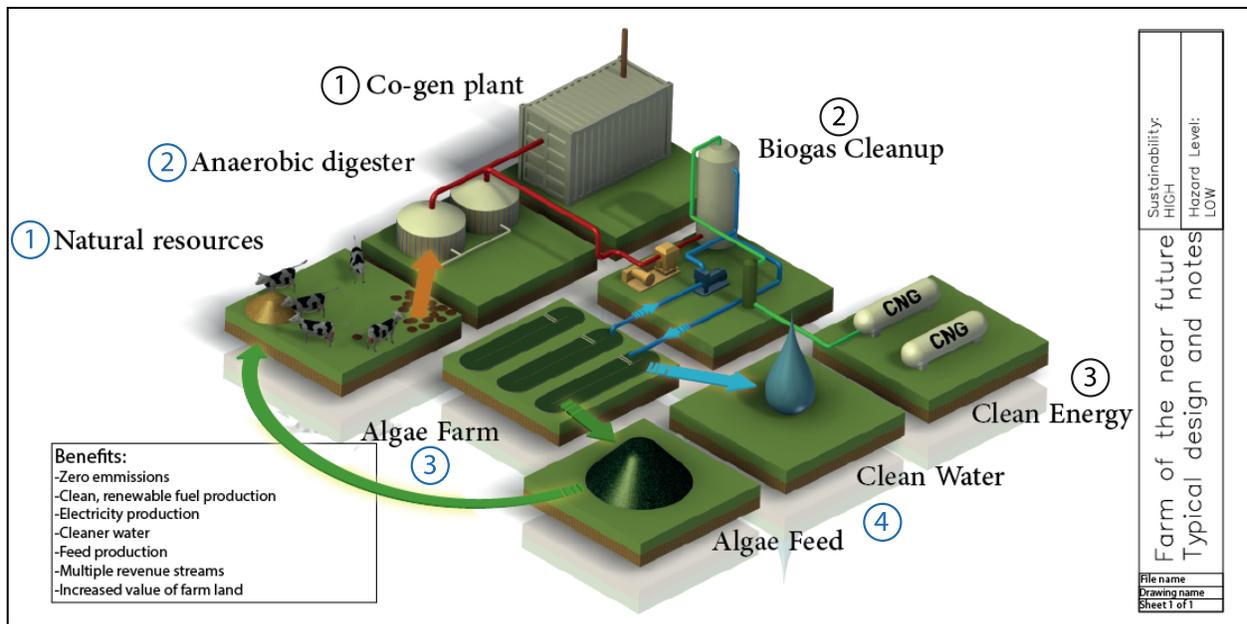
This project demonstrated the feasibility of a low-cost algae-based solution to addressing the water and energy challenges facing California's largest agricultural sector. Beyond the large energy savings that the system can provide, there are a number of other benefits of using an algae-based system for wastewater treatment. While the benefits are numerous, the typical

farm cannot justify the expense to convert a simple lagoon system into an advanced treatment system, unless they are either forced to by stricter water/energy/nutrient regulations or motivated by an opportunity to improve their bottom line. As California faces increasing strains on both limited water supplies and finite energy resources, the “farm of the future” must maximize its resources by setting up a fully integrated operation, which will clean its own water, grow its own animal feed, generate its own electricity and fuel, and produce valuable co-products. The QBI technology represents a carefully engineered solution that leverages multiple farming resources to improve the bottom line, by remediating and recycling water for improved crop irrigation, producing biomethane for use as a vehicle fuel, generating high-protein biomass for use as a fertilizer or livestock feed, and reclaiming valuable land that was previously used for wastewater treatment operations.

CHAPTER 1: Facility Design and Site Selection

Microalgae wastewater treatment has historically been shown to be an extremely effective method for greatly improving water quality at minimal cost. The main hurdle to system wide adoption has been an economic model that produces monetary value when extensive land area is converted to open algae ponds. The QBI system overcomes this challenge by fully integrating microalgae and anaerobic digestion waste processing to generate value in the form of clean water, algae feed, and reduced greenhouse gas emissions (Figure 1). In addition, biogas can be produced via the anaerobic digestion process, which can be used either to generate electricity or as a vehicle fuel.

Figure 1: Components of an Integrated Algae-based Wastewater Treatment Facility



QBI's vision of the farm of the near future using an integrated approach to wastewater management for clean water and the generation of biomass. Blue numbers indicate the flow of water from (1) waste to (2) anaerobic digestion to (3) shallow algae farms for enhanced cleanup, a process which ultimately yields algae biomass and clean water. Black numbers indicate the flow of gas, which is produced by anaerobic digestion and can be used both for electricity co-generation (1) and cleaned via transmission through the algae water (2) to produce compressed natural gas (3) that can be used as fuel on-site.

1.1 System Overview

The centerpiece of the integrated QBI system is the raceway-shaped algae pond. Only one foot deep, the algae pond captures sunlight and nutrients in the waste stream to fuel rapid microalgae growth via photosynthesis. This process converts carbon dioxide in the atmosphere into algal biomass and oxygen. The oxygen aids in further break down of waste nutrients by resident aerobic bacteria. The algae biomass can be used onsite as a slow release fertilizer or as animal feed.

1.2 Siting System Components on the Van Ommering Dairy

The Van Ommering Dairy has the benefit of being in extremely close proximity to the San Diego metropolitan area, which is a renowned hub of biotechnology innovation. The team was fortunate to strike an early partnership with the owners of the dairy, Rob and Dave Van Ommering, and they were enthusiastic to have their dairy serve as a demonstration site.

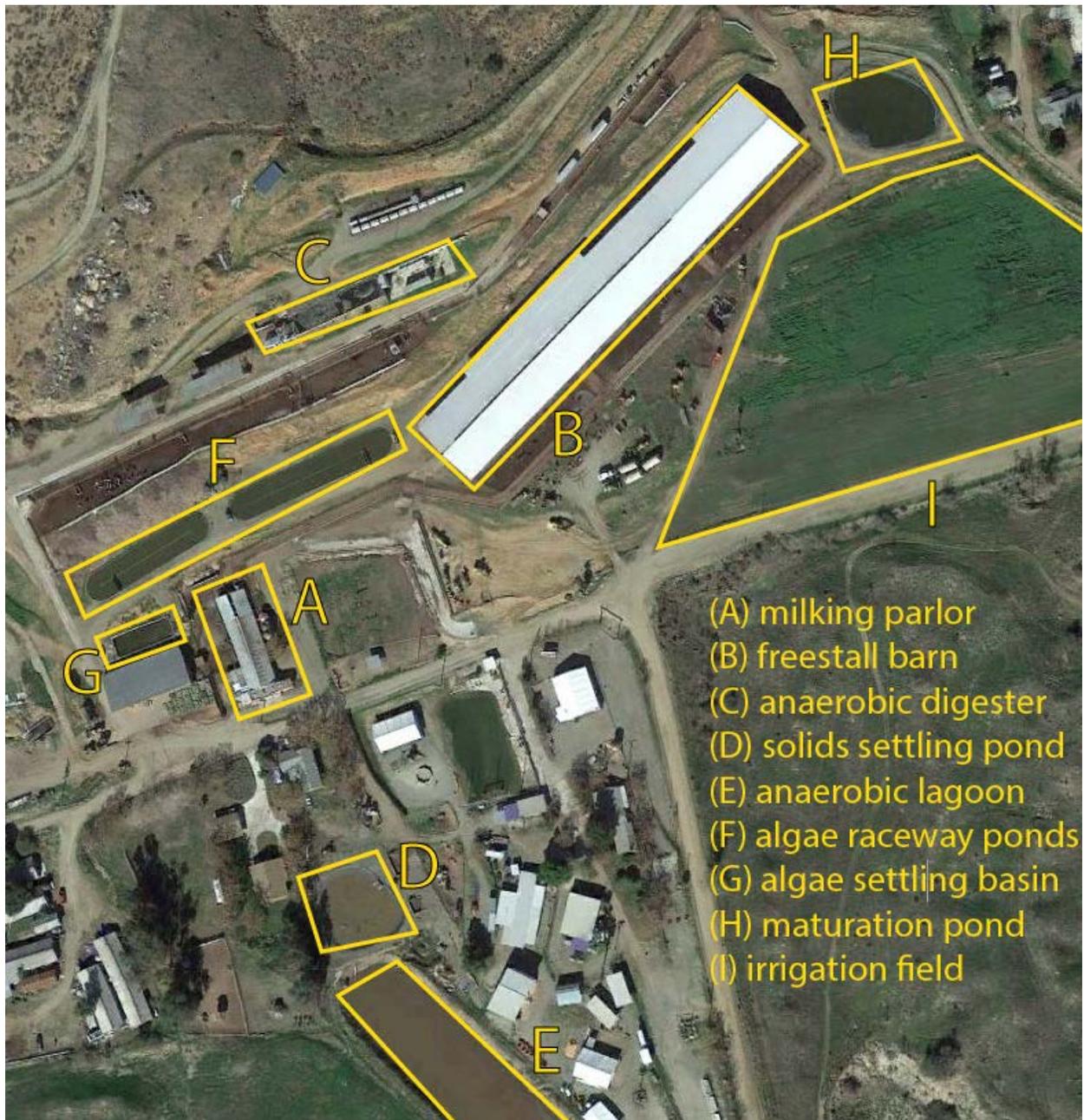
Figure 2: Topography Surrounding Demonstration Site at Van Ommering Dairy



The Van Ommering dairy's land is primarily steep hillside, which presented challenges for the deployment of shallow, large surface area treatment ponds.

As is immediately evident from Figure 2, which displays a merged image of aerial photography and topography data, the majority of the dairy's available land is relatively steep hillside. For constructing the demonstration facility the team was forced to place the system components near each other in favor of selecting available flat land parcels that were often separated by considerable distance. This increased the length of piping and electrical among the system components well beyond what would be normally required in a future deployment scenario of this technology on a dairy farm in the central valley with adequate flat land. Figure 3 illustrates the dispersed connectivity among the various system components, the detailed descriptions of which follow.

Figure 3: Wastewater Treatment System Components (A through I) on the Van Ommering Dairy



Due to the vast majority of the available land being sloped, system components had to be spaced farther apart than desired, which increases the energy costs due to the need to transport water over large distances and changing elevations.

1.3 Process Flow in Detail

On the Van Ommering Dairy, wastewater is generated at two locations: the milking parlor (A), where cows are washed down prior to manual milking, and the freestall barn (B), where cows

spend the majority of their time eating, sleeping, and defecating (Figure 4). The characteristics of the waste streams from these two sources are shown in Table 1 below.

Figure 4: The Freestall Barn and Milking Parlor Washdown Areas of Van Ommering Dairy



The freestall barn is a large housing structure (background left) that the cows periodically leave to access the milking parlor washdown area (foreground right) prior to milking.

Table 1: Waste Stream Generation at the Van Ommering Dairy

Waste stream	Typical flow rate (gal/day)	Typical percent solids
Milking parlor	10,000 - 40,000	2
Freestall barn	10,000	10

This data demonstrates that the two waste streams are quite different in terms of nutrient concentration, which ultimately dictates the optimal mode of processing. The freestall barn wastewater is essentially a slurry of manure due to the fact that the dairy does not have a flush alley for manure processing and instead resorts to manual scraping for its collection. As a result this manure is ideally suited for anaerobic digestion in the plug flow digester (C).

An operational digester is essential to the process to ensure complete breakdown of manure slurry into simpler nutrients that can fuel rapid algae growth for downstream processing of this concentrated waste stream. The digester was originally constructed by RCM International and commissioned in 2005 but failed after several years due to corrosion of the internal heating pipes (Figure 5). The QBI team worked with the Van Ommering Dairy to salvage the enormous value of the anaerobic digester by retrofitting the piping system with new galvanized steel

components (furnished by QBI and the Van Ommerings) to prevent corrosion and a new synthetic rubber membrane cover for biogas containment.

Figure 5: Existing Plug Flow Anaerobic Digester



The rust-colored columns had completely deteriorated due to corrosion and failed to support the internal heating pipes of the digester. The cause of the original failure was inappropriate materials selection during RCM's design process. Piping was replaced and the digester covered.

In contrast to the freestall barn waste entering the digester, the milking parlor wastewater is extremely dilute. Therefore it requires only minimal processing to initiate anaerobic breakdown and removal of large solids prior to feeding the algae growth in the raceway ponds. The solids processing is achieved by gravity in the settling pond (Figure 6), which also contains a concrete cleanout structure mated to the plastic liner to allow for periodic removal of solids using an excavator bucket. After solids removal, the milking parlor waste stream joins the digester waste stream effluent to enter the large holding lagoon on the dairy, where nutrients are further broken down by anaerobic action (Figure 7).

Figure 6: New Solids Settling Pond Constructed as Part of this Project



The solids settling pond has a sloped bottom directing the settled sludge towards a concrete cleanout slot that is the width of an excavator bucket to allow simple solid removal and drying on adjacent concrete pads.

Figure 7: Existing Holding Lagoon



The large holding lagoon on the dairy serves to facilitate anaerobic bacterial breakdown of complex nutrients prior to pumping the wastewater into the algae raceway ponds for the next step of the treatment process. Before integrating this system, this water was used directly to irrigate the nearby fields, which resulted in the over-application of nutrients.

Once the complex nutrients have been broken down by anaerobic bacteria into simple nitrates and phosphates, the wastewater is fed into the raceway algae ponds where rapid microalgae growth acts as a sponge to remove these dissolved nutrients (Figure 8). Because the algae cells

divide every 8 hours or so under optimal conditions, their extremely vigorous rate of replication fuels a biomass productivity often ten times higher than that of most terrestrial crops.

Further, the oxygenation of the water through photosynthesis promotes aerobic bacteria to further break down nutrients in a cycle that feeds additional algae growth. In this way, drastic improvements in water quality can be achieved with this system at a minimal operational cost compared to the aeration basins used at a typical municipal plant. The only energy input to the algae raceway ponds is the minimal electrical power required for the motorized paddlewheels to continually mix the water to ensure optimal sunlight exposure to all of the algae in the ponds.

Figure 8: New Paddlewheel-Mixed Algae Raceway Ponds



The algae raceway ponds are continuously mixed by a paddlewheel that only requires a $\frac{1}{4}$ horsepower motor, ensuring a high level of energy efficiency.

The microalgae species that tend to dominate growth in the continuously mixed environment of the raceway pond are often prone to rapid settling once they enter a holding vessel with minimal fluid flow. The QBI system takes advantage of this phenotype by using a gravity-settling basin downstream of the raceway ponds to capture some of the algae biomass (Figure 9). The concrete basin has a sloped bottom so the deep end can be periodically pumped to remove the biomass for downstream incorporation in fertilizer mix or animal feed. The algae settling basin would ideally be an earthen pond with a geosynthetic membrane liner in order to minimize construction costs. However, due to the space constraints at the Van Ommering Dairy, the algae settling basin was constructed in a swimming-pool style fashion using shotcrete to form the vertical walls and gain volume capacity in a smaller footprint than would be possible via earthen construction.

Figure 9: New Algae Settling Basin



The algae settling basin receives water by gravity from the two algae raceway ponds at the far end of the basin and allows for a long fluid path to promote algae settling prior to pumping to the maturation pond for the final portion of the treatment process.

The microalgae not captured by gravity in the algae settling basin continues on to enter the final component of the QBI system, the maturation pond (Figure 10). This ultimate polishing pond serves to further clarify the water by various naturally occurring zooplankton that graze on the remaining microalgae. The maturation pond has a much larger capacity than the raceway and settling ponds in the system to allow for a longer retention time to improve the water quality of the final effluent. The treated water then leaves the QBI system by pumping to irrigate the nearby fields at the dairy.

The amount of treated water is approximately 40,000 gallons per day with a retention time of about 20 days. The previous irrigation process involved the overapplication of nutrients to the crop fields; by treating the water with this system prior to irrigation, those nutrients are transferred to the algae biomass and helps prevent leaching of excess nutrients into the groundwater.

The quality of the irrigation water is significantly improved by the QBI algae system in several respects. First, the water is essentially free of large solids which otherwise tend to clog and break sprinkler heads. Second, the treated water has greatly reduced levels of dissolved nutrients (nitrates/phosphates), which allows for more efficient watering without the risk of over-fertilizing the fields and contaminating nearby groundwater. Finally, some microalgae remains in the final effluent and serves as a good source of slow-release fertilizer to further improve crop quality. This system could also be used to enable a dairy to expand its herd size. While the Van Ommering Dairy is limited in flat land, which prevents expansion, a typical dairy could size the system to match their desired herd size.

Figure 10: New Maturation Pond and Existing Irrigation Field



Maturation pond (foreground) is used to supply water to pressurize the big-gun sprinklers that irrigate the crop field (background)

Table 2 summarizes the design characteristics and primary functions of each component in the QBI algae-based treatment system. Overall the flow of wastewater through this set of connected pond components achieves a high level of water treatment at minimal operational cost.

Table 2: Summary of QBI Process Flow Characteristics on the Van Ommering Dairy

Component	Maximum capacity (gal)	Daily throughput (gal)	Retention time (days)	Function
Anaerobic digester	350,000	10,000	10	Bacterial breakdown of manure slurry into simple nutrients and biogas
Solids settling pond	250,000	50,000	5	Gravity-based removal of macroscopic solid particles
Algae raceway ponds	125,000	40,000	3	Rapid microalgae growth soaks up nutrients and CO ₂ while oxygenating water to promote further treatment
Algae settling basin	100,000	40,000	2.5	Gravity-based settling of microalgae for subsequent removal as fertilizer/feed amendment
Maturation pond	350,000	40,000	9	Zooplankton grazing of remaining algae for final water polishing before irrigation

CHAPTER 2: Construction

QBI's construction effort proceeded rapidly thanks to the proactive cooperation of the Van Ommerings as well as the many talented service providers involved in contributing to the project.

2.1 Algae Raceway ponds

As previously described, the primary challenge to deploying the shallow but large surface-area algae ponds for this project was allocating sufficient flat land. On most dairy farms in California's central valley, flat land is plentiful, but the Van Ommering dairy in San Diego had limited land available for this purpose due to its hilly topography. As a result the team conducted an extremely thorough analysis of the various potential deployment locations at the dairy site, taking into careful consideration the impact of stormwater flows, piping connectivity for efficient pumping, and potential disturbances to dairy operations.

Two separate raceway ponds were built rather than one single algae pond because of the split-level elevation of the main parcels available just west of the freestall barn. To further maximize volume capacity for the algae ponds, vertical walls were formed using a concrete curbing machine because forming the pond berms out of earth would take up a prohibitively large area of land at this site. An operational digester is essential to the process to ensure complete breakdown of manure slurry into simpler nutrients that can fuel rapid algae growth for downstream processing of this concentrated waste stream.

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Figure 11: Earthwork Pad Preparation for Algae Raceway Ponds



Decomposed granite (top left) was imported onsite to ensure a uniform earthen base free of large rocks that could puncture the geomembrane liner of the ponds. The DG material was spread using a grader (right) prior to absolute leveling by laser grading (bottom left).

For future installations, earthen berms would be more cost effective than concrete, assuming that flat land is readily available.

To ensure that the earthen pads for the algae raceway ponds were completely level in elevation, 300 tons of decomposed granite (DG) was imported and used a laser grading machine for absolute accuracy. Piping for draining the ponds was buried prior to compacting the DG with a 15-ton roller (Figure 11). The concrete curbs forming the vertical pond walls and centerline of each algae raceway pond were constructed by an experienced local curbing crew from H&D. The QBI team provided stakelines to guide the construction and the H&D machine was able to form the walls for both ponds in one day (Figure 12).

Figure 12: Concrete Curbing Work for Algae Raceway Pond Wall Construction



Concrete curbs were formed by H&D according to QBI stakelines.

After forming the walls, the concrete bases to support the paddlewheel in each pond were formed and poured (Figure 13). The key design parameter to improve efficiency is to ensure a semi-circular profile in the floor of the base to allow for efficient transfer of power from the paddles to the water. A concrete structure for this purpose is the most suitable design in terms of ease of construction and load bearing ability compared to a base manufactured from metal, plastic, or formed earth. To comply with regulatory requirements for lining wastewater containment ponds, the algae raceways were lined with synthetic rubber geomembrane. The team installed several panels of 45mil ethylene propylene diene monomer (EPDM) by unrolling them within each pond, and used 10 to 12 people to drag each panel into position (Figure 14).

Figure 13: Paddlewheel Base Construction



Concrete bases were formed to support the paddlewheel in each pond.

Figure 14: EPDM Lining of Algae Raceway Ponds



45mil ethylene propylene diene monomer panels were used to line the algae raceway ponds to conform with wastewater treatment standards.

Once lining was complete, the paddlewheel and associated motor, gearbox, and controls could be installed (Figure 15). The paddlewheel consists of a central steel tube structure with six blades of fiberglass-reinforced plastic (FRP) panels. The steel frame was sandblasted and hot-dip galvanized after fabrication to ensure long-term resistance to the corrosive wastewater environment. The FRP paddlewheel blade material was chosen for its high strength, low weight, and excellent inherent corrosion/ultraviolet light resistance.

Figure 15: Paddlewheel Assembly



A close-up view of one of the two paddlewheels shows the central steel tube surrounded by six blades of FRP.

2.2 Algae Settling Basin

The algae settling basin was constructed by expanding an existing small earthen settling pond immediately south of the algae raceway ponds (Figure 16). Because of the extremely limited space in this area, the team built vertical sidewalls using shotcrete to maximize volume capacity. The site was excavated to rough dimensions of 80 feet long by 35 feet wide to a depth of 15 feet on the east end and 8 feet on the west end to provide a sloped bottom for collection of algae sludge at one end of the basin. Plywood formwork was installed along the periphery to allow for shotcrete work, which covers the sides and bottom of the pond with concrete, similar to a large swimming pool. The reinforcing steel bars for this concrete work were installed by a local crew from Canyon Steel Company, Inc. The plywood backstops were pretreated by spraying with diesel to allow for release of the form after concrete setting.

The shotcrete work was completed by a crew from Freund Diversified which deployed 13 trucks' worth of concrete through a hose with a pneumatic projection nozzle that allowed shooting the concrete against the reinforcing bar internal structure of the basin (Figure 17). After completion of the shotcrete work all formwork was removed, inspected the structure, finished minor concrete defects, and backfilled the outside of the basin. The remaining pipe was trenched and placed to connect the raceway ponds to the basin. During the construction phase, two escape ladders were installed within the basin and a fence was installed to prevent unintended access to the basin (Figure 18). The basin is currently collecting algae raceway effluent successfully.

The water from this settling basin is pumped via a self-priming centrifugal pump with 3/8" solids handling capacity to the final maturation pond. Finally, an AMT model 276D-95 self-priming centrifugal pump was installed and connected on the outlet of the algae settling basin to take effluent to the maturation pond via a buried 3 inch Schedule 40 polyvinyl chloride (PVC) line (Figure 17).

Figure 16: Shaping the Algae Settling Basin to Final Dimensions and Installing Reinforcing Bar



Earthworks to enlarge the existing pond (left) and allow for rebar mesh placement (right).

Figure 17: Shotcrete Work for Algae Settling Basin



Shotcrete is deployed by pressurized pump to form the walls of the concrete basin.

Figure 18: Finishing Algae Settling Basin and Installing Pump to Transfer Water to Maturation Pond



The finished concrete basin is fitted with emergency escape ladders (left) and effluent pump and protective chain link fence (right).

2.3 Solids settling pond

To improve solids capture and enable periodic cleanout for optimal system performance the QBI team retrofitted the existing settling pond on the dairy. The contents of the old pond were drained and the sludge dredged to allow shaping of the new pond. As the old pond was simply an open earthen containment with rocky substrate, new clean fill dirt was imported to allow for lining with geomembrane for improving wastewater retention.

The manure solids settling pond involved construction of a large concrete cleanout structure within the pond. The purpose of this structure is to allow an excavator bucket to reach into the pond to remove settled solids during periodic maintenance (Figure 19). The earthen slopes of the pond were shaped to interface smoothly with this concrete structure. This process required careful discussions with the geomembrane liner representative to plan the joining of the liner to this structure in a manner that would ensure the long-term integrity of the liner.

Once the structure was complete, the surrounding area was backfilled and compacted/rolled to smooth the surface for installing the geomembrane liner. To line this pond the team elected to install a 60 mil linear low density polyethylene (LLDPE) material in 22.5 foot wide rolls that were patterned to cover the pond surface in a “piecrust” manner and wedge welded together at the seams (Figure 20). A geocomposite substrate consisting of 14.5 foot wide rolls of double-sided 6 ounce material was installed below the liner to cushion it against sharp rocks and to provide a gas escape ventilation layer.

The liners were installed by the experienced FML crew from Huntington Beach with the aid of the QBI crew. Sandbags were used to hold down the liner during installation due to the potential for windlift. The liner was mechanically attached to the concrete structure via grade 316 stainless steel batten bar; any remaining seams welded; and the anchor trenches finally

backfilled prior to filling the pond with effluent from the milking parlor. Figure 20 (bottom, right) shows the completed solids settling pond being filled with water and the sandbags for anchoring being removed.

Figure 19: Forming the cleanout for the manure settling pond



The concrete cleanout structure is formed (left) and finished (right) prior to finalizing earthworks for liner deployment.

Figure 20: Deploying the Double-sided Geocomposite Liner in the Solids Settling Pond



Geocomposite is positioned in place as a cushion and gas escape layer (top left) prior to placing panels of LLDPE (top right) and wedge welding them (bottom left). The finished pond begins to fill with water (bottom right).

2.4 Maturation Pond

The maturation pond was constructed in a similar fashion to the solids settling pond by incorporating a geocomposite cushion and a geomembrane liner for wastewater containment. The pond was excavated to the necessary dimensions for volume capacity as described above, and the earth was subsequently compacted and rolled prior to liner deployment. The FML crew with assistance from the QBI team deployed 8oz Geotextile cushion Fabric in 22.5 foot wide rolls, which was heat welded along the seams and secured in the perimeter anchor trench. Two panels of 40 mil LLDPE were then carefully positioned to span the pond and join along a central seam (Figure 21). The panels were wedge welded along a single axis running through the center of the pond, and extrusion welds were used for minor patching. Berm vents were installed for both ponds on the slope just above the water line to allow for gas to escape from underneath the liners.

Water from the maturation pond (final pond in system) is pumped to pressurize sprinkler lines laid out in the crop fields (Figure 22). The two big-gun sprinklers have camlock connections to the pressurized lines, making them easy to disconnect and move about the field to water different sectors as required. A drastic improvement in the performance of the irrigation system is expected due to the removal of large solids, which was subject to frequent clogging of the sprinkler heads. Large solids are now captured in the first settling pond in the treatment system via a concrete cleanout structure that allows an excavator to access the pond and move the solids to nearby drying beds. The solids are then composted and sold by the farm as a soil amendment. The team also expected significant improvement in nutrient delivery to the irrigated crops by the conversion of soluble nutrients to microalgae biomass. Rather than leaching into the groundwater, the nutrients captured in the algae biomass remain available on the field as a slow-release fertilizer.

Figure 21: Liner Deployment and Filling the Maturation Pond



One panel of 40 mil LLDPE is placed to form the centerline (left) prior to positioning the second panel and wedge welding the seam. The finished pond begins to fill with water (right).

Figure 22: Irrigation Using Maturation Pond Water



Water from the maturation pond is used to irrigate the nearby fields.

CHAPTER 3: Data Collection and Analysis

3.1 Wastewater Treatment Test Plan

The team evaluated the performance of the algae treatment system via remote sensors as well as water quality testing in the laboratory (Figure 23). The sensors in the algae ponds are recording dissolved oxygen, pH, oxidation reduction potential (ORP), conductivity and temperature, which was correlated with solar irradiation data from the weather station to monitor algae growth. Also, the custom algae fluorescence sensor has been successfully deployed and is gathering data to monitor algae concentration and health. Finally, affordable remote webcams were installed for real-time remote monitoring of the system.

Figure 23: Water Testing is Carried Out on Site and in the Laboratory



Water testing kits and equipment are used to run tests several times a week to monitor water quality (left). Controls for pumps and electronic equipment are housed on site in a weatherproof container for easy automation (right).

Water testing begins at the solids settling pond (SSP), which receives the raw wastewater influent from the milking parlor wash-down area. The SSP serves to separate large settleable solids out of the process stream and is expected to reduce turbidity and overall nutrient load of the effluent pumped into the high rate ponds (HRPs). Solids are periodically removed from the SSP using an excavator to clear out the concrete sump portion of the pond. SSP influent and effluent are sampled on Mondays and Wednesdays in three daily replicates.

The clarified effluent from the SSP enters the algae high rate ponds where vigorous microalgae growth promotes nutrient recovery from the waste stream while oxygenating the wastewater via photosynthesis. Significant reductions in dissolved nutrients occur at this stage as ammonia and phosphorus are incorporated into the algae biomass. The oxygenation promotes further

breakdown of complex nutrients via aerobic bacterial action and increased dissolved oxygen acts to inhibit growth of bacterial coliform. The algae HRP's effluent is sampled on Tuesdays and Thursdays in three daily replicates.

The algae-rich effluent then flows by gravity into the algae settling basin (ASB) where a long fluid path from influent to effluent promotes settling of much of the microalgae biomass to the bottom of the concrete slab (sloped to retain solids at influent end). This serves to reduce total suspended solids and acts as a capture vessel for algae biomass prior to harvesting (periodic pumping out of the settled concentrated algae). The ASB effluent is sampled on Tuesdays and Thursdays in three daily replicates.

Treated effluent is finally pumped into the maturation pond which acts as a final polishing reservoir using solar radiation to clarify the treated water prior to discharge via irrigation of the nearby crop fields. The final treated effluent has reduced levels of suspended solids and dissolved nutrients along with minimal turbidity.

Water quality data from the various test kits and instruments has been organized in a spreadsheet format and that is backed up and stored on a cloud-based drive. The time series data for each water quality parameter is extracted from the spreadsheet files using Matlab software. Custom Matlab scripts are used to analyze/visualize the data in order to make meaningful inferences about the efficiency of the algae-based treatment process.

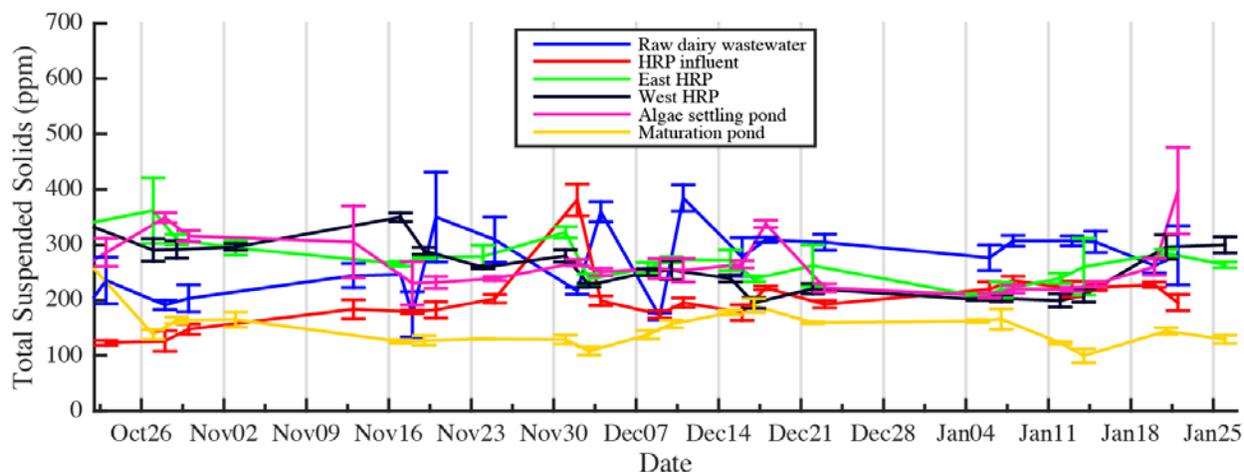
3.2 Water Quality Results

The plots in the figures shown below that track each of the parameters described in the Final Wastewater Treatment Test Plan are from data taken starting in October 2014. This date marks the beginning of the revised data acquisition protocol, which included the acquisition of triplicate data. The revised protocol enabled the team to plot error bars and ensured that they compensated for any issues with sample collection (due to a lack of homogeneity in wastewater ponds) that had a tendency to cause misleading spikes in the data. The complete data plots are shown in Appendix C.

Overall, the data is highly consistent and accurately represents the desired outcomes of the wastewater treatment system. Occasionally spikes in certain parameters are observed due to the team's lack of control over farm activities, which in a few instances, led to inconsistent input into the waste stream. The team, however, found that by travelling through the series of ponds, that the waste is able to normalize by the final pond and therefore the system can accommodate unexpected loads.

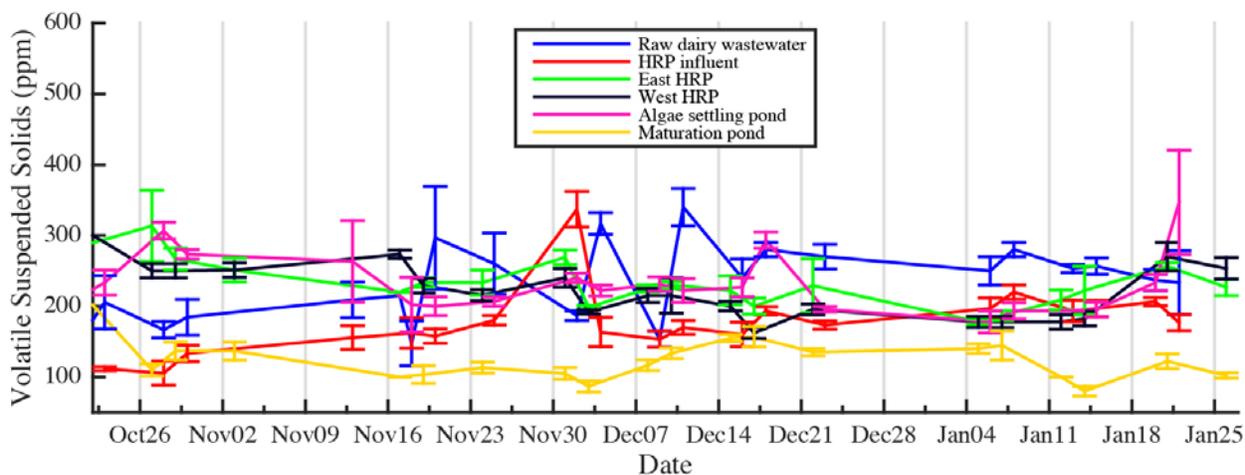
The total suspended solids (TSS) test determines the amount of solids, which are retained after passing the sample through a standard glass fiber filter and drying to a constant weight at 105 °C (Figure 24). This value decreases between the raw water (blue) and the influent to the HRP pond (red), as many of the solids separate out in the initial solids settling pond. The value increases in the two HRPs, as the algae organisms are large and will contribute the measurement of TSS. But by the time the waste gets to the maturation pond (yellow), the value drops to its lowest point as all of the solids, including the algae, continue to settle out.

Figure 24: TSS Data



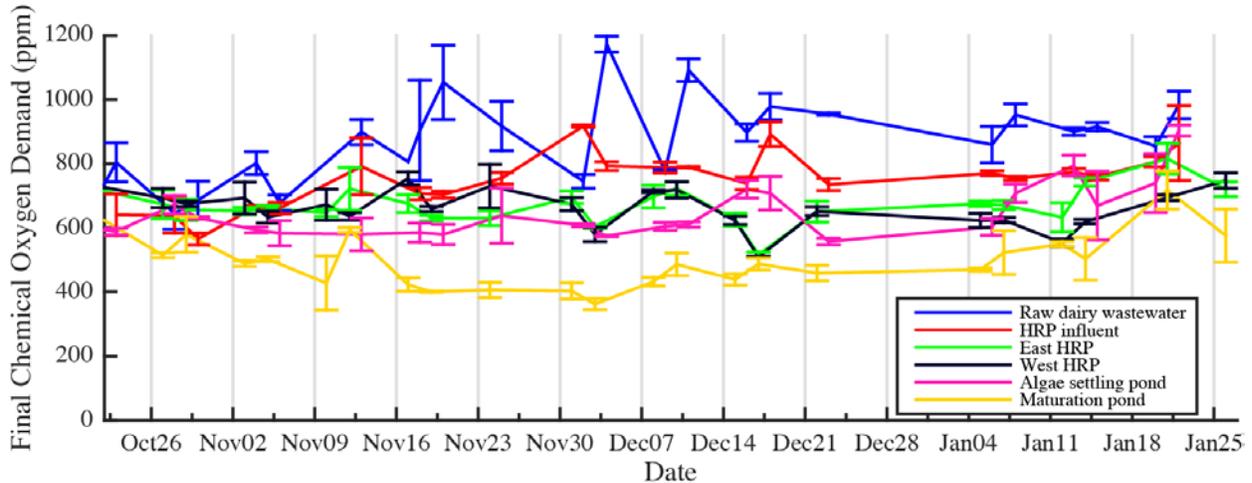
The volatile suspended solids (VSS) test determines the organic solids fraction of TSS present in the sample (Figure 25). The VSS fraction is obtained by igniting the solids in a furnace at 550 °C and weighing the remaining inorganic solids fraction. This is similar to the VSS test, however this test only reflects the organic solids and is therefore a more direct measurement of the concentration of organisms in the samples. As with TSS, an increase is observed as the algae begin to grow in the two HRP's (green and black lines), but an overall decrease is observed in the final pond (yellow).

Figure 25: VSS Data



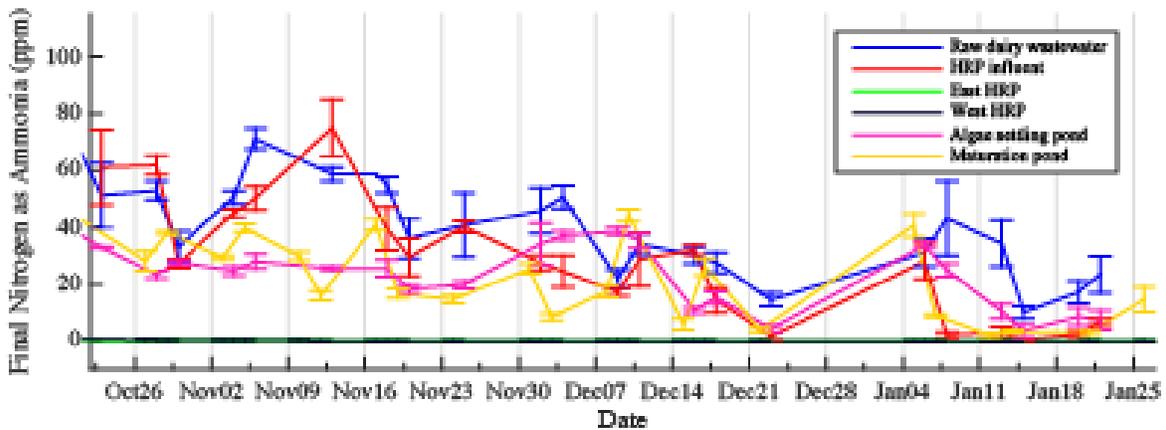
The chemical oxygen demand (COD) represents the level of organic compounds present in the sample, which can be fully oxidized by a strong chemical oxidant (Figure 26). Test kits from Hach (TNT 822/823) were used according to Hach methods 8000 and 10212. As expected, COD levels steadily decreased through the series of ponds as the waste is treated and organic material is consumed.

Figure 26: COD Data



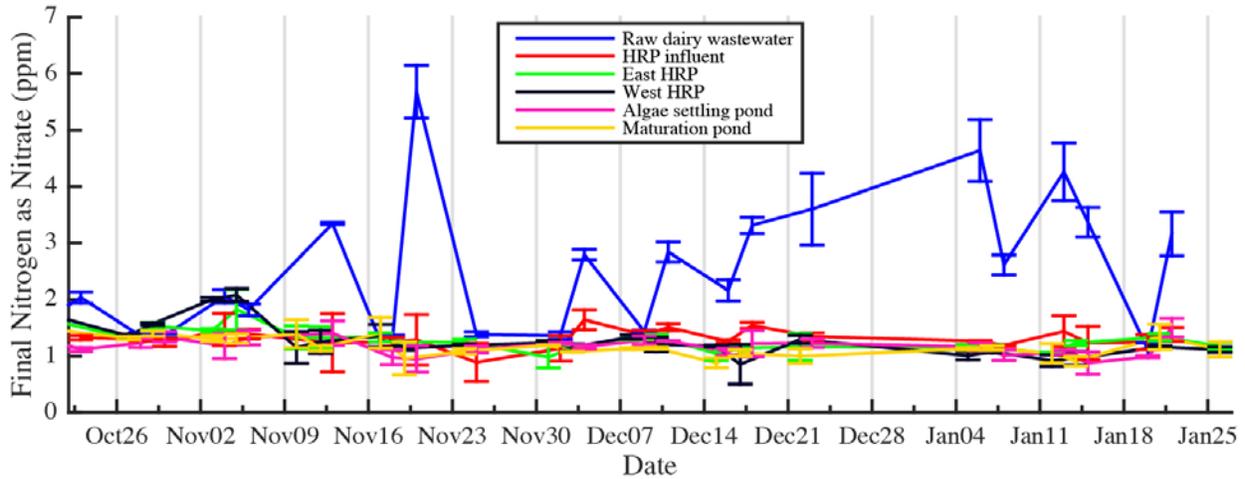
The ammonia test determines NH_3 and NH_4^+ levels, where the unionized form (NH_3) is a toxic compound to many aquatic organisms (Figure 27). Test kits from Hach (TNT 830/831/832) are used according to Hach methods 10205 ULR/LR/HR. The ammonia level drops down to nearly zero in the algae ponds, as the algae rapidly consume it, and the levels rise again in the following ponds as the residual algae decompose.

Figure 27: Ammonia Data



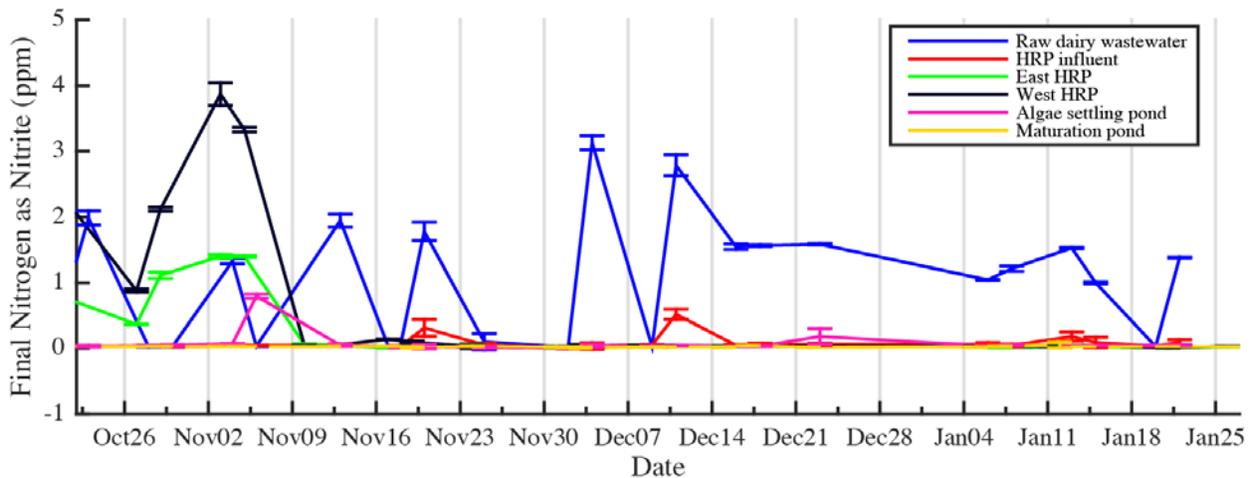
The nitrate test determines the level of NO_3^- , which is generally regarded as a nontoxic nutrient for photosynthetic species. Excessive levels can indicate an unbalanced ecosystem at risk of eutrophication (Figure 28). Test kits from Hach (TNT 835/836) are used according to Hach method 10206. As expected, the nitrate level drops upon the wastewater's entry into the algae ponds as the algae rapidly consume it.

Figure 28: Nitrate Data



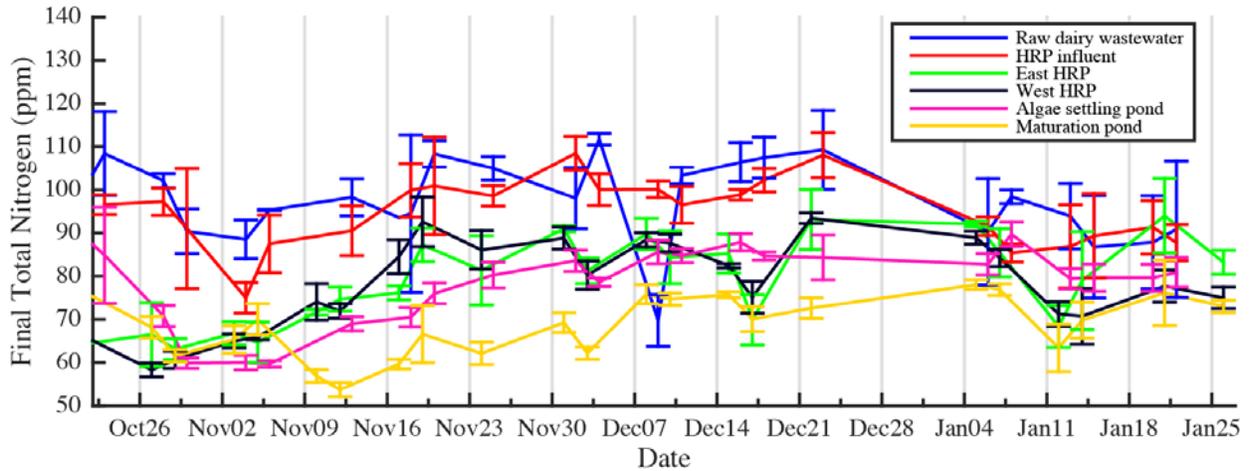
The nitrite test determines the level of NO_2^- , which is extremely toxic to aquatic life but is generally present in only trace amounts in oxygenated environments due to its rapid oxidation to nitrate (Figure 29). Test kits from Hach (TNT 839/840) are used according to Hach methods 10207/10237. As expected, this value rapidly drops when the waste enters the highly oxygenated algae ponds.

Figure 29: Nitrite Data



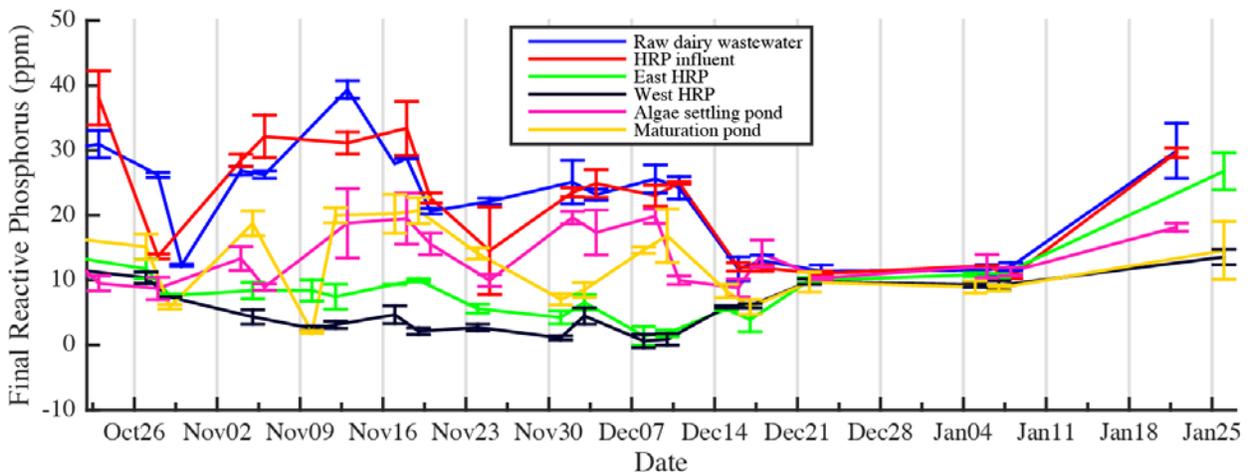
Total nitrogen was measured to determine combined levels of all nitrogen species. Test kits from Hach (TNT 826/827/828) are used according to Hach method 10208 (Figure 30). As expected, this drops throughout the series of ponds, as some species are taken up by the algae and some are oxidized.

Figure 30: Total Nitrogen Data



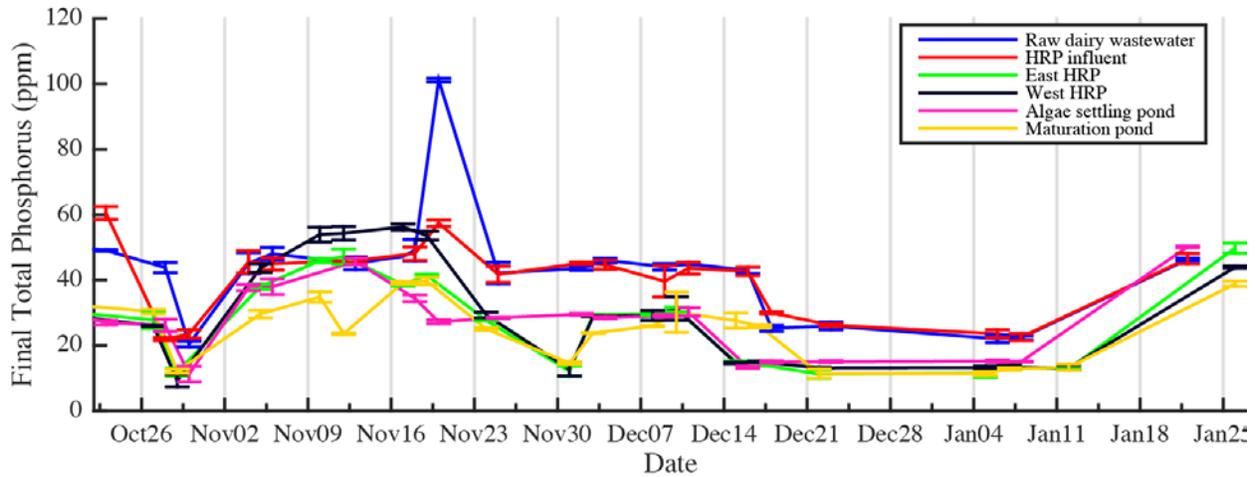
The reactive phosphorus test determines the level of inorganic phosphate (PO_4^{3-}), which is the form most readily available to plants. Excessive levels of this compound serve as a potential indicator for problematic algae/plant blooms downstream (Figure 31). Test kits from Hach (TNT 843/844/845) are used according to Hach method 10209. Like nitrogen, this drops throughout the passage through the ponds as it is taken up by the algae and increases slightly after as the algae decompose.

Figure 31: Reactive Phosphorus Data



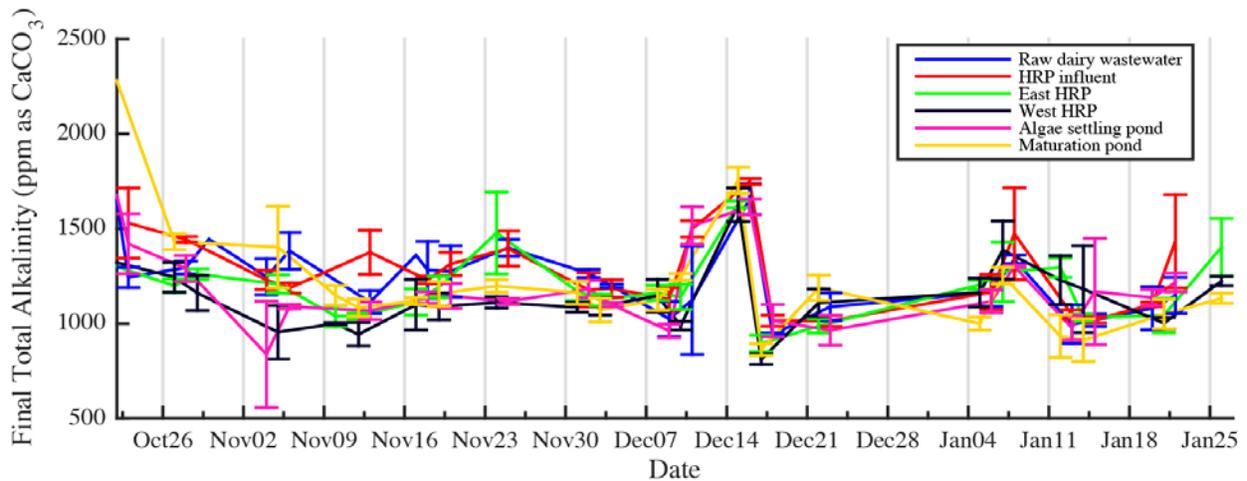
The total phosphorus test is performed to indirectly determine levels of organic phosphorus, which is the form bound to plant and animal tissue (Figure 32). Test kits from Hach (TNT 843/844/845) are used according to Hach method 10210. As this measures all sources of phosphorus in the wastestream, it is not expected to change much throughout the ponds as one kind of phosphorus will be converted to another (e.g. inorganic phosphorus is incorporated into algae, becoming organic phosphorus), and the only loss should be due to volatilization.

Figure 32: Total Phosphorus Data



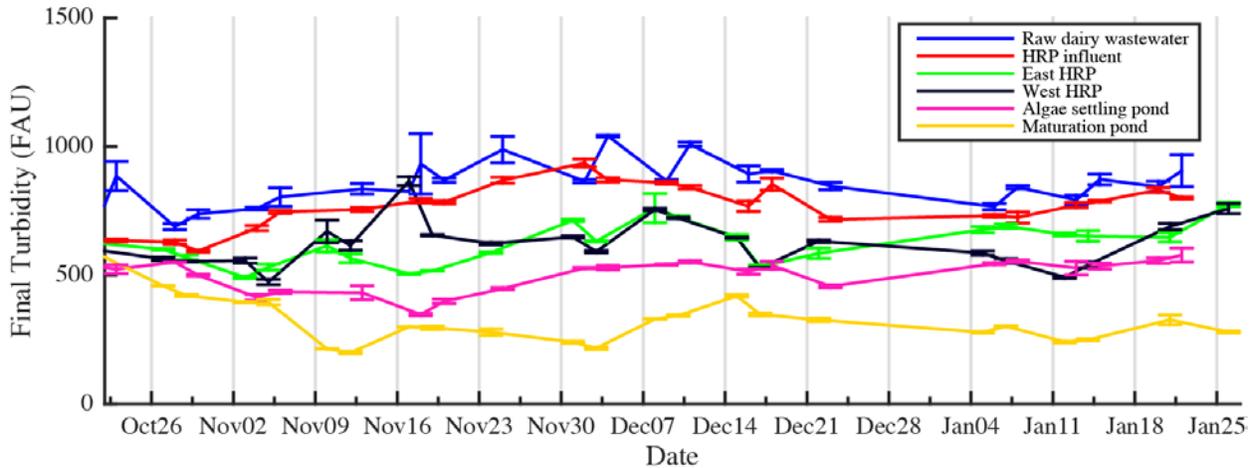
Alkalinity measures the buffering capacity of the water, or its ability to resist changes in pH (Figure 33). Typically this is a proxy for alkaline compounds in the water such as carbonates, bicarbonates and hydroxides. Test kits from Hach (TNT 870) are used according to Hach method 10239. This is not expected to change as a result of treatment.

Figure 33: Alkalinity Data



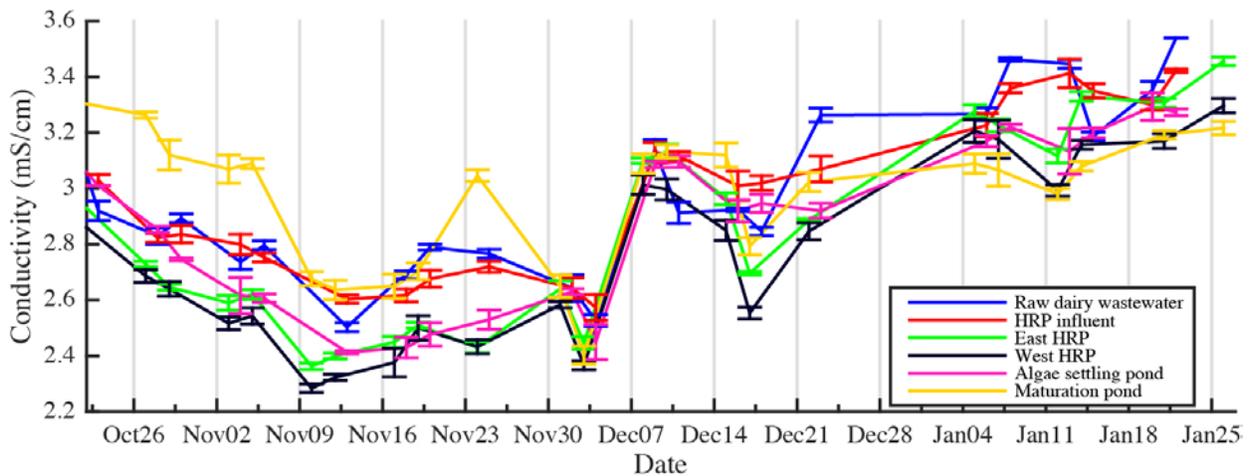
The turbidity test determines the cloudiness of the water as caused by suspended solids in the water column (Figure 34). High turbidity blocks out sunlight penetration into the water, thus inhibiting algae growth. Turbidity is measured using the Hach DR3900 instrument. This drops slightly in the algae ponds as the large waste solids settle out, but drops more significantly in the settling and maturation ponds as the majority of the solids (including algae) settle out.

Figure 34: Turbidity Data



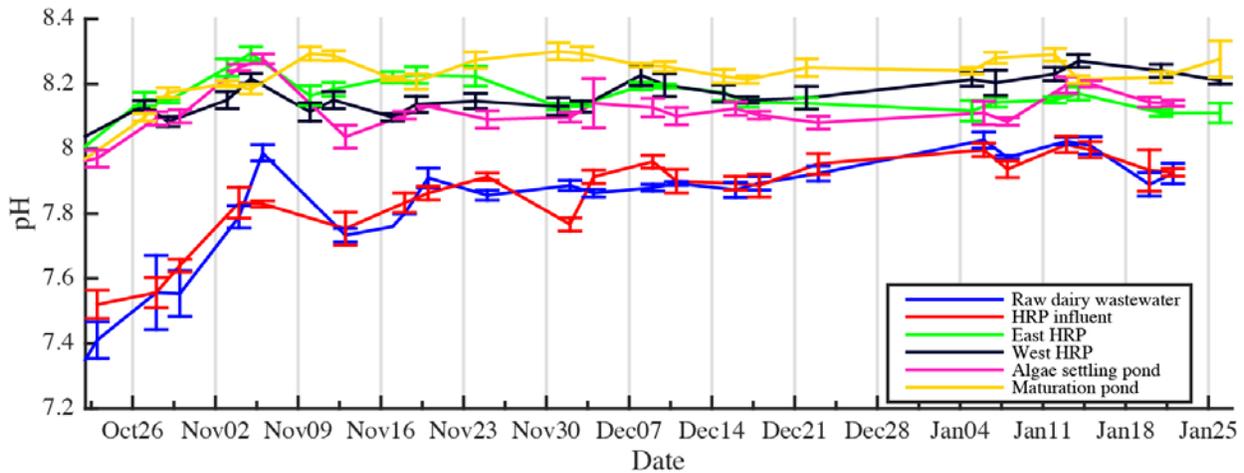
The conductivity measures how easily the water can pass an electrical current which serves as a proxy for the presence of ionic compounds such as chloride, nitrate, sulfate, phosphate, sodium, magnesium, calcium, iron and aluminum (Figure 35). Conductivity is measured using the Hach HQ40d instrument and CDC401 standard conductivity probe. As with alkalinity, this is not expected to change as a result of treatment.

Figure 35: Conductivity Data



The pH determines how acidic or basic the sample is by measuring the ratio of H⁺ and OH⁻ ions (Figure 36). Changes in pH have strong effects on water chemistry and biological reactions of aquatic species. Generally values should range between pH 6 and 9 in a healthy aquatic ecosystem. The pH was measured using the Hach HQ40d instrument and PHC101 gel filled pH electrode. The pH increases significantly in the algae ponds as the algae consume carbon dioxide, making the water more basic.

Figure 36: pH Data



3.3 Energy Savings Results

Working together with CADMUS, an energy metering services company, several power meters (WattNode WNC-3D-240-MB) were installed to monitor electricity consumption of the system. Metering points included the various pumps required to move water through the pond system as well as the motors powering the paddlewheels in the algae raceways. The data was transmitted via Modbus to a gateway, which then enables continuous data logging via the Ethernet network. Additional webcams were also installed at each paddlewheel location and at the algae settling basin to enable remote monitoring of the health of the algae ponds simply by visual inspection of a live video feed.

The QBI demonstration project improves dairy waste treatment compared to a standard anaerobic lagoon by adding algae ponds after the anaerobic lagoon to further process the wastewater. The algae ponds improve the quality of the treated water and create biomass which can be converted to fertilizer or animal feed. Municipal wastewater treatment plants can also apply this system design as it provides a similar level of water treatment with increased benefits.

This section presents the methodology and results for quantifying the energy consumption of the algae-based wastewater treatment system at the dairy and compares these to two baseline systems: 1) a standard unstirred anaerobic lagoon at a dairy, and 2) an activated sludge municipal wastewater treatment system.

3.3.1 Measuring Electricity Consumption

The system required two pumps and two paddlewheel motors that aerate the algae settling pond. The dairy where the demonstration project was constructed is not on flat land; therefore the system requires two pumps to move water uphill. These pumps would likely not be required if similar systems were built at other dairies or municipal wastewater treatment plants, which are typically on flat land in California.

QBI installed meters to record electricity consumption for two pumps and two paddlewheel motors:

- Anaerobic lagoon pump (2 horsepower [hp])
- Algae settling pond pump (2 hp)
- HRP east paddlewheel motor (1/4 hp)
- HRP west paddlewheel motor (1/4 hp)

The meters began recording one-minute interval data in August 2014. QBI collected the data and sent it to CADMUS for analysis. CADMUS reviewed the data and calculated the total average power consumption for each pump and paddlewheel motor and then calculated average daily energy consumption.

To compare energy consumption with traditional wastewater treatment plants, energy consumption per million gallons of water treated per day (kWh/MGD) was calculated. QBI reported that the algae-based wastewater treatment system at the dairy treats five to ten thousand gallons of water per day. CADMUS assumed that an average 7,500 gallons were treated per day for the purposes of this demonstration.

3.3.2 Electricity Consumption Results

CADMUS found that the two pumps and two paddlewheel motors consumed an average of 25 kWh per day, or approximately 3,400 kWh per MGD. Since the two pumps would likely not be required at other dairies or municipal wastewater treatment plants, only the electricity consumption of the paddlewheel motors was considered for comparison to the baseline systems. The two paddlewheel motors consumed 3 kWh per day on average, or approximately 407 kWh per MGD.

3.3.2.1 Compared to an Unstirred Dairy Anaerobic Lagoon

An unstirred anaerobic lagoon does not require any equipment that uses electricity; therefore the addition of the aerobic ponds and the paddlewheels results in an increase in electricity consumption of 407 kWh per MGD.

Though the aerobic ponds increase electricity consumption, this is not a meaningful comparison, as the lagoon method does not provide sufficient waste treatment. The QBI system provides many benefits over an unstirred anaerobic lagoon including valuable biomass, which can be converted to animal feed or fertilizer. Also, the removal of nutrients (tertiary treatment) is critical on a dairy, where the disposal of highly concentrated waste can pollute groundwater.

3.3.2.2 Compared to the Baseline Municipal Wastewater Treatment System

A municipal system that aerates wastewater to enhance treatment is a more appropriate baseline for comparison. To determine the baseline energy intensity of a municipal wastewater treatment system, CADMUS and QBI referred to a report authored by the Water Research Foundation and Electric Power Research Institute in 2013 that researched electricity use in wastewater facilities. The report presents average energy use intensity for different sizes and types of wastewater treatment plants. The team selected an activated sludge waste treatment system that treats less than two MGD as the baseline. This system type on average uses 3,300 kWh per MGD.

QBI's demonstration project with the aerobic lagoons performs the same level of treatment as an activated sludge waste treatment system at a municipal facility, yet only uses 407 kWh per MGD. This is an energy savings of 2,893 kWh per MGD. However, like the lagoon case, this does not take into account tertiary treatment, which would consume even more energy on a municipal plant, so the savings would be even more significant.

3.4 Additional Benefits

Beyond the large energy savings that the system can provide, there are a number of other benefits of using an algae-based system for wastewater treatment. While the benefits are numerous, the typical farm cannot justify the expense to convert a simple lagoon system into an advanced treatment system, unless they are either legally obligated by stricter water/energy/nutrient regulations or motivated by an opportunity to improve their bottom line.

As California faces increasing strains on both limited water supplies and finite energy resources, the "farm of the future" must maximize its resources by setting up a fully integrated operation which will clean its own water, grow its own animal feed, generate its own electricity and fuel, and produce valuable co-products. The QBI technology represents a carefully engineered solution that leverages multiple farming resources to improve the bottom line by remediating and recycling water for improved crop irrigation, producing biomethane for use as a vehicle fuel, generating high-protein biomass for use as a fertilizer or livestock feed, and reclaiming valuable land that was previously used for wastewater treatment operations.

3.4.1 Cleaner Water

Several years of drought conditions in California have made it clear that sustainable farming operations will not succeed without a plan that incorporates the economic realities of water as a resource. This technology enables the growth of higher value crops that require a lower nutrient load by using algae to remove excess nutrients from the waste stream. In addition, the potential to use digester gas to enhance biomass growth will enable the diversion of carbon dioxide (CO₂) from environmental emission to algae production.

3.4.2 Clean Energy Production

Generating energy for sale on the natural gas market represents a significant economic opportunity for dairy farms. The biogas cleanup system developed by QBI will enable a farm to harness the full energy content of its wastewater stream. The platform will couple two processes that possess complementary advantages. Anaerobic digestion will be used to break down

primary waste and generate biogas (composed primarily of CO₂ and methane) while the water from the algae ponds will be used to absorb the CO₂ and convert the biogas to purified biomethane. Biomethane can then be compressed and used as a clean-burning vehicle fuel. A typical 2,000-cow dairy could produce about 180,000 diesel gallons equivalent of biomethane per year.

3.4.3 Renewable Biomass Generation

Feed expenses represent nearly 60% of a dairy farmer's production costs. Purchasing feed from the mid-west is increasingly unsustainable due to high transportation costs and high prices for feed crops, which are increasingly being diverted to biofuel production (e.g. corn for ethanol). To alleviate these challenges, California farmers are searching for local sources of high quality livestock feed. The high-protein algae produced in the high rate ponds can be used as a nutrient-rich animal feed to reduce a farm's feed costs. A typical 2,000-cow dairy could offset over \$550,000 in yearly feed costs using algae biomass as a high quality feed supplement.

3.4.4 Land Reclamation

In addition, using algae, which is 4-5 times more productive than most terrestrial crops, to replace feed grown on agricultural land will provide an opportunity to reclaim land for the growth of more lucrative crops. A typical farm could achieve land reclamation of up to 80%.

3.4.5 Reduced Greenhouse Gas

QBI's algae cleanup technology will have an exceptional effect on reducing the emission of GHG in California. Compared to an uncovered lagoon, which is "business as usual" for 99% of dairies in the state, this technology can reduce GHG emissions by 586%. That is equivalent to displacing 261,878 metric tons of CO₂ per year.

3.4.6 Conservation of Resources

Nitrogen and phosphorus are limited resources yet contribute to environmental pollution (leaching into groundwater) unless actively managed. Since algae growth serves to recycle these valuable nutrients, the facility will eliminate downstream pollution such as eutrophication, which can destroy ecosystems and harm nearby economies.

CHAPTER 4:

Technology Transfer: Tailoring a System for Future Clients

Successfully completing the construction of a large scale dairy wastewater treatment system is an invaluable experience that will help with future installations. While every system will have to be specifically tailored based on the new location, one of the benefits of this system is that has very broad applicability and can be easily replicated on new sites with no major changes to the overall engineering plans. The team performed careful quantitative analysis and have come up with a table that estimates the expenses, the space requirements, the outputs, and the benefits of an arbitrary system based on the findings of the operation (Appendix A). The process described evaluates the demands of future clients to tailor a system for each specific site.

Upon encountering a new dairy client for this technology, the most important first step is to assess the quantity and strength of the client's waste stream. Initial estimates can be made initially based on the size and composition of the dairy's herd, but before any formal designs are developed the water must be tested for common water quality parameters. In general the team tested for pH, conductivity, alkalinity, turbidity, TSS, VSS, COD, total phosphorus, reactive (inorganic) phosphorus, total nitrogen, ammonia nitrogen, nitrate nitrogen, and nitrite nitrogen. After the water quality parameters are determined, the next step is to determine the raw water flows in the dairy's existing wastewater treatment system. A dairy using a flush system for waste handling is going to generate greater wastewater flows than one using a scrape system, and while flush system volumes should be correlated with herd size, site specific differences (such as recirculation number, evaporation on site, leakage etc.) will cause the volumes to differ between sites. Before beginning a design, it is critical to get the most data possible concerning average and peak flows over the course of the year so the waste treatment ponds can be designed to an appropriate size.

If site specific data is not available, or if a design estimate must be developed prior to acquiring it, then representative numbers can be used from established sources. The team used American Society of Biological and Agricultural Engineers (ASAE Standard D348.2, ASABE 2005) for manure composition on a per animal basis. Information from this reference can then be combined with an assumed manure recovery estimate (90%) and flush volume per animal per day (50 - 150 gallons) to estimate a manure waste volume and strength. It should be noted that this technology is best suited to dairies using a flush system rather than a scrape system since flush systems generate larger volumes of a more dilute waste, which are more amendable to algae based treatment. Flush systems are generally installed on larger, newer dairies which typically have more capital than smaller dairies and are therefore better able to install such a system. For the purposes of this report, the team focused on applying the algae technology to a flush dairy.

Another reason that it will be important to test the waste stream is that some dairies may be processing more than just manure. Typically larger dairies either have or are considering installing digesters at some point in the future. Often these digesters will be candidates to

accept "co-digestate" materials to boost revenue from tipping fees and increased gas production. These co-digestate materials are typically some combination of food waste, grease trap waste, or crop residues depending on what is available in the local area. Some of these materials can drastically increase the nutrient concentrations of the dairy's wastewater stream. While this can be a benefit for installing an algae based system, in the sense that there will be a greater (or even critical) need for effective, low cost nutrient removal systems, it is important that all current and future waste management practices be accurately assessed before the design of the waste handling system has begun.

After the dairy's current and future waste stream composition has been assessed the next task is to identify potential sites for the algae pond system. Algae ponds should be situated near existing waste handling lagoons to minimize pumping, but other factors such as soil composition, steepness of the terrain, regulatory factors such as required set backs from milk processing facilities (both existing and those planned in the future) can complicate the site selection process. As land availability is commonly a constraint, the team developed a design protocol based on the available land that then can be used to determine how much of the dairies waste can be treated with an algae based system.

An Excel-based spreadsheet was created to assist in the calculations necessary for designing an algae based treatment system (Appendix A). The first item is land area available for high rate algae ponds (HRP's), which is generally the constraining factor for the installation of a system. The next parameter is a target algae productivity, which for Southern California or the Central Valley is 15 g/sq. meter/day of HRP culture (22.2 metric tons/acre/year). This number is a reasonable approximation of algae productivity in a temperate climate, in a nutrient rich media with moderate temperatures and most importantly an adequate CO₂ supply. While atmospheric CO₂ can be limiting in some cases, one option to overcome this issue is to use the gas from an on-site digester to provide supplemental CO₂. The Van Ommering Digester will be an excellent source of CO₂, and a system for transferring this gas into the algae water was designed and constructed. However, the digester was temporarily turned off to upgrade the cover, and the farmers restarted it with a large load of grease trap waste that created an imbalance in the microbial community and has limited its gas production. The team is working on increasing the gas production so the gas to boost biomass production in the ponds can be used. While this is not essential to perform complete cleanup of the waste, it will enhance the process even further.

One of the most important factors affecting productivity of an algae based treatment system, especially one using dairy waste is the turbidity of the incoming waste stream. Turbidity has a negative effect on algae growth because it scatters the sun's light and thus reduces photosynthetic activity. Light is an essential nutrient and depending on the culture conditions can often be the limiting nutrient for algae growth (along with carbon dioxide). High turbidity in dairy waste streams will have a pronounced negative effect on algae productivity, and therefore it is critical that steps are taken to lower turbidity values before the water is passed to an HRP system. One method to do this is to include upstream treatment ponds, variations of which already exist on most dairies. All dairies in California will have some type of holding lagoon where wastewater is held for at least 60 days for stabilization prior to land application.

Generally the longer the water is held, the greater the waste breakdown and the fraction contributing most to turbidity (total and volatile suspended solids) will be removed over time. Unfortunately, even a holding time of 60 days is usually not sufficient to lower the turbidity of the incoming waste stream to levels optimal for algae growth (<100 FAU, preferably < 50 FAU). Again there is a tradeoff between lagoon size and treatment quality. In general most dairy farm lagoons are present due to government requirements and are often placed in an area of the dairy where there was enough space, leading to a lagoon shape that may not be optimal for treatment (i.e. the potential for short circuiting between the inlet and the outlet may be high).

The turbidity problem may be exacerbated if an anaerobic digester is present, given that the turbidity values from such systems are generally very high and usually flow directly into the holding lagoon. Given the space constraints on existing California dairies the team believes that the best method to remove fine solids and corresponding turbidity is to use chemical flocculants combined with mechanical solids separation devices. Flocculants have a long history in wastewater treatment and work well for clarification in conjunction with primary or secondary treatment. Care has to be taken when choosing a flocculant that the compound is compatible with any downstream use for produced biomass. For example if the algae biomass is to be used as animal feed then the flocculant must be chosen with this requirement in mind. Flocculants also have been extensively investigated for use in removing algae from the effluent of HRP systems. If this method is to be pursued, again the compatibility with feed or other uses of the algae is of paramount importance. Flocculant cost is also of critical importance and can limit the types of feeds produced to only those of relatively high value if they are used.

After available land area and algae productivity have been determined, generally a retention time for the HRP pond system is specified. Anywhere from 3 to 10 days can be acceptable, but it is generally assumed a retention time of five days. The team specified the pond depth to be between 6 to 10 inches depending on the size of the pond. Obviously grading a pond which may be over an acre in size to a precise depth of six inches is a challenge, but it can be accomplished using modern laser grading tools. It was necessary to course grade the high rate ponds using a general excavation contractor and then bring in a grading specialist to finish grade the HRP's to the required tolerance. Care must also be taken to adequately compact the HRP subgrade and ensure adequate drainage to prevent settling of the pond floor over time.

After the pond depth and surface area have been specified, the HRP volume can be easily calculated. With knowledge of the culture volume and the expected retention time the expected HRP effluent flow can be calculated. Using the target areal productivity and the HRP surface area, the total expected daily biomass production from all ponds combined can be calculated. Next, using the effluent flow rate and the biomass production rate, the average HRP algae concentration can be calculated, and you can compare your predicted algae concentration to that expected from existing algae literature, which provides this empirical equation: $\text{maximum concentration (mg algae / L)} = 9000 \div \text{pond depth in centimeters}$. This limitation on algae concentration is essentially due to the algae cells "self shading" each other and limiting the available light as the culture depth increases. Practically, if the calculated algae concentration is much higher than what can be reasonably achieved, this indicates that either the assumed productivity is too high or the retention time is too long (or both).

The next step is to consider the incoming nutrient loadings from the waste influent stream. The team assumed that algae biomass is 47% Carbon, 8% Nitrogen and 1% Phosphorus by dry weight. Knowing the expected daily biomass production, the team can determine how much of each of these elements is required. Carbon can be derived from a variety of sources (atmosphere, aerobic waste breakdown, generator exhaust, etc.). However, from a waste treatment standpoint, nitrogen and phosphorus removal is most important. These systems are generally designed around removal of these elements and generally focus on nitrogen removal as it will usually become limiting before phosphorus will. The team specified the desired nitrogen removal percentage and also the desired algae nitrogen recovery. Ideally these numbers would be the same, but ammonia nitrogen can be removed because of volatilization which will obviously not be recovered by the algae. Ammonia volatilization is especially pronounced in algae ponds having high pH (the pH of a HRP in noon day sun can easily reach 9.0 and even 10.5-11 if not run properly). The high surface area to volume ratio of an algae pond combined with paddlewheel mixing also contributes to ammonia volatilization. This volatilization can actually be the dominant method of nitrogen removal, which while achieving the goal of preventing discharge to receiving bodies of water is still not the most environmentally friendly method of removal. To prevent excessive volatilization, pH control of the HRP ponds is crucial.

The necessary influent flow rate as the effluent rate is calculated plus the amount lost from evaporation. Pan evaporation data for California is available from the Western Regional Climate Center [<http://www.wrcc.dri.edu/htmlfiles/westevap.final.html>]. Once the influent flow rate has been calculated, it can be multiplied by the incoming total nitrogen (TKN) concentration to determine the nitrogen mass loading of the system. Because of the concentrated nature of dairy manure it will usually be found that the nitrogen loading is in excess of the requirements of the algae. This is essentially due to the algae becoming light limited (hence limiting their maximum concentration and productivity) before they become nitrogen limited under these conditions. At this point the options for greater nitrogen removal are:

1. Dilute the incoming waste stream with fresh or brackish water
2. Remove the algae from the HRP effluent and recirculate the water back into the HRP
3. Raise the pH of the HRP and remove nitrogen through volatilization.

Adding CO₂ will not have an effect on this nitrogen removal issue, since light rather than CO₂ is assumed to be the limiting nutrient. It is believed that the best course of action is to combine some degree of recirculation with fresh water addition, such that no more than 50% of the influent is lost to evaporation. These future systems will take the effluent from the algae settling ponds (which have the algae removed) and recirculate it back into the HRP ponds to remove the maximum amount of nitrogen possible. The recirculation number will be primarily determined by the algae productivity and incoming nitrogen concentration.

As mentioned above, effluent from an HRP is passed to an algae settling pond before either recirculation or discharge to the next treatment stage. Ideally such a settling pond would have

a retention time of 2-3 days but can be designed with a retention time of as little as one day. Generally algae settling ponds are designed to remove algae simply by gravity settling of the biomass and species cultivated in well mixed HRP's are usually amenable to this method. However it will not be possible to remove all algae biomass using gravity. In fact when the final process water is to be used to irrigate crop land it will be beneficial to have some residual algae biomass, because the algae will act as a slow release fertilizer when applied to a field (unlike mineral fertilizer, whose components can rapidly pass through soil into groundwater). However, if complete removal of algae is desired, then some type of flocculation combined with gravity settling will likely be necessary.

The effluent from an algae settling pond will generally be split into a recirculation stream and a discharge stream with the ratio determined by the recirculation requirements of the system. The discharge stream can be transferred to a final holding or maturation pond depending on the requirements of the system. A maturation pond can be useful for improving the treatment quality of the system. The sun exposure can reduce residual pathogen numbers and the pond can serve as an aquatic habitat. However, one of the biggest benefits of a maturation pond from an operational perspective is simply to serve as a reservoir for final crop irrigation.

Given all of these considerations, a template for performing detailed calculations for pond configurations, dimensions, surface areas, and volumes can be found in a second spreadsheet (Appendix B). Also included in this spreadsheet are calculations for the HRP paddlewheel power requirements based on pond sizes and depths. Torque calculations based on paddlewheel size and flow velocities are also presented which are useful when sizing gearboxes and motors. Using all of these tools, a system specifically tailored for future clients can be developed that will help them improve the quality of their treated water while preventing groundwater contamination and conserving energy.

GLOSSARY

Term	Definition
ASB	Algae settling basin
°C	Degrees Centigrade
CO ₂	Carbon dioxide
COD	Chemical oxygen demand
DG	Decomposed granite
EPDM	Ethylene propylene diene monomer
EPIC	Electric Program Investment Charge
FRP	Fiberglass-reinforced plastic
g/sq. meter/day	Grams per square meter per day
hp	Horsepower
HRP	High rate pond
kWh	Kilowatt-hour
kWh/MGD	Kilowatt-hours per million gallons per day
LLDPE	Linear low-density polyethylene
Mg algae/L	Milligrams of algae per liter
MGD	Million gallons of water treated per day
ORP	Oxidation-reduction potential
PVC	Polyvinyl chloride
QBI	Quantitative Biosciences, Inc. (company)
RD&D	Research, development, and demonstration
Smart Grid	Smart Grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities.
SSP	Solids settling pond
TKN	Total incoming nitrogen

TSS	Total suspended solids
UV	Ultraviolet
VSS	Volatile suspended solids

APPENDIX A

This is an Excel spreadsheet and can be found online.

APPENDIX B

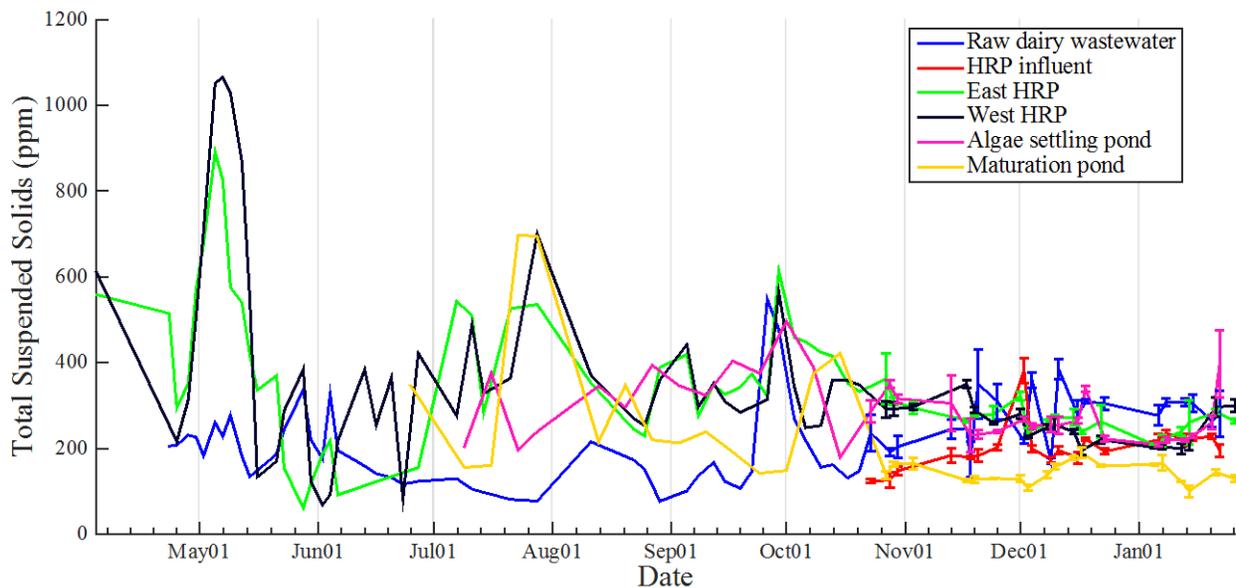
This is an Excel spreadsheet and can be found online.

APPENDIX C: Full Time Series Data from Ponds

In this section presents plots that track each of the parameters described in the Final Wastewater Treatment Test Plan for the entire duration of the data collection. While data collection began in April 2014, the process was refined in November, when the error bars begin and data triplicates were then done to ensure reliability of the tests.

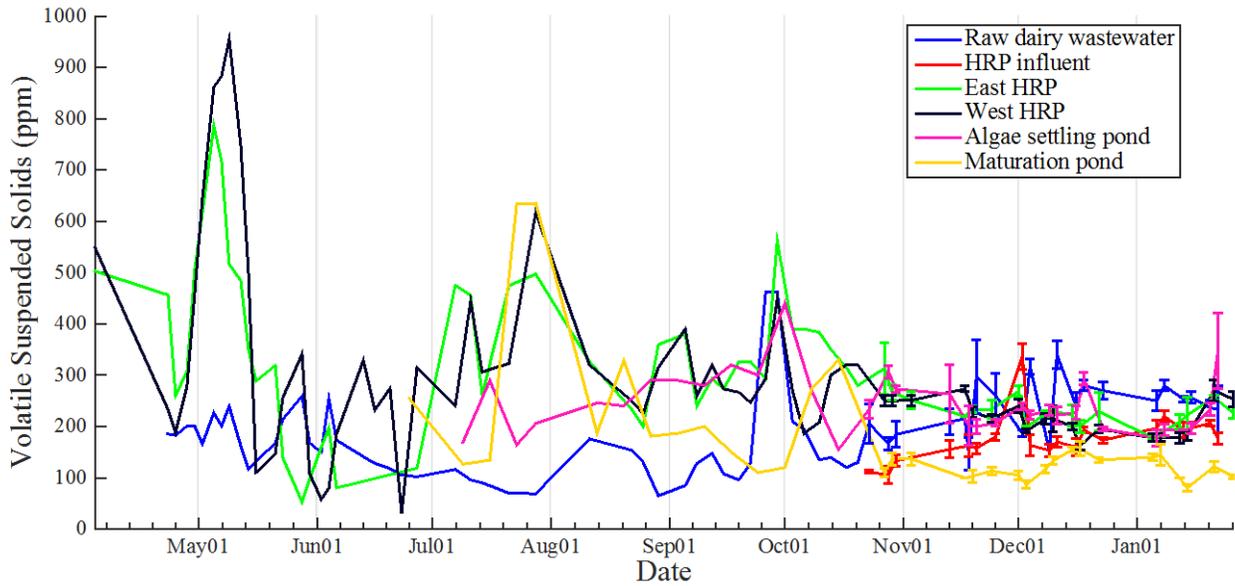
The **total suspended solids (TSS)** test determines the amount of solids, which are retained after passing the sample through a standard glass fiber filter and drying to a constant weight at 105 oC.

Figure C1: Complete TSS Data



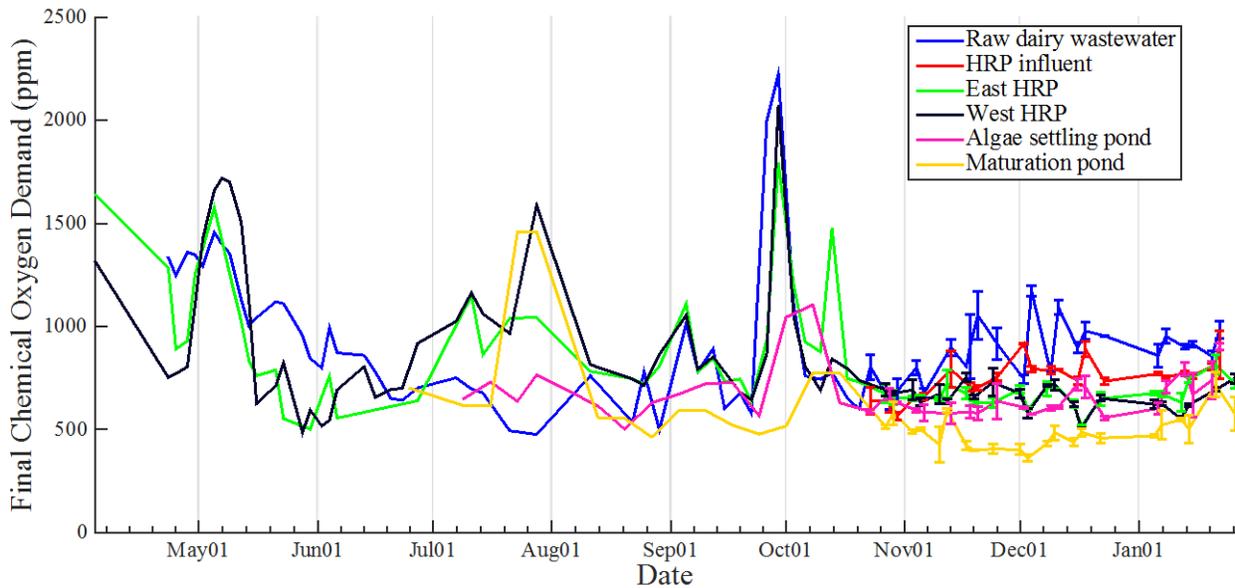
The **volatile suspended solids** test determines the organic solids fraction of TSS present in the sample. The VSS fraction is obtained by igniting the solids in a furnace at 550 oC and weighing the remaining inorganic solids fraction.

Figure C2: Complete VSS Data



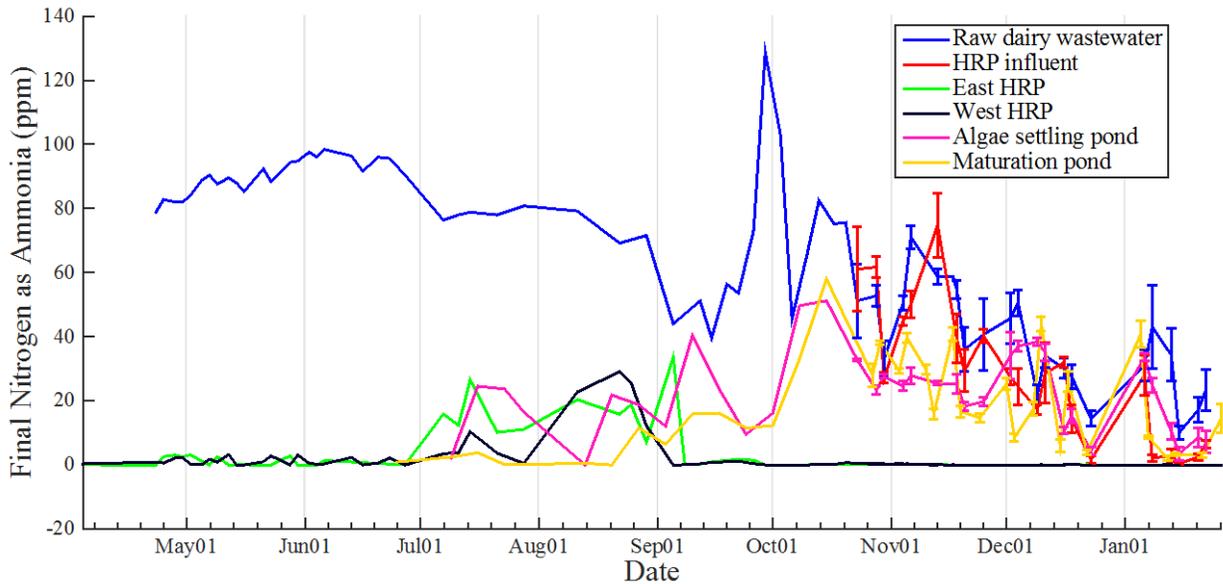
The **chemical oxygen demand** represents the level of organic compounds present in the sample, which can be fully oxidized by a strong chemical oxidant. Test kits from Hach (TNT 822/823) are used according to Hach methods 8000 and 10212.

Figure C3: Complete COD Data



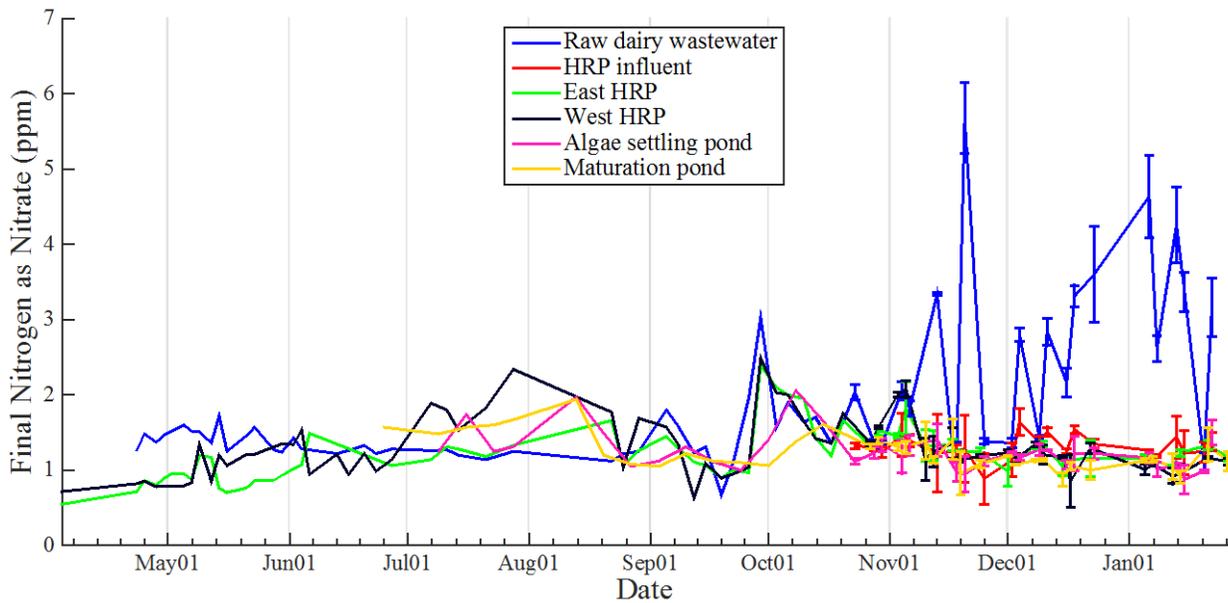
The **ammonia** test determines NH_3 and NH_4^+ levels, where the unionized form (NH_3) is a toxic compound to many aquatic organisms. Test kits from Hach (TNT 830/831/832) are used according to Hach methods 10205 ULR/LR/HR.

Figure C4: Complete Ammonia Data



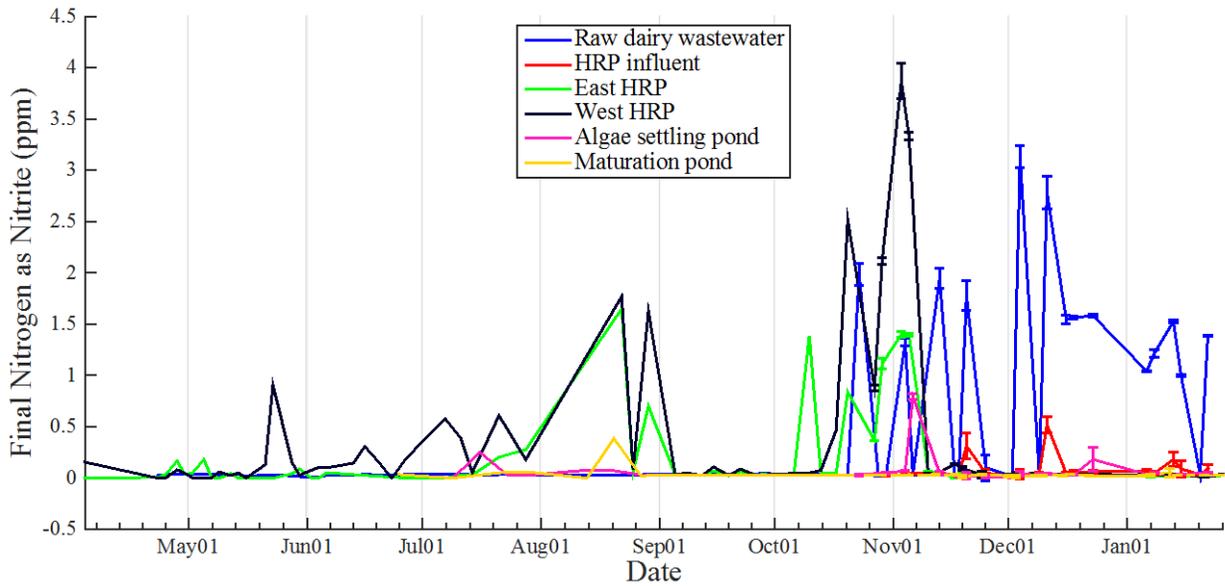
The **nitrate** test determines the level of NO_3^- , which is generally regarded as a nontoxic nutrient for photosynthetic species but excessive levels can indicate an unbalanced ecosystem at risk of eutrophication. Test kits from Hach (TNT 835/836) are used according to Hach method 10206.

Figure C5: Complete Nitrate Data



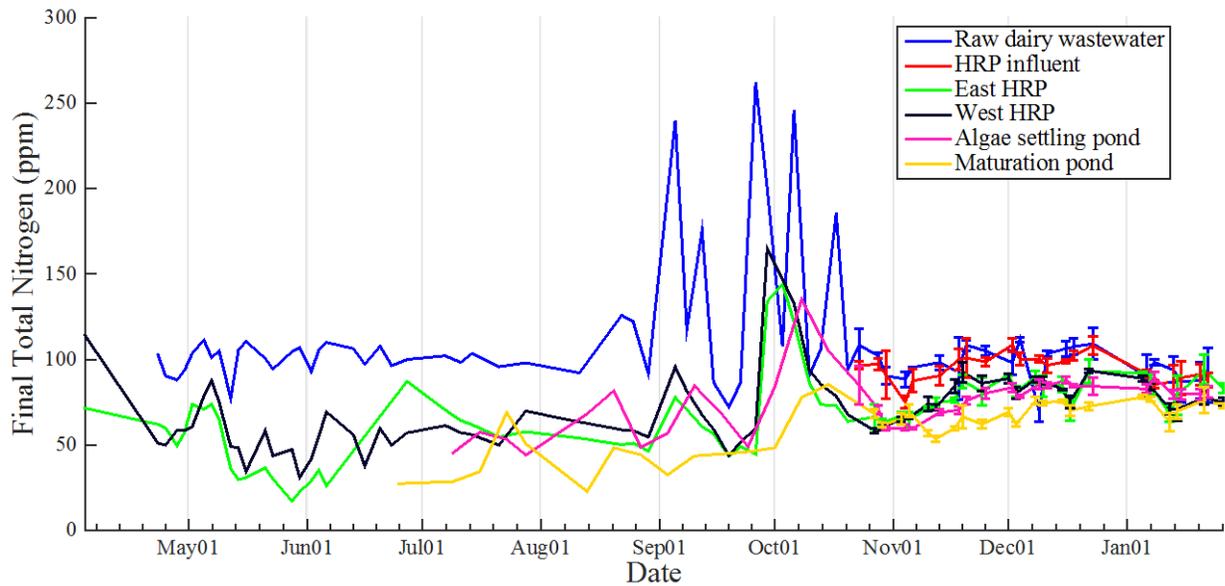
The **nitrite** test determines the level of NO_2^- , which is extremely toxic to aquatic life but is generally present in only trace amounts in oxygenated environments due to its rapid oxidation to nitrate. Test kits from Hach (TNT 839/840) are used according to Hach methods 10207/10237.

Figure C6: Complete Nitrite Data



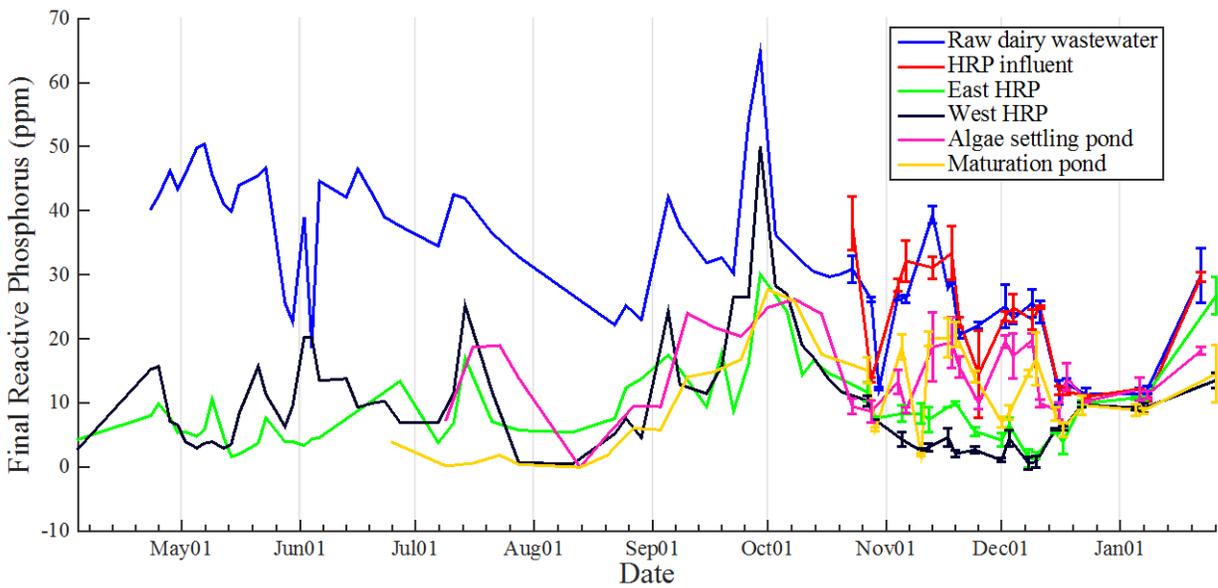
The **total nitrogen** is measured to determine combined levels of all nitrogen species. Test kits from Hach (TNT 826/827/828) are used according to Hach method 10208.

Figure C7: Complete Total Nitrogen Data



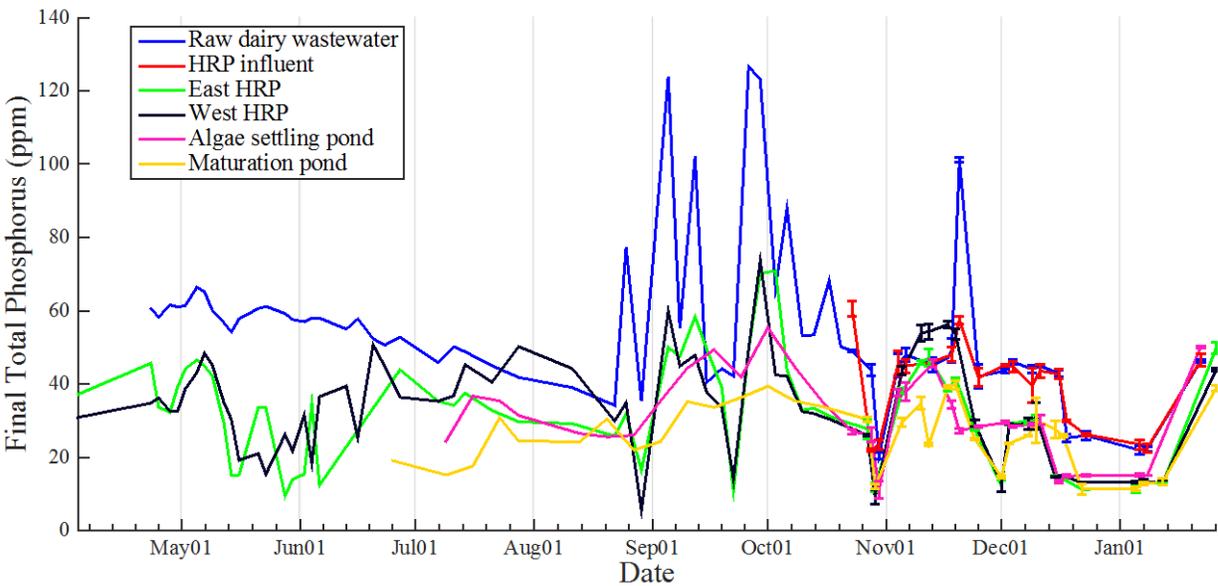
The **reactive phosphorus** test determines the level of inorganic phosphate (PO_4^{3-}), which is the form most readily available to plants and thus excessive levels serve as a potential indicator for problematic algae/plant blooms downstream. Test kits from Hach (TNT 843/844/845) are used according to Hach method 10209.

Figure C8: Complete Reactive Phosphorus Data



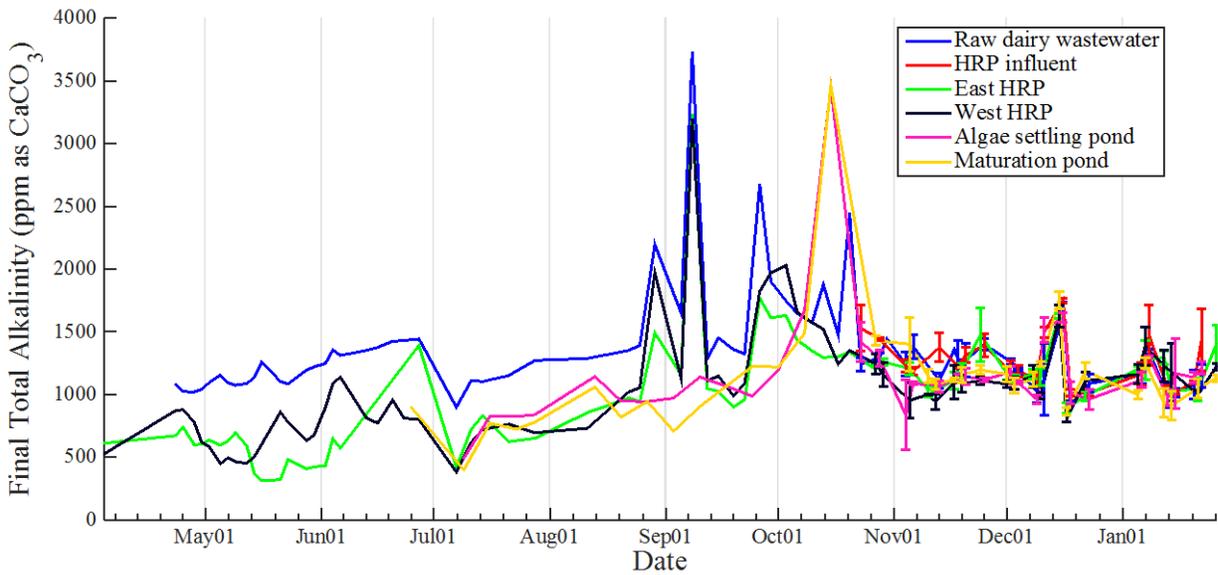
The **total phosphorus** test is performed to indirectly determine levels of organic phosphorus, which is the form bound to plant and animal tissue. Test kits from Hach (TNT 843/844/845) are used according to Hach method 10210.

Figure C9: Complete Total Phosphorus Data



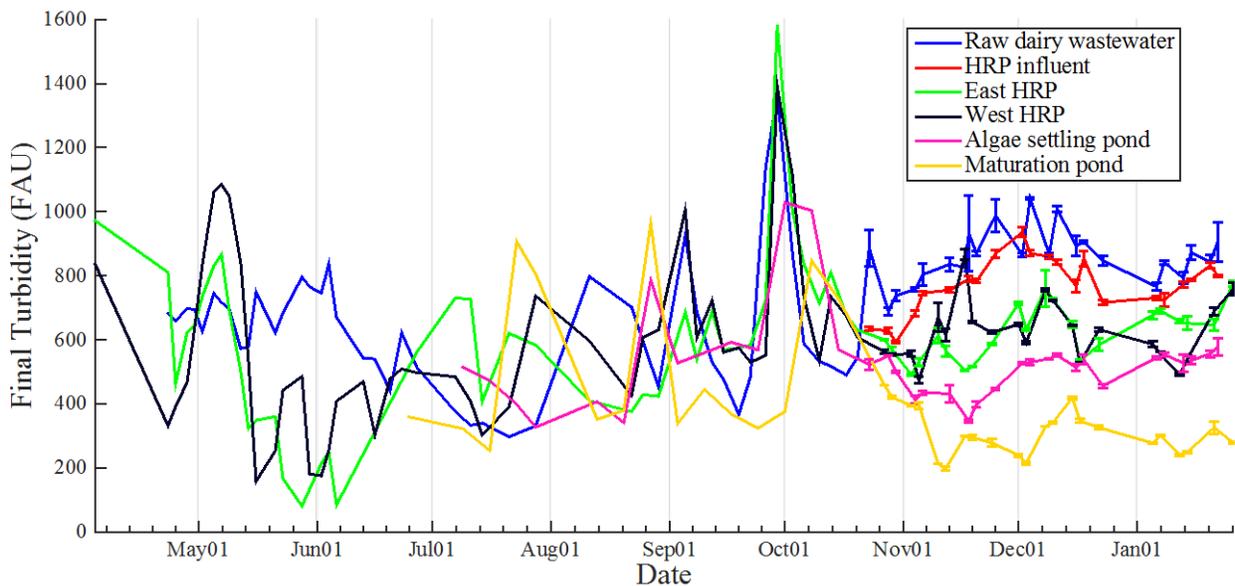
Alkalinity measures the buffering capacity of the water, or its ability to resist changes in pH. Typically this is a proxy for alkaline compounds in the water such as carbonates, bicarbonates and hydroxides. Test kits from Hach (TNT 870) are used according to Hach method 10239.

Figure C10: Complete Alkalinity Data



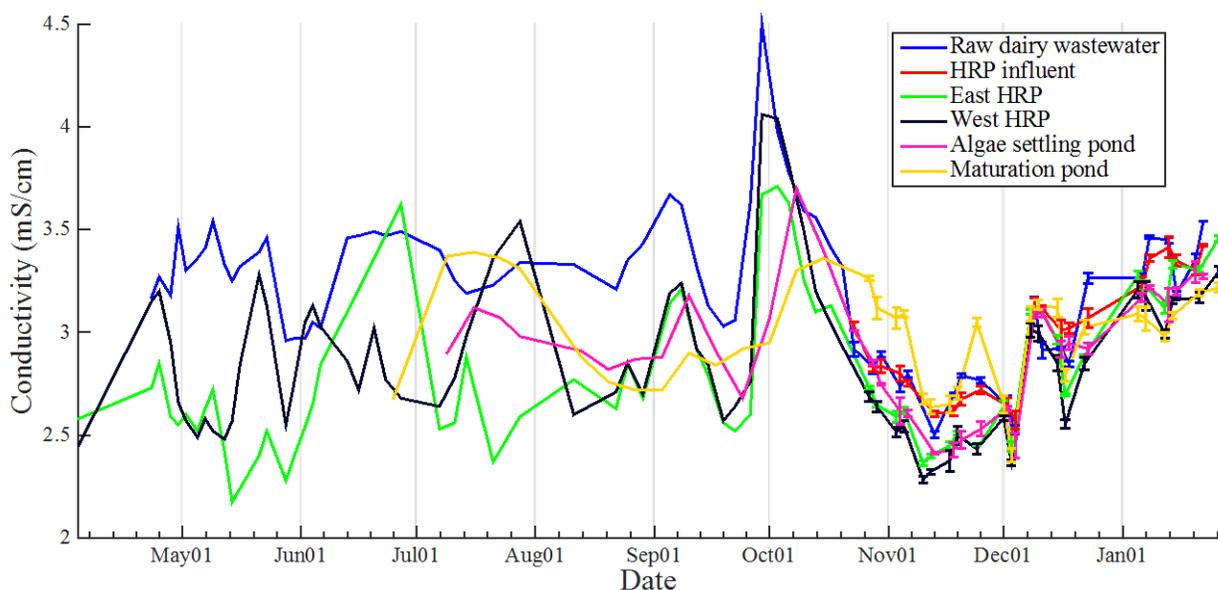
The **turbidity** test determines the cloudiness of the water as caused by suspended solids in the water column. High turbidity blocks out sunlight penetration into the water, thus inhibiting algae growth. Turbidity is measured using the Hach DR3900 instrument.

Figure C11: Complete Turbidity Data



The **conductivity** measures how easily the water can pass an electrical current which serves as a proxy for the presence of ionic compounds such as chloride, nitrate, sulfate, phosphate, sodium, magnesium, calcium, iron and aluminum. Conductivity is measured using the Hach HQ40d instrument and CDC401 standard conductivity probe.

Figure C12: Complete Conductivity Data



pH determines how acidic or basic the sample is by measuring the ratio of H⁺ and OH⁻ ions. Changes in pH have strong effects on water chemistry and biological reactions of aquatic species. Generally values should range between pH 6 and 9 in a healthy aquatic ecosystem. pH is measured using the Hach HQ40d instrument and PHC101 gel filled pH electrode.

Figure C13: Complete pH Data

