Phosphorus Removal

Maryland Center for Environmental Training
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Phosphorus Removal

7 contact hours

9 CC10 hours

To protect the Chesapeake Bay, phosphorus removal is required at Maryland wastewater treatment plants. Enhanced levels or additional removal of phosphorus may be required in newly issued discharge permits. This course will explain how phosphorus, as a nutrient, adversely affects the Chesapeake Bay and how phosphorus can be removed to less than 0.1 mg/l using physical, chemical and biological methods. Use of iron and aluminum salts, their competing reactions with ortho-phosphorus and alkalinity, best chemical addition points, and common application methods will be thoroughly discussed. This course will also explain how reducing phosphorus at the source through phosphate detergent bans has been a great benefit to WWTPs. Finally, the course will provide the benefits of biological uptake of phosphorus and how to maximize this effect using modern day Biological Nutrient Removal (BNR) process to minimize chemical addition and the costs and sludge generation associated with chemical addition.

1. Define phosphorus as it relates to wastewater; list the origins and concentrations and chemical nature; and cite at least three reasons for removing it from the waste stream;
2. List five methods of removal of phosphorus; including one biological process, and cite the principles in effect that allow each method to be effective;
3. Develop a jar test program that will simulate a typical treatment process;
4. Perform a jar test;
5. Interpret a jar test's results;
6. Identify appropriate application points; and
7. Describe the anticipated impact of phosphorus removal on sludge handling capabilities.

Agenda:

8:00 AM to 8:30 AM	Introduction Hand out material
8:30 AM to 9:00 AM	Chesapeake Bay and Phosphorus
9:00 AM to 10:30 AM	Removal of Phosphorus
10:30 AM to 11:00 AM	Benefits of Biological Uptake of Phosphorus
11:00 AM to 11:30 PM	BNR
11:30 PM to 12:30 PM	LUNCH
12:30 PM to 1:00 PM	Chemical Addition and costs
1:00 PM to 2:30 PM	Performing Jar Tests
2:30 PM to 3:00 PM	Evaluation Jar Tests

3:00 PM to 3:30 PM	Post-Test
3:30 PM to 4:00 PM	Evaluations and Wrap Up

McET
environmental, health, and safety training

Maryland Center for Environmental Training
at the
COLLEGE of SOUTHERN MARYLAND

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Phosphorus Removal

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Housekeeping

- 1–day class
- Start class – 8:00 am
- 10-minute Breaks – every hour
- Lunch ~ 11:30 am – 12:30 pm
- End class ~ 3:30 to 4:00 pm

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Ice Breaker

- Before we start, let's introduce ourselves.
  - Name,
  - What do you do, and
  - How do you remove phosphorus at your WWTP?

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Introduction

Objectives, Focus, and Agenda

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Agenda

- Phosphorus Sources, Forms and Trends
- Regulatory Framework
- Fundamentals of Phosphorus Removal:
  - Physical (Sedimentation and Filtration)
  - Biological (Conventional and Excess Uptake)
  - Chemical (Iron and aluminum salts; lime)
- Biological and Enhanced Nutrient Removal (BNR/ENR) processes
- Recycle Side Stream Removal of Phosphorus

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Learning Objectives

Participants will be able to discuss:

- Phosphorus removal strategies
- **Sources, forms and trends of phosphorus**
- **Regulatory framework for phosphorus Removal from wastewater** in the Chesapeake Bay
- Biological and enhanced **(BNR/ENR)** nutrient removal processes

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Introduction

Definitions and Acronyms

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Wastewater Characteristics

- Q – Flow, gpd, gallons/day (or gpm, MGD)
- BOD – Biochemical Oxygen Demand, mg/l
  - cBOD – Carbonaceous BOD
  - nBOD – Nitrogenous BOD
- DO – Dissolved Oxygen, mg/l
- Suspended Solids, mg/l:
  - TSS – Total Suspended Solids
  - VSS – Volatile Suspended Solids

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Acronyms

- BNR – Biological Nutrient Removal
- ENR – Enhanced Nutrient Removal
- TMDL – Total Maximum Daily Loading
- BNR Processes:
  - MLE – Modified Ludzack-Ettinger
  - A2O – Anaerobic/Anoxic/Oxic
- IFAS – Integrated Fixed Film Activate Sludge
- MBBR – Mixed Bed Bioreactor
- SBR – Sequencing Batch Reactor

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Microorganisms

- **Aerobic** (Oxic) - Organisms requiring, or not destroyed, by the presence of free oxygen
- **Anoxic**: Organisms requiring , or not destroyed, by the absence of free oxygen; nitrates (NO_3) are present.
- **Anaerobic** - Organisms requiring, or not destroyed, by the absence of free oxygen and NO_3
- **Facultative** - Organisms able to function both in the presence or absence of free oxygen
- **Heterotrophic** - Organisms that use organic materials as their source of cell carbon
- **Autotrophic** - Organisms able to use carbon dioxide and other inorganic matter as their source of carbon
- **Filamentous** – Bulking organisms that grow in thread or filamentous form

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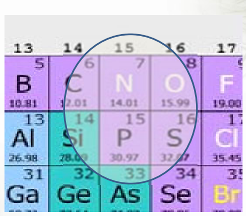
Nutrients - Overview

Part of the Periodic Table



- ✓ Both Phosphorus and Nitrogen are considered essential for plant and animal life
- ✓ Both are called nutrients

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Nutrients in Wastewater

- Total Phosphorus – TP
  - Soluble & particulate
    - PO_4 – Ortho-P
    - P_{org} – Org-P
    - P_{poly} -Polyphosphates

$TP = PO_4 + P_{org} + P_{poly}$

- Total Nitrogen – TN
  - Soluble & particulate
    - N_{org} – Org-N
    - NH_3 – Ammonia
    - NO_3 – Nitrate
    - NO_2 – Nitrite

$TN = N_{org} + NH_3 + NO_3 + NO_2$

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Nutrients

- Nutrients stimulate algae production in receiving waters and need to be removed
- Eutrophication – nutrient induced increase in phytoplankton production
- Depending on I/I, typical raw wastewater concentrations range from:
  - TN – 25 to 45 mg/l
  - TP – 2.5 to 6 mg/l

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Historical Overview

- 1920s - 1960s
  - cBOD Removal
  - Nitrification
- 1970s – Phosphorus removal w/chemicals
- 1980s to 2000 – BNR development and application
- Past 20 years – BNR to ENR

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Nutrient Removal "Driver"

Chesapeake Bay and CWA Regulations

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Regulatory Drivers

- 1972 Clean Water Act
  - EPA: Given authority to set nutrient water quality standards
- Chesapeake Bay Regulations
  - Biological Nutrient Removal Program (1980s – 1990s)
  - Enhanced Nutrient Removal Program (after 2000)

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Clean Water Act (CWA)

- EPA can/will impose more stringent **water quality discharge standards** for contaminants:
  1. If chemical, physical, and biological integrity of the receiving water requires more removal (e.g., BNR to ENR program in the Chesapeake Bay)
  2. As new technologies become available to offer cost effective solutions to water quality problems (e.g., automated SBRs for WWTPs < 0.5 MGD)

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Nutrient Removal - Basics

- In Bay watershed, **<u>Nutrients (nitrogen and phosphorus)</u>** contribute to algae growth
- Excess nutrients lead to excess algae growth
- Excess algae growth depletes oxygen and blocks sunlight penetration in water
- Submerged aquatic vegetation (SAV) dies off due to lack of sunlight (photosynthesis)
- Marine organisms die-off due to lack of DO

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Chesapeake Bay Watershed

- The largest estuary system in the contiguous United States
- Watershed is almost 64,000 square miles
- Surface area of the Bay is 3,830 square miles
  - Of these, 153 square miles are tidal fresh waters
  - 3,562 square miles constitute the mixing zone
  - 115 square miles are salt waters

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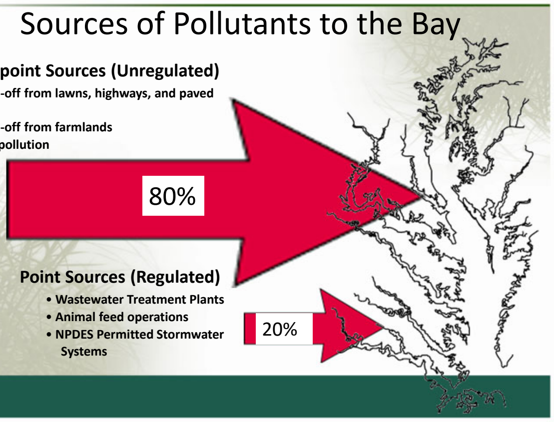
Sources of Pollutants to the Bay

Nonpoint Sources (Unregulated)
- Run-off from lawns, highways, and paved areas
- Run-off from farmlands
- Air pollution

Point Sources (Regulated)
- Wastewater Treatment Plants
- Animal feed operations
- NPDES Permitted Stormwater Systems



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BNR Program

- EPA created the Chesapeake Bay Program in 1983; first Chesapeake Bay agreements signed in 1987
- BNR Programs initiated by Bay states
- For WWTPs greater than 0.5 mgd:
  - 95% of wastewater discharged into the Bay
  - Grant funding available for WWTP upgrades
- WWTP discharge goals:
  - **Reduce TP from ~ 6 mg/l to < 3.0 mg/l**
  - Reduce TN from ~ 20 mg/l to < 8.0 mg/l

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BNR Program

- **To reduce total phosphorus concentrations, most WWTPs began adding chemicals like $FeCl_3$ or alum**
- To reduce total nitrogen concentrations, most WWTPs initiated a capital improvement project to add "Pre" anoxic zones to already existing nitrification processes for partial denitrification

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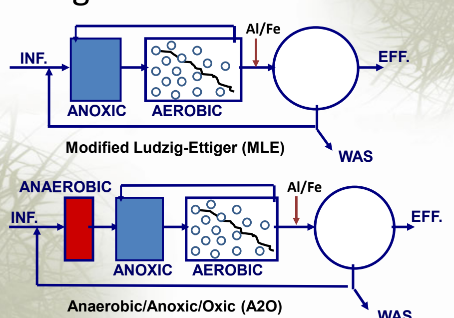
Biological Nutrient Removal



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ENR Program

- New Chesapeake Bay Agreement enacted in 2000; beginning of ENR Program
- For WWTPs greater than 0.5 mgd
  - 95% of wastewater discharged into the Chesapeake Bay
  - Grant funding available for upgrades
- WWTP discharge reduction goals:
  - **Reduce TP from < 3.0 mg/l to < 0.3 mg/l**
  - Reduce TN from < 8.0 mg/l to < 3.0 mg/l

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ENR Program

- **To further reduce total phosphorus concentrations, most WWTPs began adding increased quantities of chemicals**
- To further reduce total nitrogen concentrations, most WWTPs initiated a capital improvement project to add “Post” anoxic zones to already existing BNR facilities

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Wastewater Nutrient Removal

- Enhanced (ENR) **Total Nitrogen (TN)** removal is now required:
  - BNR standard, 3 to 5 mg/L of TN is not adequate
  - **Bay 2010 TMDL Target: < 3.0 mg/l TN**
  - Low threshold - Limit of Technology /State of the Art (LOT/SOA) is about 1.0 mg/l TN (soluble Org-N)
  - TMDL – Total maximum daily loading

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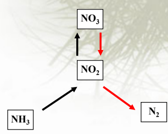
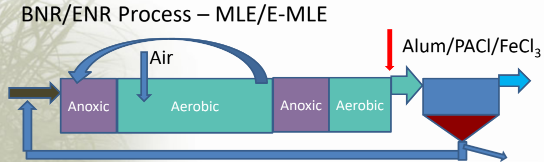
Nutrient Removal Strategies

- Nitrification (*Nitrosomonas, Nitrobacter, and Nitrospria*)
  $NH_3 + O_2 \rightarrow NO_2^- \rightarrow NO_3^-$
- Denitrification
  $NO_3^- + \text{organics} \rightarrow CO_2 + N_2$
- BNR/ENR Process – MLE/E-MLE





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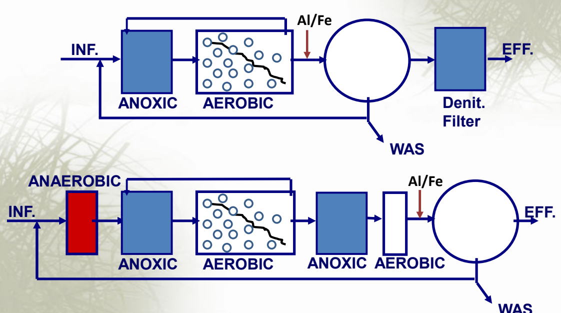
Enhanced Nutrient Removal



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Wastewater Nutrient Removal

- Enhanced (ENR) **<u>Total Nitrogen (TN)</u>** removal is now required:
  - BNR standard, 5 to 8 mg/L of TN is not adequate
  - **Bay 2010 TMDL Target: < 3.0 mg/L TN**
  - TMDL – Total maximum daily loading
  - Low threshold - Limit of Technology /State of the Art (LOT/SOA) is about 1.0 mg/L TN (soluble Org-N)

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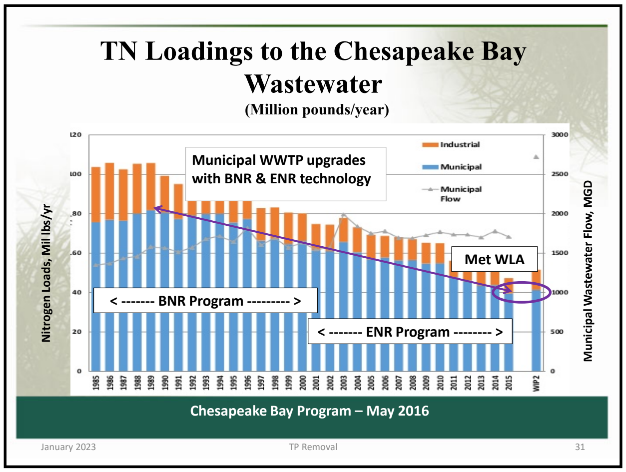
TN Loadings to the Chesapeake Bay Wastewater
(Million pounds/year)
Nitrogen Loads, Mil lbs/yr
Municipal Wastewater Flow, MGD
Industrial
Municipal
Municipal Flow
Municipal WWTP upgrades with BNR & ENR technology
Met WLA
< ------- BNR Program --------- >
< ------- ENR Program -------- >
Chesapeake Bay Program – May 2016
January 2023
TP Removal
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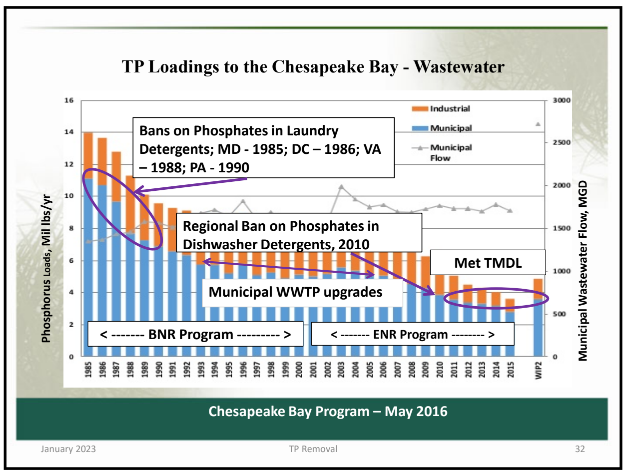
TP Loadings to the Chesapeake Bay - Wastewater
Phosphorus Loads, Mil lbs/yr
Municipal Wastewater Flow, MGD
Industrial
Municipal
Municipal Flow
Bans on Phosphates in Laundry Detergents; MD - 1985; DC – 1986; VA – 1988; PA - 1990
Regional Ban on Phosphates in Dishwasher Detergents, 2010
Met TMDL
Municipal WWTP upgrades
< ------- BNR Program --------- >
< ------- ENR Program -------- >
Chesapeake Bay Program – May 2016
January 2023
TP Removal
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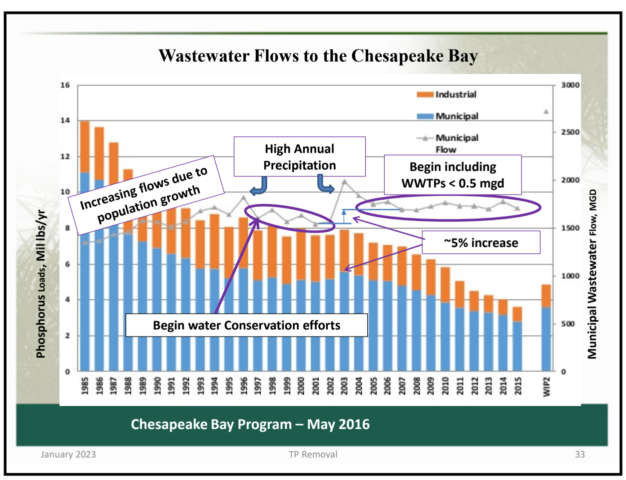
Wastewater Flows to the Chesapeake Bay
Phosphorus Loads, Mil lbs/yr
Municipal Wastewater Flow, MGD
Industrial
Municipal
Municipal Flow
Increasing flows due to population growth
High Annual Precipitation
Begin including WWTPs < 0.5 mgd
~5% increase
Begin water Conservation efforts
Chesapeake Bay Program – May 2016
January 2023
TP Removal
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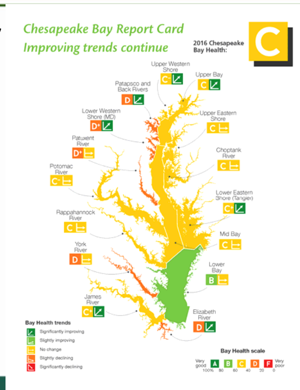
Key Water Quality Indicators

- Chlorophyll a
- SAV – Submerged aquatic vegetation
- Dissolved Oxygen
- All three are showing improving trends in recent years



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Chlorophyll a

- Chlorophyll *a* is used to determine algae quantities present in the Bay
- Algae, a food chain foundation, is necessary for a balanced Bay ecosystem
- Too much algae:
  - Can block sunlight from reaching underwater grasses
  - Reduce habitat and oxygen needed for underwater life
- The range of acceptable chlorophyll a concentrations varies by season and salinity

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Submerged Aquatic Vegetation

- SAV areas are important habitats for fish and molting crabs
- SAV contributes to the reduction of shoreline erosion and the trapping of sediments and nutrients from overlying waters, which leads to improved water quality and clarity
- A decline in SAV populations began in the 1960s

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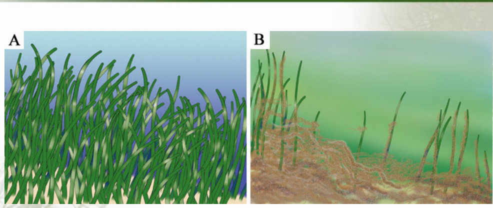

a) A healthy bay grass bed

b) An unhealthy bay grass bed shaded and overgrown by phytoplankton and algae as a consequence of increased nutrients

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Submerged Aquatic Vegetation

- SAV is rooted vegetation that grows under water in shallow zones where light penetrates

Wild celery
Upper Bay

Redhead grass
Mid-Bay

Eel grass
Lower Bay

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SAV Decline

- Increased turbidity resulting from water quality degradation has been reported as the primary cause of the SAV decline in the Bay
- Restoration of SAV is key to improving the overall health of the Chesapeake Bay and its tributaries

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Enhanced Nutrient Removal (ENR)

- Over the past two decades, BNR facilities have been upgraded to ENR improving phosphorus and nitrogen removal efficiencies:
  - A2O enhancements
  - SBRs
  - Mixed Bed Bio-reactors (MBBR)
  - Biological Aeration Filters (BAF) for nitrification
  - Tertiary denitrification filters

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Nutrient Removal

Nutrient	Removal Process
• Nitrogen	• Nitrification – Ammonia Conversion – NH_3^+-N to NO_3^-N – Oxygen and alkalinity needed • Denitrification – Nitrate Removal – NO_3^--N to Nitrogen gas (N_2) – Carbon source needed
• Phosphorus	• Biological Uptake – Conventional – Excess • Chemical Precipitation

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Nutrient Removal

FORM	Removal Mechanism	LOT[1], mg/L
TN		**< 1.5**
NH_3-N	Nitrification	< 0.1
NO_3-N	Denitrification	< 0.1
Org-N:		
Particulate	Solids Separation	< 0.5
Soluble	Ammonification	0.5 – 1.0
TP		**< 0.05**
Particulate	Solids Separation	< 0.05
Soluble	Biological uptake and chemical precipitation	< 0.05

[1] LOT – Limit of Technology

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Nutrient Removal

Phosphorus

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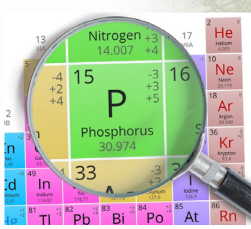
Phosphorus - Overview

Part of the Periodic Table



- ✓ Phosphorus is considered essential for plant and animal life
- ✓ Phosphorus and nitrogen are called nutrients

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Phosphorus

WHY IT'S REGULATED:

PHOSPHORUS IS A NUTRIENT

100:5:1 (C:N:P)

INCREASES PLANT GROWTH

Good for Food Crops

Not Good for Aquatic Systems

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Phosphorus

Wastewater Discharges

USUALLY LIMITED IN MARYLAND TO 0.3 mg/L OR LESS IN DISCHARGES TO SURFACE WATER

(Many Have Pounds Limit)

Limits Could Get More Restrictive…!!!

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Background Removal

- Background removal of particulate organic phosphorus
  - 10 to 30% of particulate phosphorus can be removed in settled sludge (Primary Treatment)
  - Nutrients are removed from the treatment process when sludge is wasted

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Assimilative Uptake

- Assimilative uptake of phosphorus for biomass growth
  - 2 to 3% of phosphorus can be removed by assimilative uptake (Secondary Treatment)
  - Nutrients are removed from the treatment process when excess biomass is removed

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Nutrient Removal

- Particulate organic phosphorus removal and assimilative uptake combined cannot meet low effluent phosphorus limits
- To meet low phosphorus effluent limits, chemical and filtration processes are needed

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Phosphorus Removal

- **Total Phosphorus (TP)** is removed to high degree with chemicals and effluent filtration:
  - Less than 0.3 mg/l TP; even less than 0.1 mg/l
  - Low threshold - Limit of Technology /State of the Art (LOT/SOA) is less than 0.05 mg/l TP (soluble Org-P)
  - TMDL – Total maximum daily loading (2010)

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WWTP Discharge Limits

Typical **Total Phosphorus** Standards, mg/l

- Moderate 0.5 - 1.0 (BNR)
- **Bay Target < 0.3 (ENR)**
- **Potomac River < 0.18 (ENR)**
- Very Severe < 0.1
- LOT/SOA(a) < 0.05

(a) Limit of Technology/State of the Art

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Phosphorus

Forms, Sources and Trends

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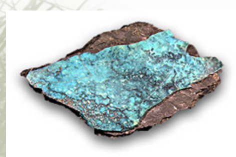
Sources of Phosphate Rock

- Phosphate rock/Apatite - $Ca_5(PO_4)_3(OH, F, Cl)$
  - hydroxylapatite $Ca_5(PO_4)_3OH$
  - fluorapatite $Ca_5(PO_4)_3F$
  - chlorapatite $Ca_5(PO_4)_3Cl$



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Phosphate Rock is a Limited Resource

- US produces 25% of world resources
- In less than 50 years, high grade phosphate ore will run out
- At the present rate of consumption, phosphate ore will last for 200 years
- Can't afford to use it once and waste it
- Phosphorus recovery from sludge?

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Phosphorus Compounds

- Uses:
  - H_3PO_4 - Phosphoric Acid; used in soft drinks and fertilizers
  - Calcium phosphates:
    - $Ca(H_2PO_4)_2 \cdot H_2O$ - Additive in baking powder and fertilizers
    - $CaHPO_4 \cdot 2H_2O$ - Additive in animal food and toothpowder
  - Sodium phosphates: Na_3PO_4 – Trisodium phosphate; water softener

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Sources of Phosphorus in Wastewater

- Human waste and digested food
- Wasted food scraps
- Organo-phosphorus flame retardants in children's clothing
- Corrosion and Scale Control
  - Sodium Hexametaphosphate

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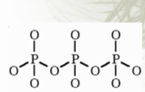
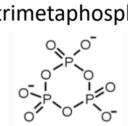
Forms of Phosphorus

- Organic Phosphorus
- Condensed Phosphate:
  - Polyphosphates (linear; e.g., tripolyphosphate)
  - Metaphosphates (cyclic; e.g., trimetaphosphate)
- Orthophosphate (Ortho-P)
  - Phosphoric acid





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Forms of Phosphorus

	Phosphate	Polyphosphate	Organic Phosphate
Chemical form	Orthophosphate Reactive phosphate	Condensed phosphates	Organically bound (part of proteins)
Soluble or particulate	Soluble / may be adsorbed to particles	Soluble / may be adsorbed to particles	Soluble, colloidal, or particulate

Source – Water Environmental Foundation

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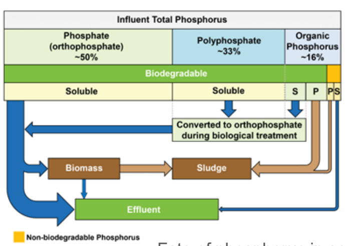
Forms of Phosphorus



S = soluble
P = particulate

Fate of phosphorus in secondary treatment processes

Source – Water Environmental Foundation

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Forms of Phosphorus

FORM

- Organic-P
- Condensed Phosphates
  - Poly
  - Meta
- Orthophosphate

REMOVAL PROCESS

- Converts to orthophosphate form; **a small soluble portion is non-reactive (e.g., 0.05 mg/l)**
- Converts to orthophosphate form
- Most abundant form; chemically reactive and consumed by biological growth

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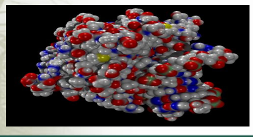
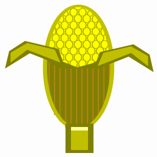
Sources and Forms of Phosphorus

Organic Phosphorus

- Complex organic human and food compounds
- Mostly particulate with some soluble
- Physical removal of particulate forms
- Decomposes to Ortho-P





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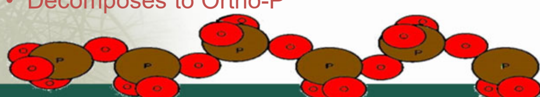
Sources and Forms of Phosphorus

Condensed Phosphates

- Chained molecules
- Inorganic; soluble and particulate
- Laundry detergents (~1950's - 1993)
- Automatic dishwasher detergents (~1970's – 2010)
- Water treatment (~ Early1990's to date)
- Decomposes to Ortho-P



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Sources and Forms of Phosphorus

- Eventually, the detergent industry voluntarily removed phosphates from US manufactured detergents nationwide:
  - From laundry detergents: 1993
  - From automatic dishwasher detergents: 2010

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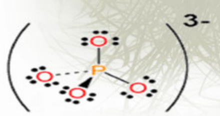
Sources and Forms of Phosphorus



Orthophosphate (Ortho-P)

- Simple Phosphate, PO_4
- Inorganic; mostly soluble
- Phosphoric acid
- Dark soft drinks (e.g., colas; not root beer)
- Preferred form for biological uptake and chemical removal
- Conversion of organic and polyphosphates to PO_4

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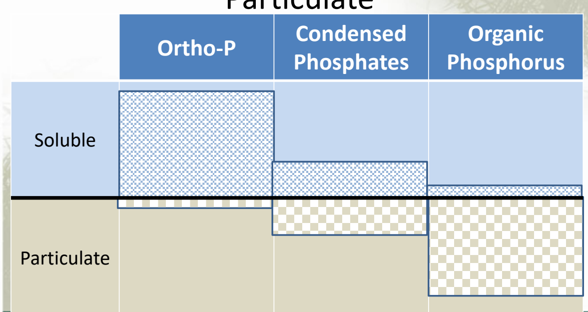
Phosphorus Forms – Soluble versus Particulate



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Phosphorus Forms – Soluble versus Particulate

- Removal of soluble forms:
  - Biological:
    - Assimilation (In microbial cells)
    - Excess uptake – Enhanced Biological Phosphorus Removal (EBPR); A2O
  - Chemical precipitation and adsorption
    - Fe and Al salts
    - Lime

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Phosphorus Forms – Soluble versus Particulate

- Removal of Particulate forms:
  - Sedimentation and Effluent Filtration:
    - Particulate organic phosphorus
    - Biological floc
    - Chemical precipitates

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Sources of Phosphorus in Raw Sewage

- 1.0 mg/L of phosphates added to drinking water for corrosion (and scale) control in water distribution systems (beginning in 1990's). Drinking Water Lead & Copper Rule.
  - Phosphoric acid, ~ 1 mg/L as PO_4^{-3}
  - Sodium hexametaphosphate, ~ 1 mg/L as PO_4^{-3}

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Nutrient Removal Process Control

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Process Control

- Three physical properties are typically monitored in wastewater:
  1. Liquid flow: Influent/effluent, recirculation, return activated sludge (RAS), sludge wasting quantities, chemical addition
  2. Constituent Concentrations: DO, MLSS, BOD_5, TSS, **nutrients**, sludge solids
  3. Gas volumes: air, digester gas

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Common Controlled Variables

- Aeration
- BOD_5 and TSS loadings
- **Ammonia, Nitrate, and Phosphate loadings**
- **Chemical Addition**
- Internal Recycles (MLE processes)
- Low water level and fill level during fill stage (SBR)
- Sludge Wasting Rates

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Common Controlled Variables

- Aeration
  - Set DO levels in different sections of process
  - Control aeration time (cyclic aeration)
- BOD_5 and TSS loadings
  - Maximize removal of BOD_5 and TSS before nitrification/denitrification
- **Ammonia, Nitrate, and Phosphate mass loadings**
  - **Avoid overloading unit processes**

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Common **Controlled** Variables

- **Chemical Addition**
  - **Methanol, Ferric/Alum, alkalinity feed rates**
- Internal Recycles (MLE processes)
  - Set recycle flow rates based on process conditions
- Low water level to fill level (SBRs)
  - Set fill level/volume based on process conditions
- Sludge Wasting Rate
  - Control Solids Retention Time – One of the most important parameters for advanced BNR

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Phosphorus Removal Strategies

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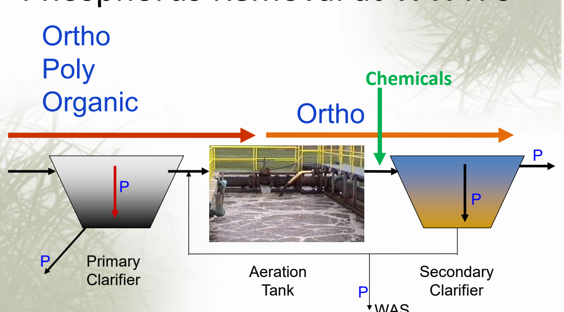
Phosphorus Removal at WWTPs



75

Phosphorus Removal at WWTPs

- Physical:
  - Sedimentation and filtration for particulate phosphorus
  - Membrane technologies
- Chemical:
  - Co-precipitation
  - Excess chemical addition
- Biological
  - Assimilation
  - Enhanced biological phosphorus removal (EBPR)

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Phosphorus Removal Strategies

1. Source control: ban phosphates in detergents
2. Remove influent particulate P in primary clarifiers
3. Biologically convert soluble P to particulate forms
4. Chemically convert soluble P to particulate forms
5. Remove particulate P in final clarifiers and effluent filters
   - Particulate organic phosphorus
   - Biological (Phosphorus in microbial cells)
   - Chemical (Phosphate precipitates)

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Meeting Nutrient Discharge Limits Process Strategies

1. **Multiple barriers for TN removal**
   - Pre-anoxic zone (first stage denitrification)
   - Nitrification – aerobic zone
   - Post anoxic zone (second stage denitrification)
   - Denitrification filters (in lieu of post anoxic zone)
2. **Multiple barriers for TP removal**
   - Particulate P removal in primary clarifiers
   - Biological uptake (conventional, excess)
   - One (maybe two) chemical application points
   - Effluent filtration for particulate P removal

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Phosphorus Removal Strategies

1. Source Control: Bans on Phosphorus in Detergents

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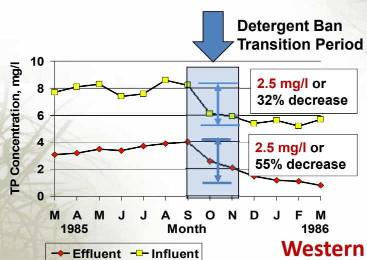
Ban on Laundry Detergent Phosphates in Maryland -1985



Western Branch WWTP, WSSC

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Phosphorus Removal Strategies

2. Particulate Phosphorus Removal in Primary Clarifiers

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Phosphorus Removal in Clarifiers

- Particulate phosphorus will be removed in the primary sedimentation tanks, e.g., 10 to 30%
- Removal in the primary clarifiers depends on influent phosphorus composition:
  - Particulate organic phosphorus
  - Particulate condensed phosphates

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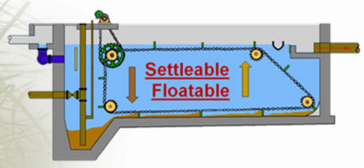
Removal of Settleable Solids Provides Some Phosphorus Removal

Primary Sedimentation 10 - 30%



83

Phosphorus Removal in Clarifiers

- Particulate organic phosphorus concentrations are likely high in “fresh” sewage
- Soluble phosphorus concentrations are likely high in “old” sewage
  - Conversion of particulate organic and condensed phosphorus forms to soluble phosphorus forms in the wastewater collection system

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Phosphorus Removal Strategies

3. Biological Uptake of Phosphorus by Microorganisms

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Biological Uptake

- Conventional Biological Uptake
  - To satisfy biological needs (2.0 to 3.0% by weight)
- Enhanced Biological uptake (5 to 7% by weight)
  - Stress induced
  - Release of phosphorus under anaerobic conditions
  - Uptake of phosphorus under aerobic conditions

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Biological Uptake

- **Assimilation** - Phosphorus removal from wastewater has long been achieved through incorporation of P as an essential element in the biomass

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Assimilation

- Microorganisms are 2-3% P (dry weight)
- Removing biological sludge removes P
- Why doesn't P go to 0?
  - Because carbon is limiting, not phosphorus

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Excess Biological Uptake

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Biological Nutrient Removal

- Removes total nitrogen (TN) and total phosphorus (TP) from wastewater
- BNR processes use microorganisms under different environmental conditions:
  - Anaerobic (w/o O_2 and NO_3-N)
  - Anoxic (w/o O_2)
  - Aerobic or oxic (with O_2)

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Biological Uptake

- **Enhanced Biological Phosphorus Removal (EBPR)** - phosphate accumulating organisms (PAOs) store polyphosphate as an energy reserve in intracellular granules

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Biological Uptake

- **Under anaerobic conditions,** PAOs release orthophosphate, utilizing the energy to accumulate simple organics and store them as polyhydroxyalkanoates (PHAs) such as poly-β-hydroxybutyrate (PHB)

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Biological Uptake

- **Under aerobic conditions**, the PAOs then grow on the stored organic material, using some of the energy to take up orthophosphate and store it as polyphosphate

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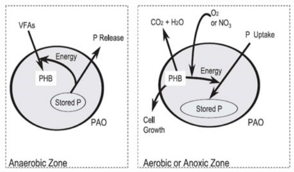
Enhanced Biological P Removal (EBPR)

- Enhanced bio-P removal depends on:
  - Anaerobic conditions (zero dissolved oxygen and zero nitrate)
  - Volatile fatty acids (VFA, rbCOD)
  - Solids management (SRT, WAS, and side streams)

PAO - Phosphate Accumulating Organisms

PAO Able to <u>store soluble organics</u> as Polyhydroxybutyrate (PHB)



January 2023 TP Removal 94

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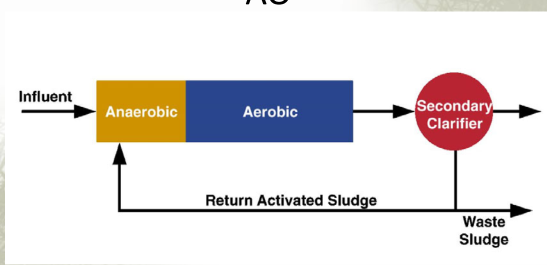
AO



For biological uptake of phosphorus

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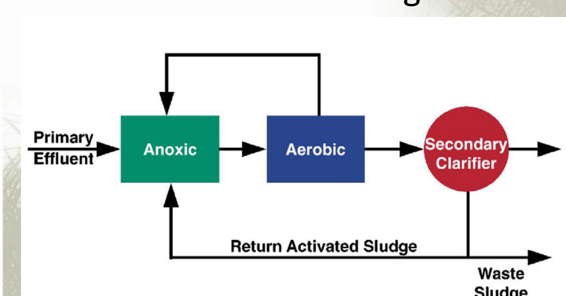
Modified Ludzack-Ettinger - MLE



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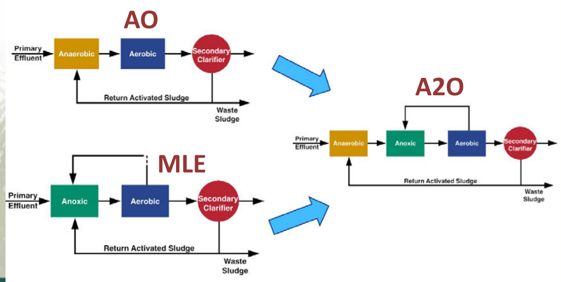
AO plus MLE = A2O



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BNR Stages

- Anaerobic stage - No oxygen nor NO_3-N; Phosphorus is released; enhances greater TP uptake in the aerobic stage
- Anoxic stage – No oxygen; NO_3-N is converted to N_2 gas (Denitrification)
- Aerobic stage – Plenty of oxygen; NH_3-N is converted to NO_3-N (Nitrification)

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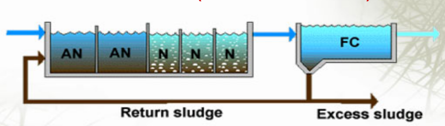
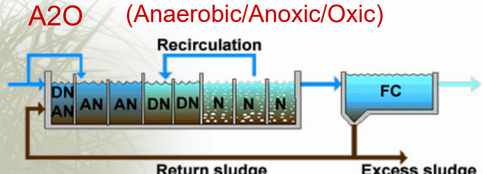
AO Process (Anaerobic/Oxic)



A2O (Anaerobic/Anoxic/Oxic)



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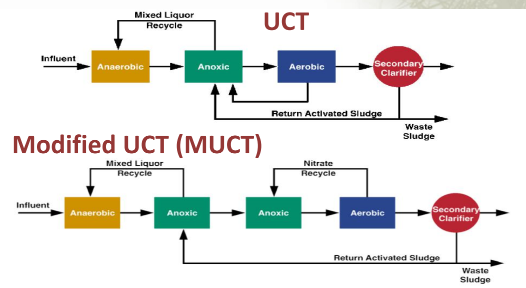
UCT Processes



For biological uptake of phosphorus and partial removal of nitrogen

100

Enhanced Biological P Removal (EBPR)

- For EBPR: must be anaerobic, then aerobic
  - P released under anaerobic conditions
  - P then taken up under aerobic conditions
  - 5 mg/L (inf.) → 15 mg/L (anaerobic) → < 1 mg/L (aerobic)
  - Biological removal or biologically mediated chemical precipitation?
  - ~1980 largely agreed it was biological

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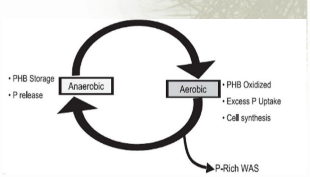
Enhanced Biological P Removal (EBPR)

- Step 1: Anaerobic Phase
  - BOD removal
  - Phosphorus release
- Step 2: Aerobic Phase
  - Phosphorus uptake and creation of new PAOs
  - Phosphorus removal by sludge wasting



PHB: Poly-beta—hydroxybutyrate
substrate for biomass – carbon storage

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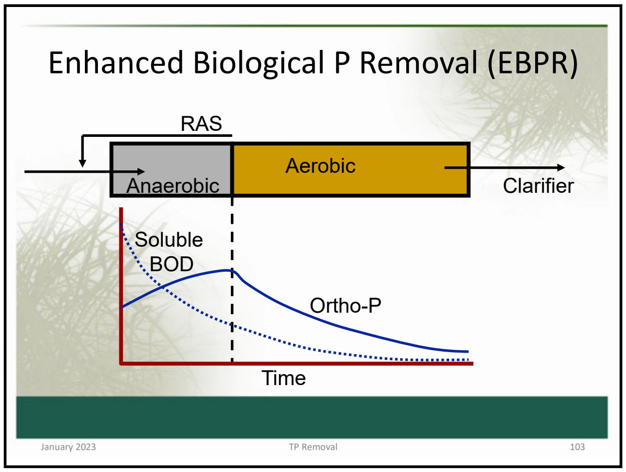
Enhanced Biological P Removal (EBPR)
RAS
Aerobic
Anaerobic
Clarifier
Soluble BOD
Ortho-P
Time
January 2023
TP Removal
103

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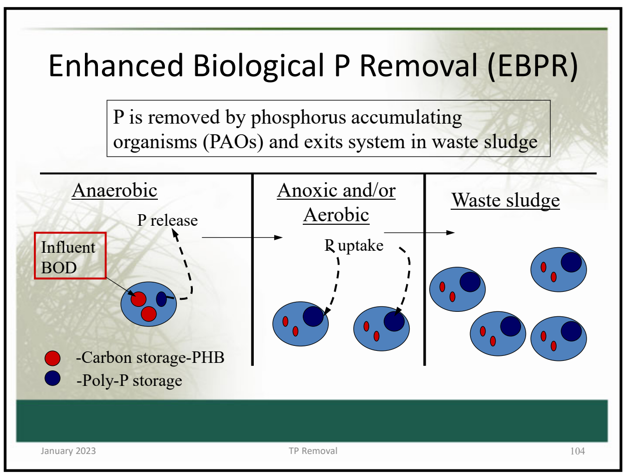
Enhanced Biological P Removal (EBPR)
P is removed by phosphorus accumulating organisms (PAOs) and exits system in waste sludge
Anaerobic
Anoxic and/or Aerobic
Waste sludge
P release
P uptake
Influent BOD
-Carbon storage-PHB
-Poly-P storage
January 2023
TP Removal
104

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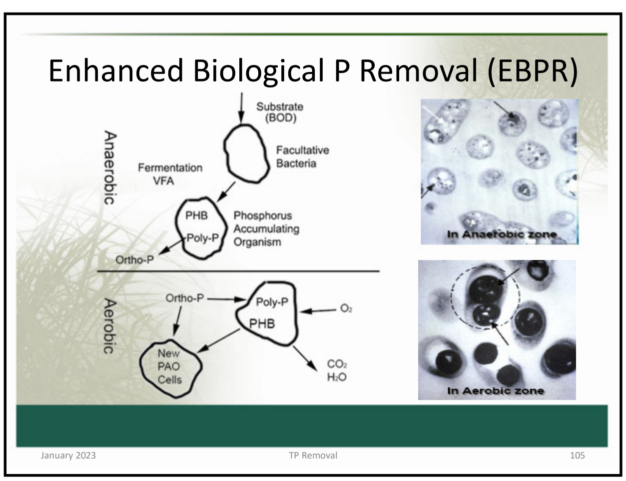
Enhanced Biological P Removal (EBPR)
Anaerobic
Substrate (BOD)
Facultative Bacteria
Fermentation VFA
PHB
Poly-P
Phosphorus Accumulating Organism
Ortho-P
Aerobic
Ortho-P
Poly-P
PHB
O2
New PAO Cells
CO2 H2O
In Anaerobic zone
In Aerobic zone
January 2023
TP Removal
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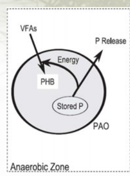
Enhanced Biological P Removal (EBPR)

Anaerobic Conditions

Heterotrophic Bacteria Break Down Organics
- **Fermentation**
  - **Volatile Fatty Acids (VFAs)**
  - **Acetate (Acetic Acid)**



Also:
Selection of **PAO - Phosphate Accumulating Organisms**
(Able to Out-Compete Other Aerobic Heterotrophic Bacteria for Food When Anaerobic)

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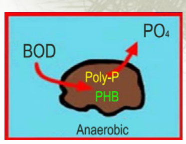
Enhanced Biological P Removal (EBPR)

Anaerobic Conditions

PAO Take Up VFAs and Covert them to Polyhydroxybutyrate (PHB)



PAO Able to store soluble organics as Polyhydroxybutyrate (PHB)

Ortho-P is Released Into Solution

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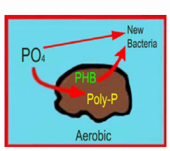
Enhanced Biological P Removal (EBPR)

Aerobic Conditions

Rapid Aerobic Metabolism of Stored Food (PHB) Producing New Cells

PO_4 Used in Cell Production
Excess Stored as Polyphosphate
("Luxury Uptake")



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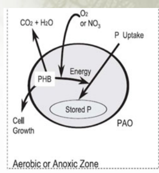
Enhanced Biological P Removal (EBPR)

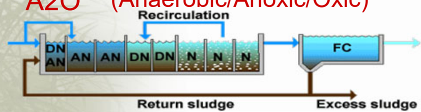
Aerobic Conditions

PO_4 Used in Cell Production
Excess Stored as Polyphosphate

Biomass 5 to 7% P by Weight
(Normal 2 to 3 %)



A2O (Anaerobic/Anoxic/Oxic)



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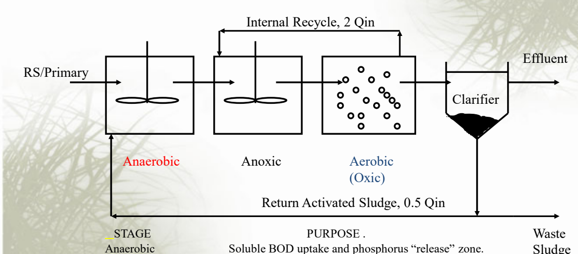
A20 Process

with Anaerobic Zone for Phosphorus Release



STAGE	PURPOSE .
Anaerobic	Soluble BOD uptake and phosphorus "release" zone.
Anoxic	Denitrification and nitrogen gas release zone
Aerobic (Oxic)	Nitrification and phosphorus "uptake" zone

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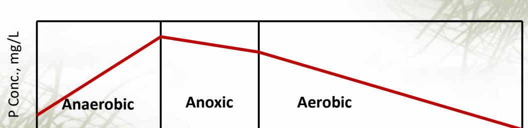
Phosphorus Profile – A2O



Anaerobic zone
P - Release

Anoxic and Aerobic zones
P - Uptake

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Advantages

- Less chemical costs
- Less chemical storage and handling
- Less chemical sludge disposal

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Disadvantages

- Not as reliable (initially – maybe it is now)
- Limitation – need enough BOD (Food)
- May be difficult to get < 0.1 mg/L consistently
- Digestion (especially anaerobic) releases P

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Phosphorus Removal Strategies

4. Phosphorus Removal in Clarifiers with Chemicals

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Phosphorus Removal with Chemicals

- Precipitation and adsorption with chemical addition:
  - Ferric chloride
  - Aluminum sulfate
  - Polyaluminum chlorides (PACl)
- With effluent filtration, TP concentrations can be reduced to ~ 0.05 mg/l

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Chemical Precipitation

- Phosphate is an anion: PO_4^{3-}
- Cations can be added to bind with phosphate:
  - Ca^{2+}
  - Al^{3+}
  - Fe^{3+}
- Each forms an insoluble precipitant with alkalinity

January 2023 TP Removal 116

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Reaction with Lime

- Reaction with lime:

  $5Ca^{2+} + 3PO4^{3-} + OH^{-} \leftrightarrow Ca_5(PO_4)_3(OH)(s)$

  hydroxyapatite
- But when lime is added to water:

  $Ca(OH)_2 \leftrightarrow Ca^{2+} + 2OH^{-}$

  $OH^{-} + HCO_3^{-} \leftrightarrow H_2O + CO_3^{2-}$

  $Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3(s)$
- So required dose of lime depends on alkalinity
  - Once carbonate is used up, P will be removed

January 2023 TP Removal 117

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Co-Precipitation with Metal Salts

Ortho Phosphates
React with
Metal Salts and Alkalinity
To form
Insoluble Phosphorus Compounds

January 2023 TP Removal 118

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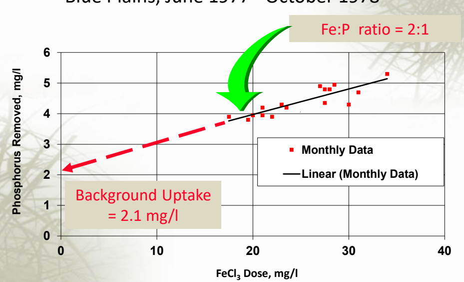
Precipitation of Phosphorus

Blue Plains, June 1977 - October 1978



January 2023 TP Removal 119

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Co-Precipitation Iron Reactions

- $FeCl_3 + PO_4^{-3}$ ---> $FePO_4$ + $3Cl^{-1}$
- $FeCl_3$ + $3HCO_3^{-1}$ ----> $Fe(OH)_3$ + $3CO_2$ + $3Cl^{-1}$
- Simplified: Fe + PO_4 ------> $FePO_4$
  Fe + 3OH ------> $Fe(OH)_3$
- Combined:
  2Fe + PO_4 + 3OH ----> $2FePO_4(OH)_3$ Complex ↓
  (Mole Ratio = 2.0)

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Co-Precipitation Aluminum Reactions

- $Al_2(SO_4)_3 \cdot 14H_20$ + $2PO_4^{-3}$ ------> $2AlPO_4$ + $3SO_4^{-2}$ + 14 H_2O
- $Al_2(SO_4)_3 \cdot 14H_20$ + $6HCO_3^{-1}$ ------> $2Al(OH)_3$ + $6CO_2$ + 14 H_2
- Simplified: Al + PO_4 ------> $AlPO_4$
  Al + 3OH ------> $Al(OH)_3$
- Combined:
  2Al + PO_4 + 3OH ----> $2AlPO_4(OH)_3$ Complex ↓
  (Mole Ratio = 2.0)

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Phosphorus Removal with Chemicals

- Precipitation of PO_4:
  - $FePO_4$ and $AlPO_4$ only exist at very low pH's (< 5.0)
- Co-precipitation: Fe and Al **along with** alkalinity form metal-phosphate-hydroxide flocs
- Adsorption of soluble (PO_4^{-3}) phosphate onto metal hydroxide flocs
- As floc is formed and settles, it also entraps particulate phosphorus

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Phosphorus Removal with Chemicals

Chemical Reactions – two mechanisms:

- **Co-precipitation** (Remove TP to ~ 0.5 mg/l)
  - 2Al + 3OH + PO_4 ----> $2Al(OH)_3PO_4$ ↓
- **Excess Chemical** (Remove TP < 0.5 mg/l to ~ 0.05)
  - *x* (Al + 3OH) ---> *x* ($AlOH_3$) ↓
  - *x* ($AlOH_3$) ↓ + PO_4 ----> *x* $(Al(OH)_3) \cdot PO_4$ ↓
  - *x* > 2; more chemical required as PO_4 levels drop
- Both reactions form Metal (Al or Fe)-Phosphate-Hydroxide floc

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Chemical Addition – Dosages

1. Determine incoming TP and background uptake
2. Assume initial chemical mole ratio of 2:1:
   - **$2Al + PO_4 + 3OH = AlPO_4 + Al(OH)_3$**
     - **1.7 mg/l of Al per mg/l P**
     - **3.3 mg/l of Al_2O_3 per mg/l P**
     - **1.21 GPH of Alum (@8.3% Al_2O_3 or 0.95 lbs Al_2O_3/Gallon) to remove 1 mg/l P in 1 mgd of flow**
3. Adjust dose to meet discharge standard

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Chemical Addition – Dosages

1. Determine incoming TP and background uptake
2. Assume initial chemical mole ratio of 2:1:
   - **$2Fe + PO_4 + 3OH = FePO_4 + Fe(OH)_3$**
     - **3.6 mg/l of Fe per mg/l P**
     - **10.4 mg/l of $FeCl_3$ per mg/l P**
     - **0.9 GPH of $FeCl_3$ (@35% $FeCl_3$ or 1.45 lbs Fe/Gallon) to remove 1 mg/l P in 1 mgd of flow**
3. Adjust dose to meet discharge standard

January 2023 TP Removal 125

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Chemical Addition – Alkalinity/pH

Chemical addition consumes alkalinity and can depress pH:

- **$Al_2(SO_4)_3 \times 14H_2O + 6HCO_3^{-1}$ ---> $2Al(OH)_3 + 6CO_2 + 3SO_4^{-2} + 14H_2O$**
  - $Al + 3OH$ ------> $Al(OH)_3$
  - 5.6 mg/L of $CaCO_3$/mg Al
  - 3.0 mg/L of $CaCO_3$/mg Al_2O_3

January 2023 TP Removal 126

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Chemical Addition – Alkalinity/pH

Chemical addition consumes alkalinity and can depress pH:

- **$FeCl_3 + 3HCO_3^{-1}$ ---> $Fe(OH)_3 + 3CO_2 + 3Cl^{-1}$**
  - Fe + 3OH ------> $Fe(OH)_3$
  - 2.7 mg/L of $CaCO_3$/mg Fe
  - 0.9 mg/L of $CaCO_3$/mg $FeCl_3$

January 2023 TP Removal 127

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Jar Tests

- Should be conducted….
  - Using wastewater sample from chemical application point
  - Using different chemicals ($FeCl_3$, Alum, and PACl)
  - Monitoring chemical dose, phosphorus removed, pH, alkalinity)

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Jar Tests

- Perform jar tests followed by full-scale testing to confirm dosing calculations
- Several large beakers are filled with wastewater from the treatment process
- The beakers are dosed with different concentrations of a chemical and mixed to determine which concentration works best

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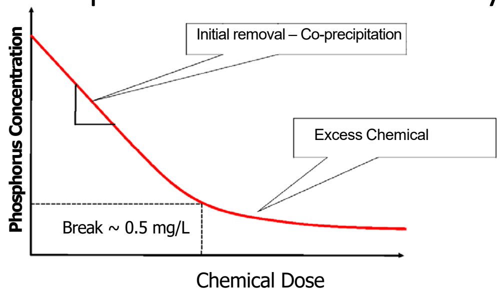
Precipitation of TP and Alkalinity



January 2023 TP Removal 130

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Precipitation of TP and Alkalinity

- Aluminum and iron salts prefer to react with phosphates and alkalinity equally
- As phosphate concentrations decrease, more of the chemicals react with alkalinity instead

January 2023 TP Removal 131

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Precipitation of TP and Alkalinity

- Chemical doses increase exponentially when achieving phosphorus concentrations below 1 mg/L as P
- Aluminum and iron addition consumes alkalinity more so at low P concentrations and may cause pH to decrease

January 2023 TP Removal 132

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Chemicals used for Phosphorus Precipitation

Chemical	***Formula***	***Removal mechanism***	***Effect on pH***
Ferric Chloride	$FeCl_3$ M.W. = 162.3	Metal hydroxides	Removes alkalinity
Aluminum Sulfate (Alum)	$Al_2(SO4)_3.14.3(H_2O)$ M.W. = 599.4	Metal hydroxides	Removes alkalinity
Ferrous sulfate (pickle liquor)	Fe_2SO_4	Metal hydroxides	Removes alkalinity
Poly Aluminum Chloride	$Al_nCl_{(3n-m)}(OH)_m$ $Al_{12}Cl_{12}(OH)_{24}$	Metal hydroxides	none
Lime	CaO, $Ca(OH)_2$	Insoluble precipitate	Raises pH above 10

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Chemical Addition Rates

- Dependent on:
  - TP Discharge Limitations
  - Influx TP Loading
  - Biological P Removal Rates
  - Chemical to P Molar Ratios:
    - Al/Fe Salts, Range: 1.6- 2.1 to reach 0.5 mg/l P
      > 3.0 to reach < 0.25 mg/l P
      > 5.0 to reach < 0.2 mg/l P
      >10 to reach < 0.15 mg/l P
    - Dependent on Alkalinity

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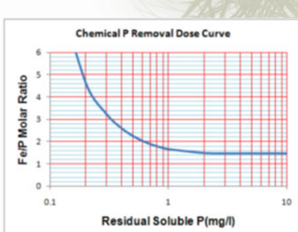
Phosphorus Removal w/Chemicals

- Add chemical to precipitate phosphorus
- Alum & ferric chloride
- Consumes alkalinity
- **Increases sludge production**



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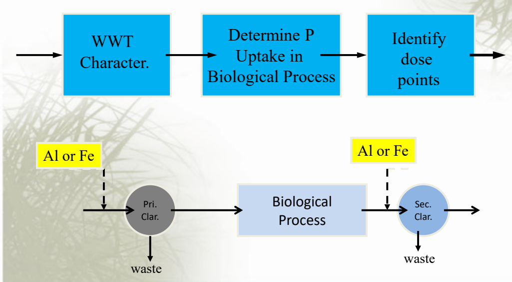
Chemical Addition Only Phosphorus Removal



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Chemical Addition - Advantages

- Can be used in every single current wastewater application from Lagoons to EBPR (Enhanced Biological Phosphorous Removal)
- Easy plant trials – chemical and feed pumps are the only requirements
- Low capital costs
- Easy to adjust to changing influent concentrations and flows
- Relatively less complicated method of removal

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Chemical Addition - Disadvantages

- Operation and Maintenance Costs can be higher due to chemical usage
- Handling and Storage of different chemicals and freeze protection
- Iron Products are not recommended in front of UV disinfection due to staining
- If fed at wrong area, it can reduce nutrient levels to beneficial bacteria and cause die off.
- Possible changes to dewatering chemistries
- Increased sludge production

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Chemical Addition

Feed Concepts

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Chemical Feed Concepts

- Manual
- Feedback
- Feedforward
- Feedback/Feedforward
- Advanced Control

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Manual Control

- Operator observes problems and takes corrective action
- Sometimes, nothing more than a guess
- “Open loop” control
  - No direct connection between desired output (setpoint) and process variable
  - Operator may have to constantly observe and change manipulated variable to ultimately correct problem

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Automation Control Loops

- **Feedback Control**: uses direct measurements of the controlled process variables (PV) to adjust the values of the manipulated variables
- **Feedforward Control**: uses direct measurement of the disturbances to adjust the values of the manipulated variables
- **Combined Control**: different combinations of the first two types
- Control objective - to keep control variables at desired levels, e.g., set points (SP)

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Feedback Control Loop

- Feedback control is a common control strategy; its simplicity accounts for its popularity.
- The feedback controller works with minimum knowledge of the process; it needs only to know which direction to move
- How much to move is usually adjusted by trial and error

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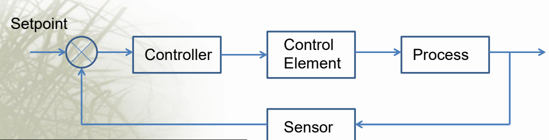
Feedback Control Loop

- Output information is used to adjust process controls
- Feedback controller receives sensor output on process variable and compares it to setpoint



SISO – Single-input single-output

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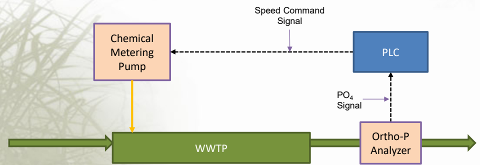
Feedback Control Loop

- Measurement is after the mechanical action (e.g., pump speed change)
- Example: Residual-based chemical feed



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Chemical Feed Equipment

Dry chemical (powder) feeders

Wet chemical (solutions) feeders

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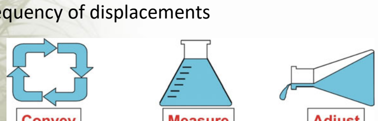
Metering Pump Definition

- Convey (like any pump)
- Measure (repeated displacement of defined volume)
- Adjust
  - Volume per displacement
  - Frequency of displacements



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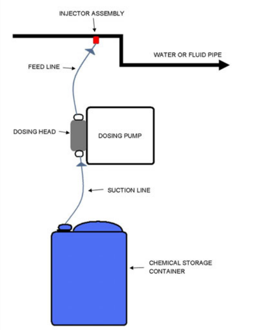
Metering Pumps

- Reciprocating – piston, **diaphragm**, or plunger
- Rotary – **gear**, screw, lobe
- Peristaltic – series of rollers to push through tubing or **hoses**



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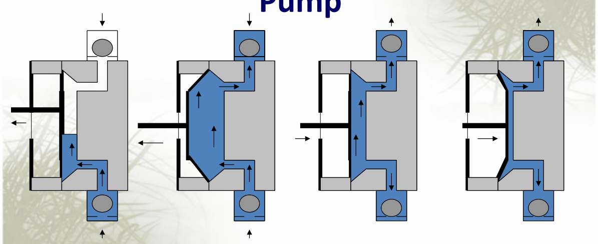
Reciprocating Diaphragm Metering Pump



Suction Stroke Begins: discharge valve closes, suction valve opens, chamber fills.

Suction Stroke Complete. Fluid chamber is full.

Discharge Stroke Begins: discharge valve opens, suction valve closes

Discharge Stroke Complete. Fluid in chamber is displaced.

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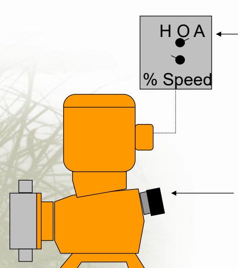
Control of Reciprocating Metering Pump Output



Variable Speed Drive adjusts frequency of strokes.

Stroke length knob (or stroke positioning motor) adjusts displacement per stroke.

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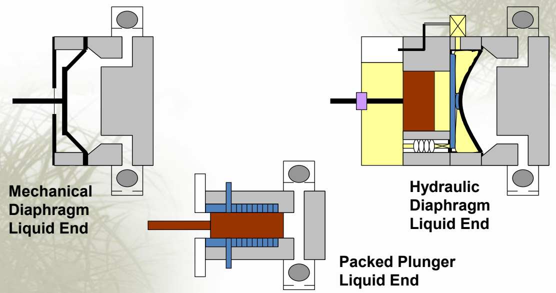
Metering Pump Liquid Ends



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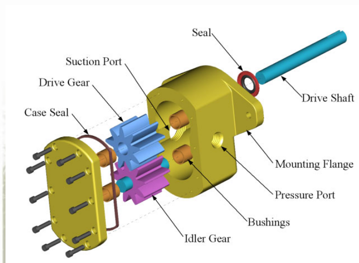
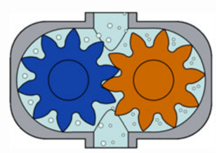
Gear Pump





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Peristaltic Pumps

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Feedback Control Loop

- Disadvantage of feedback control…it compensates for a disturbance only after the controlled variable has deviated from the set point
- Disturbance must propagate through the entire process before the feedback control scheme can initiate action to compensate

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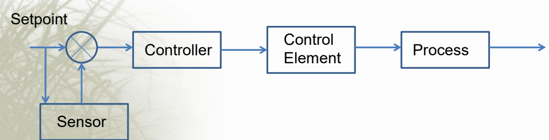
Feedforward Control Loop

- Input information is used to adjust process controls
- Controller receives sensor output on process variable and compares it to setpoint



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Feedforward Control Loop

- Objective - anticipate the effect of disturbances that will upset the process by sensing and compensating for them before they affect the process
- If applied correctly, the controlled variable deviation is minimum
- Mathematical model captures the effect of the disturbance on the process

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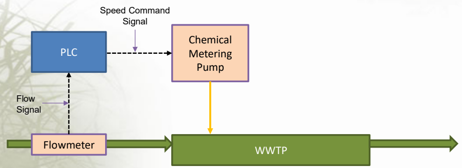
Feedforward Control Loop

- Measurement comes before the mechanical action (e.g., pump speed change)
- Example: Flow-paced chemical feed



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Feedforward Control Loop

- Feedforward control avoids delays of feedback control
- Input disturbances are measured and accounted for before they have time to affect the system
- Difficulty with feedforward control:
  - Effects of disturbances on process must be anticipated
  - No surprises

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Feedforward Control Loop

- Complete compensation for disturbances is difficult due to variations, imperfections in mathematical models, and imperfections in the control actions
  - Usually combined with feedback control
- **Feedback and feedforward controls are common in water and wastewater utility processes**

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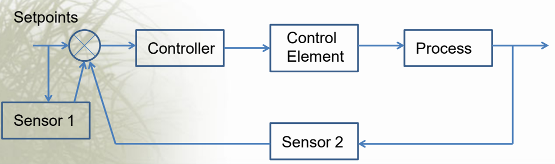
Feedback/Feedforward Control Loop

- Feedback and feedforward (e.g., compound) information is used to adjust process controls
- Controller receives sensor outputs on process input and output variables and compares it to setpoints



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Feedback/Feedforward Control Loop

- Benefits of feedback control:
  - Controlling unknown disturbances
  - Not having to know exactly how a system will respond
- Benefits of feedforward control:
  - Responding to disturbances before they can affect process

Cascade control – Feedback as primary control loop with a feedforward secondary loop

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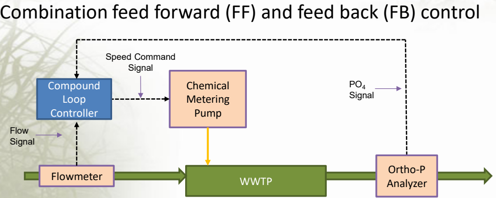
Feedback/Feedforward Control Loop

- Measurement is made before mechanical action but adjusted based upon measurement downstream of the mechanical action
- Combination feed forward (FF) and feed back (FB) control



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Phosphorus Removal Strategies

5. Removal of Particulate Phosphorus in Effluent Filters

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Effluent Filtration Application

- Removes Residual Bio-Floc
- Removes Residual Chemical/Bio Floc
- Removes Residual Coagulation Particles in Phys-Chem Treatment

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Effluent Filtration Application

- If 2-3% of organic solids is P, then an effluent total suspended solids (TSS) of 10 mg/L represents 0.2-0.3 mg/L of effluent P.
- In plants with EBPR the P content is even higher
- Sand filtration or other method of TSS removal (e.g., membrane) is likely necessary for plants with low effluent TP permits

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Rapid Sand Filter

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Effluent Filtration Applications

- Gravity filters are needed to reduce effluent particulate phosphorus to less than 0.3 mg/L
- Membranes may be needed to reduce effluent particulate phosphorus to less than 0.1 mg/L

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Filter Operation

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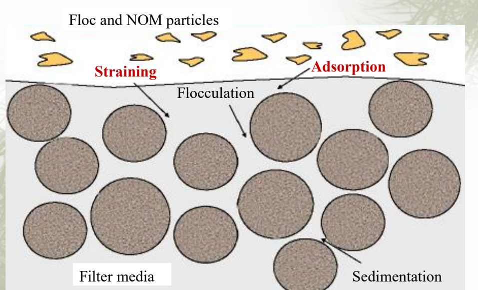
Filtration Attachment Mechanisms



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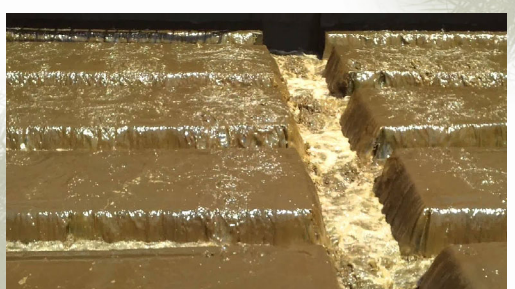
Rapid Sand Filter - Backwash



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Membrane Filter Technology

Filter type	Symbol	Pore Size, μm	Operating Pressure, psi	Types of Materials Removed
Microfilter	**MF**	**1.0-0.01**	**<30**	**Clay, bacteria, large viruses, suspended solids**
Ultrafilter	**UF**	**0.01-0.001**	**20-100**	**Viruses, proteins, starches, colloids, silica, organics, dye, fat**
Nanofilter	**NF**	**0.001-0.0001**	**50-300**	**Sugar, pesticides, herbicides, divalent anions**
Reverse Osmosis	**RO**	**< 0.0001**	**225-1,000**	**Monovalent salts**

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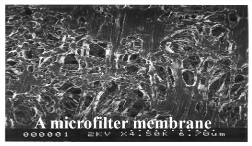
Microfiltration

- Typical pore size: 0.1 microns (10^{-7}m)
- Very low pressure
- Removes bacteria, some large viruses
- Does not filter out:
  - small viruses, protein molecules, sugar, and salts

Microfiltration water plant, Petrolia, PA



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TSS Removal Requirements

TP Limit, mg/L	Max TSS, mg/L
0.1	3.0
0.2	5.0
0.3	7.0
0.4	9.0
0.5	11

Assume soluble P = 0.05 mg/L; particulate P/TSS = 3.0%

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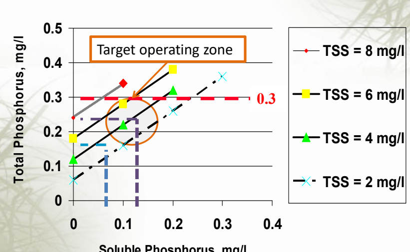
Effluent TP versus Effluent TSS



Assume particulate P/TSS = 3.0%

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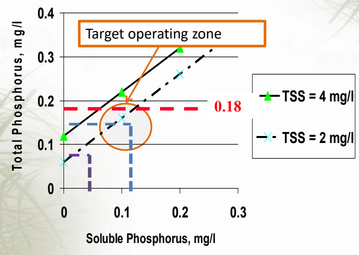
Effluent TP versus Effluent TSS



Assume particulate P/TSS = 3.0%

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Solids Handling Side Streams

Nutrient Removal Systems

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Side Stream Treatment

- Recent efforts for nutrient removal for WWTPs with limited space for expansion has lead to:
  - Membrane reactors
  - Side stream treatment for phosphorus removal:
    - Struvite precipitation
  - Side stream treatment for ammonia removal:
    - ANAMMOX

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Why consider sidestream treatment?

- Concentrated nutrient load
- Usually economical when side streams contribute:
  - ≥15% of the influent TN
  - ≥20% and TP load
  - Typ. of plants with significant biological processes in the solids train (i.e., anaerobic digestion)
- Can often reuse existing infrastructure to reduce costs
- However, sidestream treatment is not economical in many cases

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What are Sidestreams

- Any process flow resulting from the treatment of sludge that flows back into the liquid treatment train
- Examples:
  - Gravity Thickener Overflow
  - Gravity Belt Thickener filtrate
  - Belt Filter Press filtrate
  - Centrate
  - Digester supernatant

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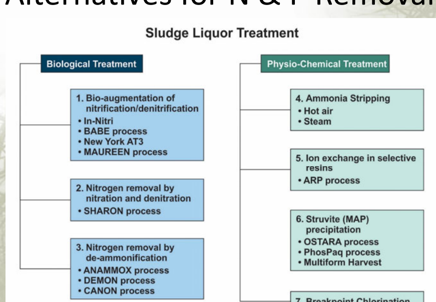
Common Sidestream Treatment Alternatives for N & P Removal



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Key Drivers for Side stream Phosphorus Removal Systems

- High side stream contribution of phosphorus affecting biological phosphorus removal, usually coupled with low TP limits (< 0.3 mg/L)
- Land application program with limitations on agronomic rates of N or P application
- Severe struvite problems

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Sidestream Phosphorus Treatment: Two Alternatives

1. Coagulant-aided phosphorus precipitation
   - Forms aluminum phosphate and aluminum hydroxide
   - Non-proprietary
2. Struvite formation
   - Forms struvite
   - Proprietary
   - Ostara & Multiform Harvest

- Of these two options, only struvite has been identified as a fertilizer additive with market value

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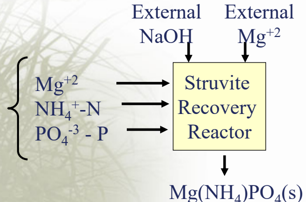
How Struvite Precipitation Works

- Struvite precipitation
  - N:P ratio in struvite = 0.45 lbs N required per lb P removed
  - N:P ratio in filtrate ~ 2.4-2.6, ammonia in excess



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Ostara Process

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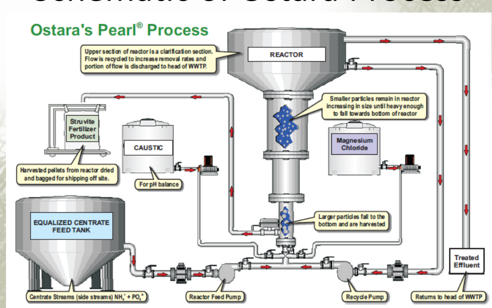
Schematic of Ostara Process



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Crystal Green ™ Fertilizer

- Fertilizer for parks and golf courses
- Specialized product
- Green attributes
  - Slow release fertilizer
  - Produced with minimal greenhouse gas emissions
  - Renewable source
  - Reduces mining of phosphorus for use in commercial fertilizers

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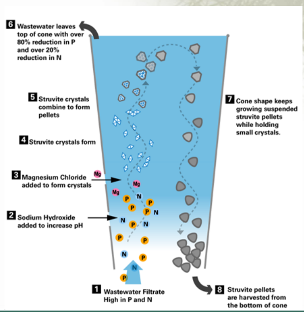
Multiform Harvest

- Simple process to operate – struvite processed offsite
- Filtrate passes through once



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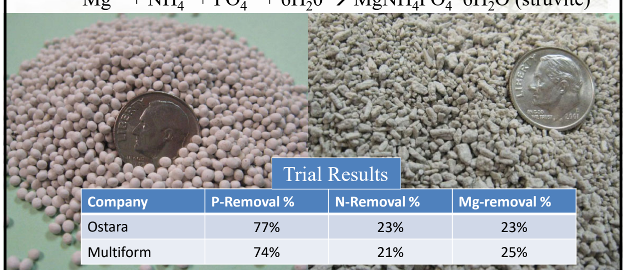
Ostara vs. Multiform product

Ostara Pearl Multiform Harvest

$Mg^{+2} + NH_4^+ + PO_4^{-3} + 6H_20 \rightarrow MgNH_4PO_4{*}6H_2O$ (struvite)



Trial Results

Company	P-Removal %	N-Removal %	Mg-removal %
Ostara	77%	23%	23%
Multiform	74%	21%	25%

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Summary

Helpful Hints - Final Comments

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Final Comments

- Consider multiple “barriers” for TP removal
- Many possible causes for poor nutrient removal
- Important to determine cause and act quickly
- Basic troubleshooting approaches are universal
- Each plant should develop troubleshooting protocols
- Side stream treatment can significantly reduce TP and TN loadings to mainstream process.

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Final Comments

- Aluminum and iron salts precipitate phosphorus
- Aluminum sulfate (alum) and ferric chloride are commonly used
- Actual dosages needed are 1.5 to 2 times stochiometric amounts to reduce soluble phosphorus to 1 mg/L as P
- Higher dosages are needed to reduce soluble phosphorus to less than 1 mg/L

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Final Comments

- Today’s DO, nitrate, ammonia, and phosphate probes and analyzers are extremely accurate and precise
- Probes and analyzers enable operators to make quicker decisions on any needed process control changes

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