Task 2.6 Final Report

Formulate Technology Alternatives

For the Project Entitled

Dairy Best Available Technologies in the Okeechobee Basin

SFWMD Contract No. C-11652

Submitted By

SWET, Inc.
Soil and Water Engineering Technology, Inc.

In Association With

MOCK·ROOS
CH2M HILL
ENTEL

August 2, 2001

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FORMULATE TECHNOLOGY ALTERNATIVES

FOR PROJECT ENTITLED

DAIRY BEST AVAILABLE TECHNOLOGIES IN THE OKEECHOBEE BASIN

SOUTH FLORIDA WATER MANAGEMENT DISTRICT
CONTRACT NO. C-11652

DEVELOPED BY

SOIL AND WATER ENGINEERING TECHNOLOGY, INC.

IN ASSOCIATION WITH

MOCK, ROOS & ASSOCIATES, INC.,

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AND

ENTEL ENVIRONMENTAL COMPANIES, INC.

AUGUST 2, 2001

THE INFORMATION PROVIDED IN THIS REPORT HAS BEEN PREPARED UNDER MY DIRECT SUPERVISION AND IS INTENDED TO BE IN CONFORMITY WITH MODERN ENGINEERING PRINCIPLES APPLICABLE TO WATER RESOURCE MONITORING.

Signed and Sealed by

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Formulation of Best Available Technology Alternatives

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Introduction

The goal of the Dairy BAT Project is an unbiased selection, implementation, and monitoring of Best Available Technologies to significantly reduce dairy industry phosphorus (P) exports to the Okeechobee Basin and to bring about the most effective and substantial water quality improvements in the shortest possible time. The first step in this process is to formulate the technological alternatives available to the dairies to meet that goal. This technical memorandum:

- Provides a list of the major types of technology that may be necessary to meet project goals.
- Identifies the farm area or areas in which the technologies may be applied and the application options for each of the farm areas
- Develops a draft set of alternatives that includes feasible combinations of options

Major Technologies

Phosphorus management can be divided into techniques that reduce the amount of P that comes onto the farm or onto an area of the farm, those that remove P that is on the farm, and those that store P on the farm in an environmentally safe fashion. A variety of best management practices to reduce the amount of P imported onto the farm and to control the location where phosphorus is applied will be considered with the development of the Comprehensive Nutrient Management Plan and final evaluation of technologies. This report deals strictly with "hard" technologies – machinery, processes, structures, or chemical applications that remove from or reduce waste stream P or make the P biologically unavailable. The major technology categories (Table 1) are applicable at one or more farm areas, but only chemical treatment (of one sort or another) is theoretically applicable at any area of the farm or point in the waste stream.

Manure Collection

The first step in any manure management system is to have an effective manure collection system that will prevent undesired losses to stormwater while efficiently delivering the manure to the waste management system. The current lactating cow systems in the Okeechobee basin vary from near total confinement in freestall barns to having the cows in pastures for up to 70% of the time. Manure from pasture-fed cows cannot be collected for later treatment. If the manure is not uniformly deposited or if it is deposited at levels greater than crop uptake rates, significant offsite losses in drainage can occur.

Freestall Barns

Freestall barns offer the greatest efficiency for manure collection because the cows can be maintained on concrete 100% of the time. However, freestall barns are expensive to build and have been known to cause hoof problems that result from cows being on concrete fulltime. Many dairymen have concerns about freestall barn for this reason and because there are extra labor costs involved in maintaining the cow beds. Cooling is also limitation because sprinklers are needed to make up for the lack of access to cooling ponds. Freestall barns cost about $500 to $800 per cow to construct.

TABLE 1. TECHNOLOGY ALTERNATIVES AND APPLICATION AREAS

	Application area for P removal technology				
Single Process Technology	**Barn wastes**	**HIA**	**Field**	**Edge of field**	**Applicability**
Manure collection			X		**High**
Freestall barns (scraped/flushed)			X		**High**
Feed/shade barns (scraped/flushed)			X		**High**
HIA confinement (with cooling ponds)			X		**High**
Solids separation					**High**
Screen, centrifuge, screw press	X	X			**High**
Settling pond (size dependent)	X				**High**
Chemical treatment of waste stream					**Intermediate**
with solids	X	X			**Low**
Without solids (including runoff)	X	X		X	**High**
Chemical treatment of separated solids	X	X			**Low**
Chemical treatment of soils		X	X		**Intermediate**
Bioprocessing					
Anaerobic lagoon	X	X			**Intermediate**
Anaerobic lagoon series	X	X			**Low**
Anaerobic digesters / covered lagoons	X	X			**Low**
Anaerobic batch or unit processes	X	X			**Low**
Aerobic Lagoons	X	X			**Low**
Aerobic digesters	X	X			**Low**
Methane generation	X				**Low**
Plant and algal based systems		X		X	**Low**
Land Application of treated/untreated effluent	X	X			**High**
Vegetated buffers				X	**High**
Surface treatment wetland					**High**
High strength	X				**Low**
low strength	X	X		X	**High**

Table 1. Technology alternatives and application areas (continued)

Single Process Technology	Application area for P removal technology: Barn wastes	HIA	Field	Edge of field	Applicability
Stormwater retention and reuse	X	X		X	**High**
Phyto-remediation pond	X			X	**Low**
Composting of separated solids	X	X			**Intermediate**
Proprietary technologies	X	X	X	X	**Intermediate**

Combined Technology Systems	Barn wastes	HIA	Field	Edge of field	Applicability
Confinement for manure collection-solids separation-composting	X	X			**High**
Confinement for manure collection-Solids separation-anaerobic digestion-land application-chemical polishing	X	X			**High**
Confinement for manure collection-Aerobic digestion-solids separation-land application-chemical polishing	X	X			**High**
Field treatment-Stormwater retention/reuse-wetland-chemical treatment		X		X	**High**

Feed/Shade Barns

Feed/shade barns are the second most efficient way to collect manure, but the efficiency of collection will be management dependent. The time spent in a feed/shade barn can vary between 30% to 60%. The remaining time is spent in the milk parlor and pastures/lots. Manure deposited in pastures or lots is not easily collected or controlled. Feed/shade barns cost about $200 to $500 per cow to construct.

HIA Confinement

The high animal traffic and staging areas near the milk parlor, feed/shade barns, and feed/water troughs where bare ground exists are called high intensive areas (HIAs). Containment of drainage from HIAs was the primary design feature of the Okeechobee Dairy Rule. The concept is still valid and most HIA areas installed as a result of the Dairy Rule continue to be used to prevent nutrient-laden runoff water from leaving the dairy. To improve containment and manure collection for manure deposited outside of concreted surfaces, it is recommended that all HIAs, sites where animal densities are greater than sustainable by the pasture grasses, be contained with a perimeter ditch system. This collection technique is not ideal because only a portion will be washed off to the waste management system. The majority of the manure deposited in the HIA remains in and on the soils. HIAs require constant management in the form of scraping manure and reshaping the surface soils to maintain the elevations.

Ideally, HIAs used with feed/shade barns should be large enough so that the animals will be confined within the HIA 100% of the time. This would prevent uncontrolled manure deposition in outer pastures. Cooling ponds can be integrated into the HIA design, but will require significant maintenance. Concrete HIA cooling ponds, currently being tried at one dairy, could prove to significantly reduce maintenance costs and improve herd health.

HIA perimeter ditches will cost about $15 to $35 per linear foot to construct and will increase waste storage ponds costs by about $10,000 to $25,000 per HIA acre contained. Concrete cooling ponds cost in the neighborhood of $15,000 to $20,000 each, but offer significant improvements over dirt cooling ponds.

Solids Separation

Removal of solids from the waste stream as a first step in management has the potential to remove up to 60% of the total phosphorus load, depending on the type of equipment used and the percent solids in the waste stream. There are several methods available (Table 1, Solids Separation), of which the screen, screw press and settling technologies are more common, and the belt press and centrifugal equipment are less common.

Solids separation can be used on scraped or flushed manure, and on scraping from the HIA areas around the barn. Benefits of solids separation include

- Reduction of waste stream TP concentration
- Reduction of the volume of manure that needs to be handled
- Reduction of organic loading to any treatment system
- Improvement in anaerobic digestion lagoon performance
- Production of value-added products
- Use of solids as directly applied fertilizer.

As a general rule Okeechobee dairies have a relatively dilute waste stream (0.5% to 1.5% total solids) and mechanical separators typically work more effectively on more concentrated streams (>3% solids). Performance of the solids separating equipment shown in Table 2 is primarily for those more highly concentrated streams. Solids may contain as much as 20% of the phosphorus in the waste (Moore 1989, in Converse et al. 2000). Lower solids concentration results in much less efficient removal of the solids, and, since the entire stream has to be passed through the equipment, a much longer processing time. However, where scraping rather than flushing is employed for removal of wastes, and water separation is necessary or desirable these technologies can be effective in removing P from the wastestream. Removal of the separated manure solids from the farm provides the greatest net benefit. This may be as raw waste solids or after other treatments (e.g. composting). Application to fields results in a reduction of P equal to the feed that is harvested and removed. It is likely however, that some of the phosphorus in the land-applied solids will be discharged from the farm as a result of stormwater runoff. The rate of loss due to runoff is crop and application rate dependent.

Settling basins have been found to be more effective for separating solids from dilute manure streams (Converse et al. 2000), but removal rates of much greater than 10 percent of the total P load were not found during the literature search process. A suggested potential of 50% manure solids removal in shallow concrete settling basins (Sheffield et al 2001) would result in a maximum 10% P load removal for manure with a P burden of 0.2% as has been found for Florida dairy manure (Harris et al. 1990). Phosphorus losses in the waste pond systems in Okeechobee have been documented with over 80% P removal rates, which can be primarily attributed to sedimentation and biological processing over long holding times. However, P is spread over the very large pond bottoms and therefore would not be easily recoverable for other uses.

TABLE 2. PERFORMANCE OF SEVERAL SOLIDS REMOVAL TECHNOLOGIES FOR DAIRY AND OTHER ANIMAL WASTE STREAMS WITHOUT CHEMICAL AUGMENTATION
Data from Zhang and Westerman (1997), Converse et al. (2000)

Technology	Size (mm)	Total Solids (%)	TP removal (%)	Waste Source
Screen Devices				
Stationary	1.68		7 – 9	Dairy
Vibrating	0.6 - 1.7		8 – 16	Dairy
Centrifuge	1 - 7.5	~15	58 – 68	Swine
Belt Press		3-8	18 – 21	Swine
Tangential Flow			50%	Scraped Dairy
Settling Basin	All sizes	.5 – 8	2 – 70	Dairy

One important application of separation, particularly prior to introduction of wastes into storage ponds, is removal of sand. Sand is a convenient and healthy bedding material for freestall bedding but it mixes with the manure and becomes difficult to separate. HIA scraping also results in sand entering the wastestream. Sand can increase periodic management of storage ponds if the manure stream is introduced directly into storage, but can be removed either by settling or by commercial sand manure separators (Wedel and Bickert 1998). Sand can then be recycled for bedding or to maintain elevations in the HIA. Use of a sized sand (e.g. DOT size D sand) may increase performance and reduce operating costs by increasing equipment lifetime, but it may be difficult to convince dairymen with relatively unlimited sand immediately processed

For this project solids separation may be a highly beneficial addition to the waste management process, if not already practiced, or if significant improvements in the existing process can be made.

Tangential flow separators have only recently been applied to dairy waste. The primary use has been by QED, an Australian firm as a proprietary technology. The technology uses large circular tanks with conical bottoms. Waste enters the tank tangential to the tank wall to create a vortex rotation. Solids drop to the bottom of the cone section and are constantly removed to a secondary-thickening tank. Chemical additives are often needed to achieve adequate solids separation. Supernatant is removed from the top of the tanks. This technology appears very promising, but technical data on the system performance were not available. This technology may be very similar to "Claricone" technology that has already been tested with Okeechobee dairy waters. This technology proved effective, but at hydraulic rates much lower than those necessary to effectively process the volume of water that the dairies generate daily.

Chemical Treatment of the Waste Stream

Treatment of the waste stream with chemicals to settle solids and remove phosphorus has been a mainstay of the wastewater treatment industry for many years. Wastewater plant chemical treatment is used to improve primary settling of wastewater, as a basic step in the independent physical-chemical treatment of wastewater, and for the removal of nitrogen and phosphorus (Metcalf and Eddy 1991). Dairy waste streams (even diluted as in flush dairy systems) are in the category of strong waste streams, particularly in the concentrations of solids, oxygen demand, and nutrients (compared to table of typical WWTP waste stream strengths found in Metcalf and Eddy 1991). Therefore, application of the technology to the raw waste streams of dairies and other high intensity animal production systems is still very much in the experimental stage, with many chemical performance and dose response experiments in the current literature (see SWET et al. 2001).

Common ionic compounds used in chemical treatment include Alum, Ferric Chloride, Ferric Sulfate, and Lime. Poly aluminum chloride (PACL) is a more recent addition to the set, and various polyacrylamide (PAM) compounds are now being tested on animal waste streams either alone or in combination with various ionic compounds. In a wastewater plant setting it is possible to remove 80 to 90 percent of the suspended solids, 70 to 80 percent of the BOD, and similarly high levels of nutrients and bacteria (Metcalf and Eddy 1991). However, under typical farm applications these efficiencies are unlikely to be met because the wastes are very concentrated, and in a setting (a dairy farm) where there is likely to be less physical control over the waste stream itself. Technologies that can be expected to be effective on farms must be simpler and less expensive than those waste water treatment systems that provide such efficient performance. PACL, although somewhat more expensive than alum, does not contain sulfur, which may be important in mercury cycling and it's entry into the South Florida ecosystem.

Costs for chemical treatment to enhance solids separation may be higher than that for treating streams with solids removed. TP removal from a solids settling pond effluent to less than 10 mg P/l (Table 3) can be relatively easily achieved, but is an expensive process at the dairy scale. Costs per kg-P removed in Table 3 range widely, and suggest that more research is needed in defining the most cost efficient application rates. Sherman et al (2000) and Vanotti and Hunt (2000) both found that removal was less efficient at lower influent P concentrations. The lowest unit P removal cost (Table 3: $1.20 per kg P removed, Worley and Das, 2000) was achieved in a very high strength raw swine waste stream, and removal rate was greater than 100% stoichiometrically. This suggests the solids had a high P content (mg/kg dry solids), that the sludge contained non-complexed (reacted or sorbed) phosphorus, or both. Costs reported in Table 3 are those that provide the best performance provided in that research or that which comes closest to the target concentration for this project within a larger set of reported cost information.

Potential negative aspects of chemical treatment include

- cost, lack of familiarity with the material or equipment on the part of the dairymen,
- additional activities (such as pH adjustment) that may be necessary depending on the chemical and chemical dose used, and
- Management of larger volumes of sludge created with chemical flocculation.

Many of the chemicals are caustic and require careful storage and handling. Bench-scale tests need to be performed to identify appropriate dosages for an identified removal target. Complete and rapid mixing of the chemical with the wastestream is necessary to ensure the most cost-efficient application.

Chemical treatment prior to solids separation

Chemical treatment of the raw waste stream is dose dependent, but assuming a sufficient dosage it has several immediate benefits:

- It can greatly reduce the availability of phosphorus in the flocculated solids
- It can greatly reduce the amount of solids entering the rest of the waste management process by enhancing solids separation at the inflow of the system
- The phosphorus can be more easily and immediately handled for spreading or off farm disposal
- It can greatly improve other solids separation technology performance.

Chemical treatment after solids separation

Chemical treatment after solids separation has much the same benefit as application before separation, except that chemical costs may be reduced for the same level of P removal. If the treatment is performed just prior to discharge of the material into a storage or other purpose waste pond the large-scale flocculation process may trap additional phosphorus within the pond.

Chemical treatment of more dilute waste streams is a well-known technology used in wastewater treatment plants (WWTP). Typically, TP effluent concentrations for wastewater treatment processes involving treatment of dilute waste streams with flocculants range from 250 ppb to 1000 ppb (See Appendix B, SWET et al. 2001). There is a general practicing limit of 0.1 mg/l TP effluent in typical WWTP chemical treatment technology (Glen Daigger, personal communication). More recently, treatment of stormwater runoff with alum or alum and sodium aluminate has been successful in reducing TP concentrations to very low levels (25 – 100 ppb - see discussions in SWET et al. 2001).

Chemicals for farm waste management are generally injected in the waste stream pipe just prior to a holding area, settling pond or storage pond. Removal performance is usually less than optimal, but costs for a particular chemical are generally consistent per unit phosphorus removed across a wide range of conditions once most of the solids are removed. Jar testing is usually employed on each specific waste stream to set an initial dosage, after which performance is evaluated and the dosage adjusted to optimize performance.

Costs for chemical application, in addition to the chemical itself, are dependent upon the application. Harper and Herr (1994) designed stormwater treatment systems with alum pumps costing about $15,000 each. An alum injection system constructed by Harper for the now defunct Zellwood Drainage and Water Control District in Apopka, FL, designed to treat a flow of 50,000 gallons or more per minute was constructed for a total cost of about $50,000. The system included pumps, flow meters for monitoring canal and monitoring alum flows, alum flow control valve system, alum storage tanks, control shed, aerator for mixing, injectors and air jets in the canal, and piping. The system, which supplied alum with air mixing to a canal draining a 6000 acre row crop area, was designed to treat and remove soluble reactive phosphorus up to about 2 mg/l at a rate of 80% or greater. The system was used to inject 10 mg/l (and later 15 mg/l) of alum into a canal just prior to a large (>100,000 gpm capacity) pump station that discharged to Lake Apopka. The system performed effectively in meeting the design goals as part of consent order with the St. Johns River Water Management District (St. Johns River Water Management District, unpublished data).

The potential use of chemical treatment at some point in the management process is high, because it is one of the few technologies that can clearly achieve the target with relatively simple technology. Cost is a significant consideration however, as well as management of the sludge produced over long periods of time.

Anaerobic Digestion

There are a variety of anaerobic digestion systems. P removal performance of some types typically found in animal production operations (Table 1) varies considerably. Phosphorus removal performance of full-scale digester systems was not identified in the reports found. However, these closed digester systems required a waste stream with relatively high solids content. Application of this technology might require a very significant reduction in water use. Covered or open anaerobic lagoons appear to be more likely candidates if this cannot be accomplished. Single stage lagoons, whether covered or not, probably function similarly, with P being mineralized, not removed from the water column. Two-stage and three-stage lagoon systems have high overall removal rates, greater storage volume, and provide biological fixation of phosphorus. P removal of 50% in the first cell of the three-stage lagoon system (Table 3: Riberio and Bicudo, 2000) was attributed primarily to solids settling from the swine manure introduced to the system. Solids separation is an essential component of the lagoon systems that operate effectively. Settling, mechanical, or chemical flocculation methods were used in the systems described in Table 3. There are many other examples in the literature of solids removal as an integral part of anaerobic lagoon systems (SWET et al. 2001).

TABLE 3. Examples of Solids and Phosphorus removal from animal production waste streams by chemical amendment. Removal efficiency and cost per kg P removed. NA = not applicable or not provided. TOP = Total Organic P. TP = Total Phosphorus All data in the table are example or average data from the several reports selected as the most efficient removal reported in each article.

Flocculant	P form	Dose	TSS conc. (%)	TSS removal %	Initial P mg/l	P removal %	Final P mg/l	$$/kg dry solids removed	$$ / kg P removed	manure source	Test setting	Reference
PAM (total organic P)	TOP	200 mg/ L	2.0	>90	102	89	14	$5.36	$11.25	swine	Lab	Vanotti and Hunt 1999
PAM (total organic P	TOP	100 mg/ L	4.1	>90	33	100	0	$8.89	$14.85	swine	Lab	Vanotti and Hunt 1999
Alum	PO_4-P	1 g alum/ L	1.1 - 2.7	NA	3.4	85	0.5	NA	$180.00	dairy	Lab	Jones and Brown2000
Alum+ PAM	PO_4-P	2.9 g alum /L +1.49 mg PAM/ L	1.1 - 2.7	NA	34.08	99	0.38	NA	$62.00	dairy	Lab	Jones and Brown 2000
Alum	TP	2.9 g/ L	1.52	71	500	87%	65	$0.022	$1.20	swine	Full scale - Swine farm	Worley and Das 2000
Alum (TP)	TP	53 mg AL/ L	0. 1 – 1	NA	49	80%	9.7	NA	$12.11	Dairy	Lab/field	Sherman et al 2000
Alum (TP)	TP	106 mg AL/ L	0. 1 –1	NA	49	91%	4.4	NA	$24.22	Dairy	Lab / field	Sherman et al 2000
Fe CL (TP)	TP	94 mg Fe / L	1.10%	NA	49	80%	9.7	NA	$8.99	Dairy	Lab	Sherman et al 2000

TABLE 4. ANAEROBIC DIGESTION SYSTEMS AND SYSTEM PERFORMANCE ATTRIBUTES

Type	Influent Solids, % (wet)	Goal	P removal	Reference
Complete Mix digester	3% – 10%	Cold climate digestion, biogas	Not stated	Moser and Mattocks 1999
Plug flow digester	11% – 13%	Cold climate digestion, biogas	Not stated	Moser and Mattocks 1999
Covered Lagoon	Dilute flush, pull plug	Warm climate digestion, biogas	Not stated	Moser and Mattocks 1999
Open Lagoon	%0.5 – 5% Dilute flush after solids separation	Digestion, nutrient removal	Not stated	Barker 2001.
Open lagoon	5% after solids settling	Digestion nutrient removal	-1. 57%	Sweeten and Wolfe 1994
Two stage open lagoon	5% after solids selttling	Digestion nutrient removal	Lagoon 1 – 9% Final effluent - 91%	Sweeten and Wolfe 1994
Three-stage open lagoon	10 – 20%?	TSS, BOD, P removal (values reported as P04-P	Stage 1: 52% Stage 2: 62% Final effluent 94%:	Riberio and Bicudo, 2000

There are a number of experimental unit process /sequencing batch reactor systems reported in the literature. There are no reports found of scaled-up versions and the complexity, cost and uncertainty associated with scale-up suggests that further consideration of such technology will have to wait until such time as more research and pilot scale operations have been successful. There are other experimental approaches to P removal, such as magnesium addition for struvite precipitation (Nelson et al. 1999), but while technically feasible have apparently not been attempted at other than laboratory scales.

Costs of anaerobic lagoons is primarily in earth moving to construct the lagoons, and the necessary pipes and pumps to supply and drain the system. A rough cost estimate, based on previous lagoon construction in the basin, is approximately $50 to $100 per cow.

Benefits of anaerobic lagoons may already be partially achieved by stormwater ponds on the farms in the basin as a result of the Dairy Rule. Augmentation of the functioning of those ponds might be possible, but performance monitoring and evaluation would be necessary prior to designing any particular improvement.

Other Anaerobic Processes

An anaerobic digester is a closed vessel designed to retain decomposing manure for a sufficient time at the necessary operating temperature to allow the growth of methanogenic bacteria in a steady state condition. Anaerobic digester systems are typically constructed tanks or covered anaerobic lagoons. Covered lagoons are more effective "in warmer climates south of the Mason-Dixon Line" (Moser and Mattocks 2000) because of the higher average ambient temperatures. Both types of systems have been successfully operated for long periods of time for animal waste management (Moser and Langerwerf 2000, Moser and Mattock 2000) particularly in Europe. Advantages of anaerobic digesters include manure treatment cost savings, nutrient conversion, odor and pathogen control, and by-product recovery (gas and digested dairy solids) that can be used to offset other costs and generate a revenue stream. While there is considerable evidence that anaerobic digesters are much more effective in reducing solids that enter but no evidence that they reduce phosphorus more effectively than anaerobic lagoons.

The efficiency of container digestion systems is influenced by many parameters, including temperature, pH, alkalinity, volatile fatty acid concentration, homogeneity of waste substrate digester hydraulic and solids retention time, organic loading rate and degree of mixing. (Williams, 1999). The requirements for mechanical mixing in continuous feed systems requires 5 – 14% total solids an hydraulic retention times of 15 – 30 days. These long retention times are usually unsuited to dilute waste streams provided by flush systems due to the capital costs associated with the large volume digester needed (Wilkie 1999, Zhang and Dague 1995). Current research is focused on designing systems that maintain a long solids retention time while reducing hydraulic retention time. (e.g. Zhang and Dague 1995) Covered lagoons can use much lower (>1% solids) waste streams, but gas generation, a primary benefit, may occur at a lower rate.

Costs of constructing these systems has been provided for both container systems and covered lagoons (Table 5).

A variety of anaerobic technologies have been described in recent literature. Some form the basis or one step of proprietary technologies (SWET et al. 2001). Sequencing batch reactors, fixed film, granular, and mixed sludge and fixed film reactor technologies have been recently reported but relatively few (e.g. Ross and Valentine 1995) are reported at operable dairy scale. There are no specific reports of P removal rates either for information available on proprietary technologies or for those reported in the scientific literature. Costs are not available either.

TABLE 5. COSTS AND BENEFITS OF ANAEROBIC DIGESTERS AND COVERED LAGOONS. NA INDICATES THAT THE INFORMATION WAS NOT PROVIDED.

Capital costs include gas treatment equipment.

System	System size	Capital cost	Annual operating costs	Annual gross value of products	Reference
Plug-flow Dairy digester		$200,000 (1981 dollars)	$10,000 – 16 yr average	$43,625 / year average	Moser and Langerwerf 2000
Complete mix Anaerobic digesters (3)	1 - 1,760 m^3 reactor	$152,300	$8,000 (estimated)	0	Moser and Mattocks 2000
	2 - 2,200 m^3 reactors	$368,000	$8,000 (estimated)	$34,800 (electricity)	
	2 – 2,200 m^3 reactors	$576,000	$8,000 (estimated)	$46,600 (electricity)	
1000 cow plug flow digesters	Na	$287,300	NA	$54,000 *	Moser and Mattocks 2000
	Na	$295,700	NA	$55,400*	
	Na	$329,851	NA	$43,400*	
Covered Anaerobic lagoons (pig farms)		$92,500	NA	$16,000**	Moser and Mattocks 2000
		$289,474	NA	$29,000**	
	1 – 19,000 m^3	$230,000	NA	$16,000 (elec. Only)	
Hybrid anaerobic process (sludge +fixed media) for dairy processing plant wastewater	1,817 L (pilot study)	NA	$28,032 (estimated)	$0	Ross and Valentine 1995

*benefits include electricity, digester fiber, heat energy

** benefits include electricity 62% and the remainder in hot water

Aerobic Lagoons and Digestion Systems

Aerobic lagoons have certain advantages over anaerobic lagoons. Properly operated, bacterial digestion may be more complete, with fewer odors in the end products (Barker 2001). Shallow water depths (3-5 feet) are necessary for oxygen transfer in facultative systems, and much larger areas are thus required for this type lagoon than for an anaerobic lagoon. Mechanical aeration in deeper (>10 feet) aerated lagoons significantly reduces the space requirement while allowing for solids removal through settling. Primary disadvantages of mechanical aeration include the expense of continuously operating the aerators, problems associated with solids resuspension from the process, and the greater production of solids. P removal efficiencies may be similar to multi-stage anaerobic lagoons, but no reports of P removal performance in aerobic lagoons were found. When considering aerobic processes items that should be included are sludge production (high) efficiency, hydraulic retention time, process monitoring costs, pH controls, and energy required Costs are expected to be similar to storage pond construction, $50 to $100 per cow or about $1.50 to $3.00 per square foot, excluding the costs of the aerators.

Methane Generation

Methane generation in and of itself does not remove any P from the waste stream. However, proprietary integrated systems with enhanced solids separation power generation are being promoted as an effective P removal system. However, insufficient data have been obtained to verify the efficacy of such systems. Benefits of methane generation such as electricity and hot water produced using the gas, and saleable final solids harvested from the lagoon (e.g. Table 4) would depend on the particular waste stream available for digestion but could be estimated from available information once lagoon performance was modeled.

Land Application of Effluent and Solids

Land application of manure residues remains one of the most effective and environmentally friendly ways to limit the P imports to the dairy through forage production on-site. If land is available and the farmer needs the forage crops, then land application is an ideal technology to maximize reuse/recycling of P. The major drawback of the land application of manure residues for the current project is the goal of a 40 ppb TP discharge concentration. Under normal forage production edge-of-field discharge concentrations will not be lower than 500 to 800 ppb TP, therefore requiring additional edge-of-field treatment. However, the use of well balanced (hydraulically and nutrient wise) sprayfields offers a cost effective initial reduction of P, which can significantly lower the cost of edge-of-field or edge-of-farm treatment systems. They are also an important element in the water reuse and associated discharge volume reduction for the edge-of-farm water retention systems presented later as a combination system. If edge-of-field treatment is to be considered then a perimeter ditch or other drainage layout will be needed to direct drainage from the land application area to the treatment system. Redirection of drainage is fairly easy and inexpensive for the flatwoods soils in Okeechobee.

The cost per lb-P removed is typically assumed to be near zero because of the cost benefit of the forage produced being used as feed.

Chemical treatment of soils

Chemical treatment of soils can be accomplished by direct application of lime, aluminum or iron compounds. Other compounds such as gypsum, silicate slags from industrial processes, Wollastinite (a rock mineral) has also been proposed, and tested with varying results. Water treatment residual (WTR) from potable water plants using aluminum or iron compounds is also being tested. The residuals are primarily sediments derived from the surface water source, aluminum oxides, activated carbon, and polymer. Performance depends on the amount of amorphous aluminum content of product (Gallimore et al. 1999).

Costs for application of any amendment include the cost of the chemical amendment (based on application rate) including shipping to the point of application, spreading equipment, and application time. There are no reports in the literature providing comprehensive costs, but lime application can be used as relative guide. Heavy lime application costs have been estimated at between $250 to $500 per acre (SWET 2001). An application of WTR to treat 10,000 acres of organic soils was contracted recently for approximately $1.5 million (St. Johns River Water Management District, unpublished data). The purpose of the application was to trap available phosphorus that would be released upon flooding the land for wetland restoration. Costs included about $100,000 in modified manure spreaders to handle the material and approximately one-half the remainder in trucking costs and handling (screening and stockpiling) costs. The material itself was provided without cost by the water utility. This resulted in a projected spreading cost of less than $100 per acre. Ultimately, about 3000 acres were spread. Results of the application are not available, as the land has not yet been flooded. Any material selected for application will require solution of particular application problems, unless, like lime, it is a commonly applied agricultural substance.

Vegetated Buffers

Buffer strips are particularly effective in managing particulate phosphorus but may also be effective in trapping soluble materials in runoff. Segregation of livestock from buffer strips has a great deal to do with the performance but filtration of direct runoff is also an important mechanism.

Costs associated with buffer strips are the fencing to separate cattle from the area, loss of pasture for grazing, and potentially for hay production, and are dependent on the particular farm operation and uses of the land there. Typically, buffer zones function as storm runoff-based overland flow systems. Effectiveness in reducing runoff related P is in great part dependent on prior practices on the farm. If animals are already fenced off from main drainage swales and streams, effects may be dependent the width of the allow area between the fence and the standing water.

Surface-flow (SF) treatment wetland

Surface-Flow (SF) treatment wetlands are appealing for farm waste management because they are low cost low technology, requiring little labor after construction (Hammer 1992). They are becoming a common tool in treating high-strength dairy waste streams (Cronk 1996, Payne Engineering and CH2M HILL 1997). Typically, the treatment wetland treats wastes that have had solids removed and often after lagoon treatment to reduce BOD and ammonia to levels in which emergent wetland vegetation can survive. Typical P removal efficiencies are around 50%, although removal as high as 94% has been reported (City of Santa Rosa, in Cronk 1996). Target TP effluent concentrations for treatment of these waste streams are in the range of 20 mg/l or more TP. Basic system design parameters and formulas are described in general in Kadlec and Knight (1996) and specifically with respect to animal waste streams in Payne Engineering and CH2M HILL (1997). Consideration of potential seepage from treatment wetlands should be part of any design in South Florida, and site selection can play a major part in resolving any potential issue. After the system is in operation, the fines and organic matter produced by the wetland should also greatly reduce or eliminate seepage in the soils typically found on the dairies.

Treatment of runoff water in wetlands has a longer history, but similar treatment efficiencies. The average TP removal performance of hundreds of treatment wetlands treating a wide range of inflow concentrations was 57%, with mean inflow [TP] of 3.78 mg/l and mean [TP] outflow of 1.62 mg/l (Knight et al. 1993). Effluent concentrations in the range of the 40 ppb target for this project were achieved with inflow TP concentrations of about 1 mg/l or less. The background phosphorus concentration sets a limit to the achievable reduction in P. This value is the equilibrium concentration for a stable system, and depends on the amount of P entering the system. Kadlec and Knight (1996) provide a background concentration for a nutrient poor system of around 20 ppb. Treatment wetlands receiving dairy pasture runoff are likely to be nutrient-enriched, have plant communities typical of enriched conditions and thus display higher background phosphorus concentrations.

Costs of a number of treatment wetland construction detailed in Kadlec and Knight (1996) were $5000 or more per acre, but this price includes land and assumes contracted construction of the system. In addition to land, the major cost of these systems was earthwork, which might be accomplished by the farmer. Eliminating the cost of the land and reducing the construction costs would significantly decrease the actual cost per acre. Operation costs are minor, and include levee mowing and maintenance, regular inspection to maintain proper water levels and to make sure that inflow and outflow structures aren't obstructed by vegetation, and would likely be in the range of $5,000 per year or less using farm labor. Harvesting is not envisioned as part of the P removal process and is typically not part of treatment wetland operation, as the P removal benefits are small compared to the cost of removing and managing the harvested material.

Sub-surface Flow (SSF) treatment wetlands were not considered in detail because of their much greater capital cost per unit flow volume and their similar performance with respect to P removal (Kadlec and Knight, 1996).

Aquatic Algae and Plant treatment systems

Floating aquatic plants systems are composed of ponds where monocultures of aquatic plants take up nutrients, and are harvested, resulting in reduced nutrient concentrations in the water column, and a potentially marketable product. Several proprietary systems use floating aquatic plants as well. Costs for such systems include construction and maintenance of a pond or ponds, and harvesting and processing of the plant material, which may include composting. No costs are available on the construction or operation of such systems.

Plant and algal-based vegetative uptake systems have been tried for a variety of waste effluents with varying degrees of success. Floating macrophytes, such as hyacinths or duckweed, have been found to be effective in removing P if used in a harvested system. One problem has been that the harvested materials have not been found to have sufficient economic value to justify the cost of the systems. The systems also require significant maintenance and land costs. Other issues with these systems include identifying appropriate algal species and maintaining them, and the harvesting and processing of macrophytes in a way that retains the P in the plant material.

Some example removal rates for test systems using three different plants (Table 5) show removal rates similar to those for wetland treatment. Debusk et al. (1989) found varied rates of P removal (e.g. hyacinth removed effluent at a rate of almost 300 mg/m2/day when cultured on primary lagoon effluent for 7 days). However, uptake is only part of the process.

Table 6. **Examples of test performance of floating plants for phosphorus removal in strong wastes**.

Plant	Source water	HRT days	TP in mg/l	TP out Mg/l	Removal %	Reference
Duckweed	Swine waste lagoon	12	87.5 - 17.5	NA	11 – 61%	Bermann et al 2000
algae	Swine waste lagoon	7 – 9	180 – 1460		54	Fallowfield et al. 1999
Hyacinth	Swine waste lagoon	20	48	26	46	Costa et al 2000

Stormwater retention and reuse

The basic concept of stormwater retention on dairy farms is to retain stormwater runoff for later irrigation or other water demands thereby reduce the volume of off-farm discharge. It is estimated that a retention system occupying about 5% of the land area will be able to retain for reuse approximately 20% to 50% of existing runoff from a dairy in South Florida. The variation in potential water reuse depends on existing on-site retention, soil types, and available irrigated land. Besides water retention and reuse, the wetland system that will develop within the retention pond will provide additional removal of P prior to discharge. The retention system’s ability to reduce discharge volume and to buffer the peak discharge flows significant reduce the cost of any additional treatment that may be needed before water leaves the farm. Retention systems will cost about $5,000 to $10,000 per acre to construct by contract. The P removal efficiency will depend on inflow P concentrations. The construction costs per lb-P removed will be about $100 to $300.

Composting

Composting is a value-added technology, and can be successful in reducing P loads if the products can be marketed outside the basin in which they were produced or used to reduce P imports. Like aquatic plant systems, there are a number of proprietary technologies that use composting techniques. Many require scraped rather than flushed manure. Fresh (same day) manure is most desirable because of its high ammonia content. While composting technology has been well developed, costs for construction and operation of farm operated composting systems to produce a marketable product are not available.

Proprietary Technologies

Several private companies have proposed technologies that cannot be directly evaluated for potential use for the dairies because performance and process data were proprietary. The preprocessing system proposed by BioProcessing Technologies, Inc., the algal scrubbers proposed by Hydromentria, Inc., and the methane/solids removal system proposed by Best Solutions LLC appear to be promising and should be considered when "hard" data comes available to verify their efficacy and costs.

The main concern with the application of any proprietary technology is the long-term viability of the firm that owns the process. If the firm withdraws, or fails, can the farmer reasonably operate the technology?

The system described by Hydromentia could be inserted in many farms after the settling ponds constructed as part of the dairy rule. Costs for system would include pond construction (estimated above) an unknown amount for the algal turf scrubber system. The benefit of the harvested biomass as livestock feed would have to be proven for the farmer's herd. Algal turf scrubber systems extract P during daylight hours, but release P during the night (Craggs et al. 1996). Proving the operation of this technology for dairy farm application would have to include management of this particular aspect.

Best Solutions LLC is now operating its' system for a very large dairy facility in Australia, and a very large swine rearing operation in North Carolina. The advantage to a confinement dairy is the almost complete removal of phosphorus from the farm, and the basin, since the process generates gas, electricity, and the ash is used as part of a fertilizer base.

Technology Combinations for Phosphorus Removal

Phosphorus removal can occur at almost any point in the waste management process, including the milk and feed/shade barns, the high intensity areas (HIAs), the open pasture and forage fields, and the edge of the farm runoff discharge points. The effectiveness of different technologies will depend on the relative amount of phosphorus associated with each area and the associated technologies' efficiencies. Therefore, it is likely that the most cost effective approach for P reduction will require a combination of technologies to be applied at different points within the dairy. The most appropriate combinations of technologies cannot be determined until farm-specific information is available. However, the most likely combination systems are presented below.

Lactating herd barn and HIA wastes might be managed with one of the following technologies combinations:

1. Confinement barns for the herds; total manure collection and solids separation followed by composting.
2. Confinement of the herd; manure collection, solids separation, anaerobic digestion, and land application with final chemical polishing of the liquid waste stream.

3. Confinement barns for manure collection, which would be treated by solids separation, aerobic digestion, and the liquid pond effluent treated by land application or chemically.

And the following technology combination is for edge-of-farm stormwater treatment:

4. Stormwater retention/reuse-wetland-chemical treatment

As indicated above, the initial component for each of the lactating herd waste management systems (combination 1 to 3) is animal confinement for better manure collection. No treatment technology can work unless the manure is collected and delivered to the system. This is a particular need for many of the Okeechobee dairies because most currently depend heavily on pastures or holding lots, which have no means of direct manure collection. Even the HIA lots within the perimeter ditches, though providing containment of manure, are poor for collecting and delivering manure to a treatment system. Maintaining animals on concrete floors that allow scraping or flushing is the most effective way to manage manure. Therefore, it is suggested that every effort be made to develop animal friendly facilities (see manure collection section) that will encourage cows to stay in barns where the manure can be collected for treatment.

Combination 1 focuses on maximizing manure solids separation for composting and is not being presented as a comprehensive system to meet the project's 40 ppb discharge standard. This combination is presented first because if can and should be integrated into other two combination systems presented below. The appeal of solids separation is that it produces a marketable product, if composted for export off the farm. Solids separation is more efficient for dry scraped systems, particularly if composting is to be done. It is important to remember, however, that solids separation will normally have to be followed by additional treatment because without chemical augmentation separators technically will provide less than 30% P removal (see solids separators section above). Chemically augmented systems have been used with 100% P removal claims by proprietary systems, but the cost effectiveness of these systems is not available. The effects of the chemical additives on the composting process and marketability of the product were also not addressed in the proprietary system's literature.

Combination 2 is a complete system for treating lactating-herd barn wastes and can meet the target discharge level. This combination system is similar to existing systems in Florida except for the use of chemical polishing. The storage ponds constructed as part of the Dairy Rule modifications may often act as anaerobic lagoons or may be modified to do so. The chemical polishing is required for the TP discharge target. The system consists of concrete manure collection (typically flushed) where the flushed water is first passed through a solids separator. Effluent from the separator is then treated in an anaerobic lagoon to breakdown the BOD and reduce odors in the effluent. Anaerobic digestion in the lagoons is not as efficient as aerobic digestion, but anaerobic systems are typically preferred because of their lost cost of operation. The effluent from the anaerobic lagoon is stored in storage ponds for land application or chemical treatment.

The primary advantage of this system is the recycling of nutrients for forage production on farm through low-odor spray irrigation. The forage production has been found to provide significant economic return to dairies. However, the sprayfields, even when well managed, will have stormwater discharge of TP in exceedence of the 40 ppb project target. Therefore, chemical treatment will be needed either the sprayfield edge (see combination 4) or the effluent from the waste storage pond will have to be treated directly before being discharged (not to the sprayfield). The chemical treatment of pond effluent, however, should only be considered if no forage production or other cropping systems are available to utilize the nutrients. Though this combination still requires that the effluent be chemically treated before final discharge, the amount of P that needs to be removed from the sprayfield runoff will have been reduced over 95% during passage through by the prior components (20% solids separator, 5-60% in storage pond/anaerobic lagoon, and 15-70% in sprayfield). The amount of P to be removed by direct chemical treatment of the pond effluent will be 4 to 10 times greater.

The relative costs per lb.-P removed will be about $2- $6 for solid separators and in-pond removals and $-2 to $2 per for sprayfield-associated removals depending on forage value. Chemical treatment costs are presented in a previous section.

The third combination system is the same as combination 2 except that the lagoons and storage ponds are maintained in the aerobic state. The advantages of aerobic digestion are that it can provide rapid and more complete BOD breakdown and reduce odor further than anaerobic lagoon systems. Aerobic digestion also produces more settled solids resulting in greater P removal. The solids are produced after the primary solids separator and may therefore require additional pond cleanout. Maintaining an aerobic lagoon designed for dairy farm use is very expensive because aeration must be accomplished by energy input through mechanical aerators. Aerobic lagoons cannot be justified for most dairies due to the high-energy costs unless a value-added product can be produced. Aquaculture has been proposed as a potential value-added product, but economic data on such systems are currently not available.

The above technology combinations for barn manure are intended to present what is believed to be the most likely systems to be considered and not imply that these are the only systems available. Our choice was based on proven technologies, but it is recognized that some of the proprietary systems might well prove to be successful, but “harder” data will be needed to justify their use.

The final technology combination (4) being presented is for edge-of-field or edge-of-farm treatment of stormwater runoff. It is recognized that most of the existing technologies, though achieving significant P reductions, will not be able to meet the 40 ppb TP discharge target for this project. In addition, existing residual soil P will need to be addressed even if all of the future manure production is 100% treated. Therefore, a treatment system(s) is needed to deal with the stormwater runoff from historical HIAs, current pastures, and cropped fields including sprayfields. Again, the system being presented is not the only system available, but is felt to provide that greater potential for achieving the project goal.

Combination 4 consists of an emergent-wetland stormwater detention impoundment for water reuse combined with a chemical treatment system. The impoundment will provide wetland treatment and serve as a surge buffer for chemical treatment of any off-site discharge. Chemical treatment of the discharge will occur at the end of the wetland farthest from the inflow to reduce P concentrations as much as possible before a chemical is used. The treated water will flow into a sump of a size that ensures complete flocculation and settling prior to final discharge. The chemical system will operate only when the storage capacity of the system is exceeded. Only as much discharge as is needed to maintain capacity storage will be treated. Operation rules will need to be developed as part of a farm hydrologic model.

As mentioned in the previous section on stormwater detention, the primary advantage of this system is its ability to store water for potential reuse on the dairy, particular through irrigation and thus decrease groundwater use. Irrigation demand on the dairies is high and is not currently being met. Therefore, up to 80% (highly variable from year to year, about 50% on average) of the stormwater runoff can be used on the farm. This reduction in discharge volume will result in a direct reduction in the P load off site and significantly reduce the amount of runoff requiring treatment. The areal extent of the impoundment will likely need to be at least 5% of the total drainage area (the larger the better). Because the impoundment will support wetland vegetation, it is anticipated that a P concentration reduction between 10% to 50% will occur in the impoundment, dependent upon residence time. This concentration reduction and the reduced volume of discharge resulting from recycling water for on-farm uses will further reduce the volume of wetland discharge that requires final chemical treatment.

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