# *BNR to Enhanced Nutrient Removal*

**Maryland Center for Environmental Training**
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**BNR to Enhanced Nutrient Removal**

7 Contact Hours
9 CC10 Hours

Upgrading sewage treatment plants for nutrient removal is one of Maryland's top environmental priorities. This course addresses the implications of upgrading from Biological Nutrient Removal (BNR) to Enhanced Nutrient Removal (ENR). Topics covered will include: a review of the basics of nitrification, denitrification, and phosphorus removal; various process configurations will be discussed to accomplish the required levels of nutrient removal; and process control testing and adjustments will also be examined to optimize ENR plant performance.

1. To discuss Biological Nutrient Removal (BNR) and Enhanced Nutrient Removal (ENR) options
2. To distinguish Biological Nutrient Removal (BNR) process trains from Enhanced Nutrient Removal (ENR) process trains
3. To discuss the evolution of Biological Nutrient Removal (BNR) processes to Enhanced Nutrient Removal (ENR) processes
4. To stress the effects that nutrient effluent requirements have on treatment options and costs
5. To share nutrient removal applications and ideas

Agenda
Morning

A. Introduction - Overview
   - Nutrients – Phosphorus and Nitrogen
   - Why remove nutrients?
   - Conditions in the Chesapeake Bay
     - ✓ Submerged aquatic vegetation (SAV)
     - ✓ Loadings – phosphorus, nitrogen, and sediments

B. Nutrient Removal Options
   - Phosphorus
     - ✓ Forms, sources, and typical concentrations
     - ✓ Chemical precipitation
     - ✓ Biological uptake
   - Nitrogen
     - ✓ Forms (Nitrogen Cycle), sources, and typical concentrations
     - ✓ Nitrification
     - ✓ Denitrification
   - Biological Nutrient Removal (BNR)
     - ✓ TN requirement < 8.0 mg/l
     - ✓ With and without carbon (Methanol) addition
   - Enhanced Nutrient Removal (ENR)
     - ✓ TN requirement < 3.0 mg/l
     - ✓ With carbon addition
     - ✓ With tertiary treatment options

C. Evolution of BNR to ENR
   - TN effluent requirement from < 8.0 mg/l to < 3.0 mg/l
   - Nutrient loadings to the Bay still unacceptable

- Chemical addition for Phosphorus removal to < 0.3 mg/l is achievable
- New technologies are available to achieve TN limit of < 3.0 mg/l

Afternoon

D. Phosphorus Removal Options
   - Chemical precipitation
     - ✓ Aluminum salts
     - ✓ Iron salts
   - Biological uptake in both BNR and ENR options
     - ✓ Anaerobic zone for Phosphorus release
     - ✓ Aerobic zone for Phosphorus uptake
   - Maximize biological uptake where possible to minimize costs for chemicals and related chemical sludge disposal
   - Limit of Technology – 0.05 mg/l
   - Anticipated permit levels – 0.1 mg/l to 0.3 mg/l

E. Biological Nutrient Removal Options
   - TN requirement < 8.0 mg/l
   - Typically, three stage, anaerobic, anoxic, aerobic processes installed
     - ✓ Phosphorus release
     - ✓ Denitrification
     - ✓ Nitrification
     - ✓ Phosphorus uptake
   - Common BNR processes:
     - ✓ Ludzak-Ettinger - Three stage
     - ✓ $A_20$ – three stage
     - ✓ Bardenpho
       - o Three stage
       - o Modified five stage
     - ✓ University of Cape Town (UCT)
       - o Three stage
       - o Modified four stage
     - ✓ Virginia Initiative Project (VIP)
   - Suspended growth, fixed film, oxidation ditch, and batch reactor designs have been used
   - With and without carbon addition
   - Limit of Technology – 5.0 mg/l
   - Anticipated permit levels – 6.0 mg/l to 8.0 mg/l

F. Enhanced Nutrient Removal Options
   - TN requirement < 3.0 mg/l
   - Anaerobic, anoxic, aerobic process train usually installed with additional denitrification capability
     - ✓ Phosphorus release
     - ✓ Deitrification
     - ✓ Nitrification
     - ✓ Tertiary denitrification
     - ✓ Phosphorus uptake

- Common ENR processes:
  - ✓ Bardenpho – modified five stage
  - ✓ University of Cape Town (UCT) – modified four stage
  - ✓ Alterations/add-on options to BNR processes:
    - o Integrated Fixed-Film Activated Sludge (IFAS) Hybrid Systems (e.g., rope media, sponge media, or web media)
    - o High-rate Denitrification Biofilters (e.g., Tetra's CoLox System)
    - o Moving Bed Biofilm Reactors (MBBR) using plastic elements w/o return sludge (e.g., AnoxKaldnes)
    - o Membrane Filters (Zenon)
- With carbon addition
- Limit of Technology – 1.5 mg/l to 2.0 mg/l (Depends on Organic Nitrogen concentration)
- Anticipated permit levels – 3.0 mg/l

G. Regulations, Tributary Strategies, and the Chesapeake Bay

# BNR and ENR

**Presented by**
**Ed Jones**

Maryland Center for Environmental Training
College of Southern Maryland
La Plata, MD

ENVIRONMENTAL, HEALTH, AND SAFETY TRAINING



1

## Introduction

Administrative



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## Process Training Sessions

Before class starts, please:
- **Check in**

During class, please:
- **Asks questions**
- Feel free to get up and leave the classroom at any time (i.e., rest rooms, phone calls, etc.)

After class, please:
- **Fill out** a Class Evaluation
- **Answer questions** on class quiz



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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…
  - Name one thing you know or want to know about:
    - Biological Nutrient Removal (BNR)
    - Enhanced Nutrient Removal (ENR)



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## Instructor Expectations

- Begin and end class on time
- Be interactive – participate at your own comfort level
- Share experiences and needs
- Less lecture, more discussions
- Keep it simple
- ***Make this an enjoyable and informative experience!***



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## Ground Rules

- Discussion is encouraged; share experiences
- Use terms we all can understand
- Everyone is different, so please show respect for others in the room
- Express opinions - of things, not people
- Maintain confidences



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## Introduction

Definitions and Acronyms



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## Acronyms

- BNR – Biological Nutrient Removal
- ENR – Enhanced Nutrient Removal
- CBP – Chesapeake Bay Program
- TMDL – Total Maximum Daily Loading
- WLA – Waste Load Allocation
- MLE – Modified Ludzack-Ettinger Process (BNR)
- EMLE- Enhanced Modified Ludzack Process (ENR)
- SBR – Sequencing Batch Reactor
- MBBR – Mixed Bed Bioreactor
- COMAMMOX – COMplete AMMonia OXidation
- ANAMMOX – ANaerobic AMMonia OXidation



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## Nutrients

- TN – Total Nitrogen
  - Soluble and particulate
    - Organic nitrogen - $N_{org}$
    - $NH_3$ – Ammonia
    - $NO_2$ – Nitrite
    - $NO_3$ - Nitrate
- TP – Total Phosphorus
  - Soluble and particulate
    - $PO_4$ – Ortho-phosphorus
    - Organic
    - Polyphosphates

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## Nutrients

- TN – Total Nitrogen ($N_{org} + NH_3 + NO_3 + NO_2$)
- TP – Total Phosphorus ($PO_4 + P_{org} + P_{poly}$)

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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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## Introduction

Objectives, Focus, and Agenda

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## Learning Objectives

- Objective 1 - To discuss the Chesapeake Bay restoration efforts and regulatory "drivers" for BNR and ENR
  - 1970s/1980s Bay conditions
  - 1987 Bay Agreement (Begin BNR Program)
  - 2000 Bay Agreement (Begin ENR Program)
  - 2010 TMDL's/WLA's (Imposed by EPA)
- Objective 2 - To discuss methods for nitrogen and phosphorus removal
- Objective 3 - To discuss the evolution of BNR to ENR technologies

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## Participant Focus

- What information can you use at your work location?
  - Nutrient Removal fundamentals
  - Troubleshooting biological processes
  - Meeting nutrient discharge standards
- What information can you contribute to the discussion?
  - Nutrient removal experiences and practices
  - BNR to ENR experiences

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## OUTLINE

- Water quality in the Chesapeake Bay
  - 1970s and 1980s condition
  - Need for 40 percent reduction in nutrient loadings to restore Bay health conditions
- Regulatory Background
  - 1987 and 2000 Bay Agreements
  - 2010 Agreement - TMDL (EPA)
- Nitrification and Denitrification Overview
- BNR configurations
- ENR configurations
- Summary

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## Expected Learning Outcomes

Participants will be able to discuss:

- The regulatory framework for nutrient removal in the Chesapeake Bay watershed
- Nitrification and Denitrification
- Major BNR processes
- Major ENR processes
- Options to upgrade BNR facilities to ENR
- Process control options
- Trouble-shooting options

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## BOD and Nutrient Removal

Regulatory Drivers

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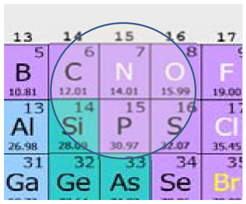
# Nutrients

**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

- TN – Total Nitrogen ($NH_3$ + $N_{org}$ + $NO_3$ + $NO_2$)
- TP – Total Phosphorus ($PO_4$ + $P_{org}$ + $P_{poly}$)
- Nutrients stimulate algae production in receiving waters and need to be removed
- Typical raw wastewater concentrations:
  - ✓ TN – 25 to 40 mg/l
  - ✓ TP – 3 to 6 mg/l



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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 (>2000)



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## Regulator Drivers

1972 Clean Water Act (CWA)

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## Clean Water Act (CWA)

- The 1972 Clean Water Act:
  - Set the basic structure for regulating point source discharges of pollutants into US waterways
  - Gives EPA authority to set **water quality standards** for contaminants:
    - Attain water quality levels that make surface waters safe to fish and/or swim in
    - Restore and maintain the chemical, physical, and biological integrity of the nation's waterways

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## Clean Water Act (CWA)

- Water Quality Concerns:
  - BOD (Biological treatment)
  - TSS (Sedimentation and filtration)
  - Coliforms (Disinfection)
  - Nutrients:
    - Nitrogen (Nitrification and denitrification)
    - Phosphorus (Physical incorporation, biological uptake, and chemical precipitation)

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## Water Use

- WWTP discharge standards are set to meet water quality standards:
  - In waterways
    - Aquatic and marine life
    - Water contact sports
      - Swimming
      - Boating
      - Fishing
  - For downstream water users:
    - Domestic water supplies
    - Industrial water supplies
    - Agriculture water supplies

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## Clean Water Act (CWA)

- EPA can/will impose more stringent **water quality discharge standards** for contaminants:
  - If chemical, physical, and biological integrity of the receiving water requires more removal (e.g., BNR to ENR program in the Chesapeake Bay)
  - 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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## Clean Water Act (CWA)

- The CWA makes it unlawful for any person to discharge any pollutant from a point source into navigable waters unless a NPDES discharge permit is obtained
- NPDES - **N**ational **P**ollutant **D**ischarge **E**limination **S**ystem
- WWTPs are self-monitored
  - Monthly “Discharge Monitoring Reports” (DMRs)
- EPA has delegated monitoring responsibility to states

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## Goals of Wastewater Treatment

- Removal of:
  - **Suspended solids and organic matter** (TSS, cBOD, and nBOD) to limit pollution
  - **Nutrients** (TP and TN) to limit eutrophication
  - **Microbiological contaminants** to eliminate infectious diseases
- Required levels of treatment are based on issued discharge permit limitations

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## Wastewater Constituent Removal

- **TSS and cBOD Removal** in primary clarifiers and secondary bioreactors/clarifiers
- **TP removal** in primary, secondary, and tertiary
  - Particulate removal
  - Biological uptake
  - Chemical precipitation
- **Nitrification**: Ammonia-N conversion to nitrate-N
- **Denitrification**: Nitrate-N conversion to nitrogen gas

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## Key Wastewater Constituents

- BOD – Biochemical Oxygen Demand
  - Typically, a five-day test is used to determine the quantity of oxygen used by microorganisms.
  - The higher the BOD concentration, the greater the wastewater strength (organic matter or food).
  - Raw sewage concentrations - 150 to 300 mg/l
  - Valid five-day BOD testing conditions:
    - BOD incubator temperature - 20ºC
    - DO uptake - 2.0 mg/l
    - DO remaining after five days -1.0 mg/l

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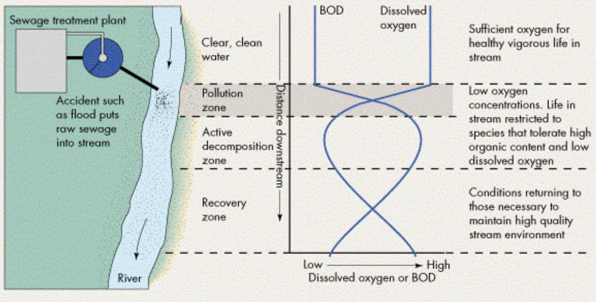
## BOD Effects on Water Quality



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## Key Wastewater Constituents

- TSS – Total Suspended Solids
  - Substances in wastewater that can be removed by physical means
  - Sedimentation and filtration unit processes are used to remove TSS from wastewater
  - Raw sewage concentrations -150 to 300 mg/l
  - Valid TSS testing conditions:
    - Temperature in a drying oven - 103ºC
    - VSS burn off at 550ºC



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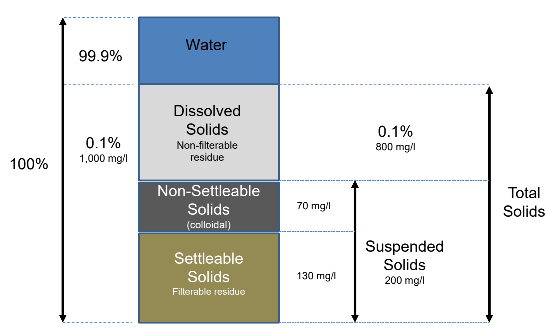
## Wastewater Solids



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## Key Wastewater Constituents

- pH
  - An expression of the intensity of basic or acidic conditions, 0 (most acidic) to 14 (most basic); 7 neutral
  - Microorganisms most active 6.5 - 8.0
  - Nitrification is inhibited at pH 6.0 or less
- Alkalinity
  - Measure of wastewater ability to buffer pH change
  - Nitrification is inhibited when alkalinity < ~ 60 mg/L
- Pathogenic organisms
  - Total Coliform and E-coli indicators
  - Numbers are limited in permit

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## Nitrogen

Sources and Forms

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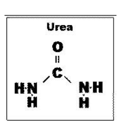
## Sources of Nitrogen in Wastewater

- Residential wastes - Humans
  - Digested/wasted food (Org-N)
    - Vegetables
    - Meats
  - Urea (converted Ammonia)
- Commercial wastes - Humans
  - Restaurants
  - Hotels/motels
  - Offices
  - Stores

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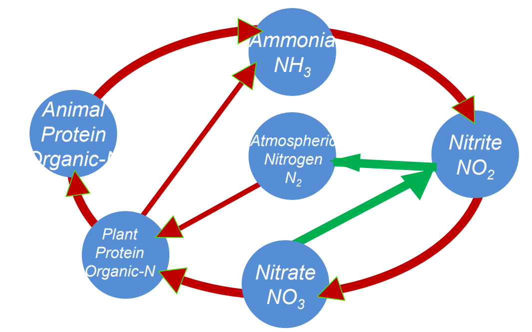
## Nitrogen Cycle in Nature



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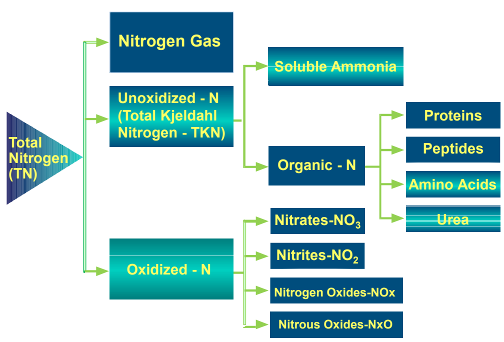
## Forms of Nitrogen



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## Forms of Nitrogen

- Ammonia(um) ($NH_3/NH_4^+$)
- Organic Nitrogen
- Nitrogen Gas ($N_2$) ↑
- Nitrite ($NO_2^-$)
- Nitrate ($NO_3^-$)

*TKN (Un-oxidized)* — Ammonia(um), Organic Nitrogen

*Oxidized* — Nitrite, Nitrate

Total Nitrogen (TN) = TKN + $NO_2$ + $NO_3$
TKN = Total Kjeldahl Nitrogen



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## Forms of Nitrogen

| FORM | REMOVAL PROCESS |
|---|---|
| Organic-N | Converts to ammonia forms; **a small soluble portion is non-reactive (1.0 mg/l)** |
| Ammonia(um) ($NH_3$/$NH_4^+$) | Most abundant form; converts to nitrites/nitrates under aerobic conditions (nitrification) |
| Nitrite ($NO_2^-$)/Nitrate ($NO_3^-$) | Converts to $N_2$ under anoxic (no oxygen) conditions (denitrification) |



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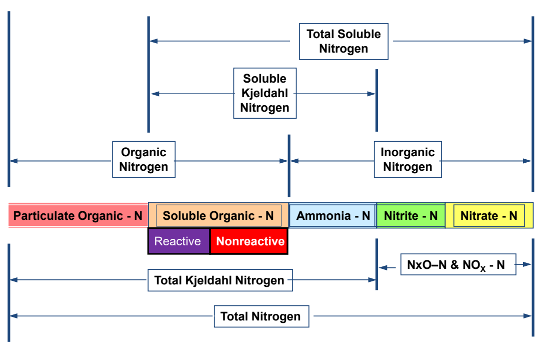
## Forms of Nitrogen



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## Phosphorus

Sources and Forms



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## Sources of Phosphorus in Wastewater

- Human Wastes
  - Digested/wasted food
  - Water softening products
- Organo-phosphorus flame retardants in children's clothing
- Corrosion and Scale Control
  - Sodium Hexametaphosphate
- Industrial
  - Commercial laundries
  - Dairy product processers (e.g., use of high phosphate detergents to clean milk and ice cream processing equipment)



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## Phosphorus Compounds

- Commercial sources: Phosphate rock/Apatite - $Ca_5(PO_4)_3(OH, F, Cl)$
  - hydroxylapatite $Ca_5(PO_4)_3OH$
  - fluorapatite $Ca_5(PO_4)_3F$
  - chlorapatite $Ca_5(PO_4)_3Cl$
- 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:
    - $Na_5P_3O_{10}$ - Sodium tripolyphosphate; detergent additive
    - $Na_3PO_4$ – Trisodium phosphate; water softener



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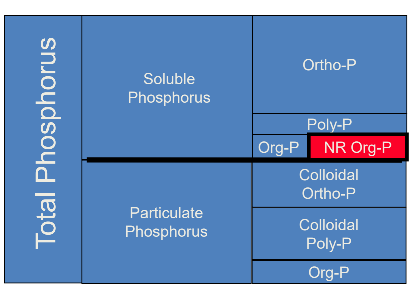
## Forms of Phosphorus



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## Forms of Phosphorus

| FORM | REMOVAL PROCESS |
| --- | --- |
| • Organic-P | • Converts to polyphosphate and orthophosphate forms; **a small soluble portion is non-reactive (0.05 mg/l)** |
| • Orthophosphate | • Most abundant form; chemically reactive and consumed by biological growth |
| • Polyphosphates | • Possibly reacts with metal salts; can be used for biological growth |



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## Chesapeake Bay

Bay Health and Regulations



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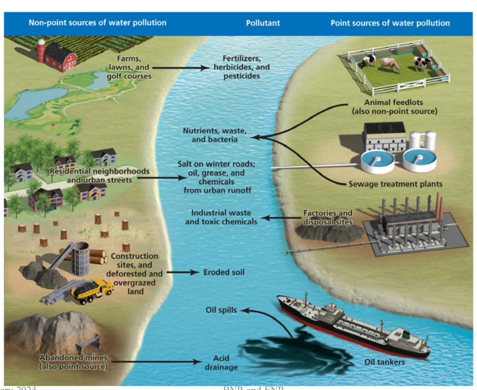
## Pollution Sources



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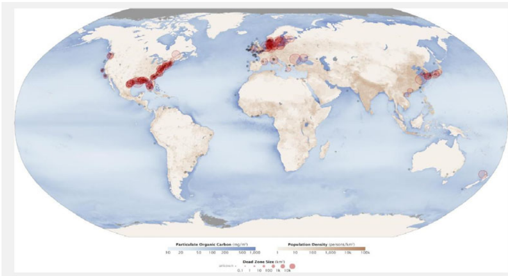
## Excess Nutrients are a Global Concern



NASA Earth Observatory



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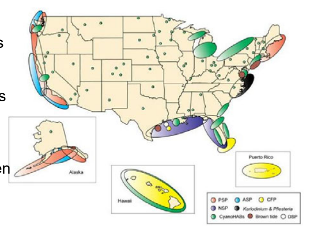
## Extent of N&P Impacts

- 14,000 Nutrient-related Impairment Listings in 49 States
- ~80% of Assessed Continental U.S. Coastal Waters exhibit eutrophication
- ~50% of streams have medium to high levels of nitrogen and phosphorus




Occurrence of Excess Algae throughout the U.S.



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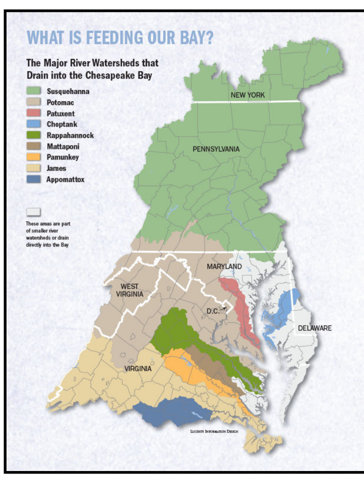


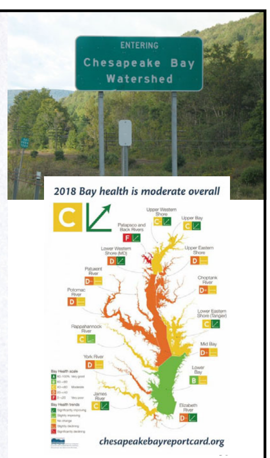


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## Water Quality Conditions

**University of Maryland**
**Center for Environmental Science**

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## University of Maryland Center for Environmental Science

- "Bay Health" Annual Reports (Since 2007)
- Bay health affected by elevated nutrient and sediment loads, which results in water quality and biotic (biological) degradation

*Aquaculture and Restoration Ecology Laboratory at Horn Point Laboratory, Cambridge, Maryland; Photo by Kirsten Frese*

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## Chesapeake Bay Health

- Bay Health - progress of six indicators towards established ecological thresholds.
- Water quality indicators/Index (WQI) are:
  - Chlorophyll *a*
  - Dissolved oxygen
  - Water clarity
- Biotic indicators/Index (BI) are:
  - Submerged aquatic vegetation (SUV)
  - Benthic Index of Biotic Integrity
  - Phytoplankton Index of Biotic Integrity

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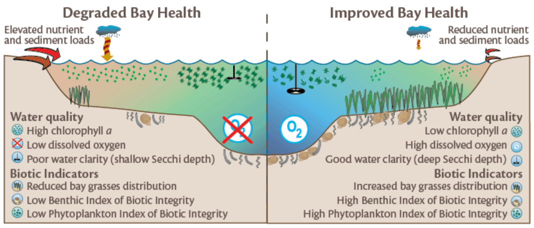
# Chesapeake Bay Health

- Bay Health Index (BHI) - average of Water Quality Index (WQI) and Biotic Index (BI) scores for each reporting region

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# Key Water Quality Indicators

- Chlorophyll a
- SAV – Submerged aquatic vegetation
- Dissolved Oxygen
- All three are showing degrading trends

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# The Chesapeake Bay Program

- In the late 1970s, a rapid loss of aquatic life was reported in a 5-year study of Bay conditions
- The study identified excess nutrient pollution as the main source of the Bay's degradation
  - Ammonia toxicity also contributed to degradation
  - Loss of submerged aquatic grasses was key observation

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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 and became a problem in the 1970s



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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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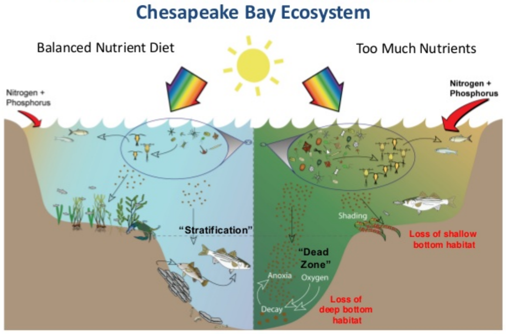
### How Too Much Nutrient Pollution Impacts the Chesapeake Bay Ecosystem



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## Development of Chesapeake Watershed Models

| Model Revision | Characteristics | | Advances | Simulation Period | Decisions Supported |
|---|---|---|---|---|---|
| | Watershed | Bay | | | |
| Phase I (1985) | 5 land uses; 64 segments | Steady state | First coupling of watershed, hydrodynamic, and water quality models | Summer data - 1965, 1984, and 1985 | General goal of 40% reductions of controllable loads (CBP, 1987) |
| Phase 2 (1992) | Expanded agriculture simulation detail | Dynamic 4,000 grid cells | Integrated sediment flux model; included atmospheric deposition | 4 continuous years (1984 – 1987), hourly time intervals | Nutrient load reductions to achieve CBP (1987) allocation goals |
| Phase 4.3 (2003) | 9 land uses; 94 segments | Dynamic 13,000 grid cells | Integrated simulation of land and soil contaminant runoff processes; included SAV and benthic deposit models | 14 continuous years (1985 – 1994) | Nutrient load allocations |
| Phase 5.3 (2010) | 25 land uses; 899 segments | Dynamic 57,000 grid cells | Enhanced segmentation, land uses, and mechanistic detail | 21 continuous years (1985 – 2005) | TMDL |

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## Chesapeake Bay Program

- Bay degradation findings led to the formation of the Chesapeake Bay Program in 1983 as a governance means to restore water quality in the Bay

**Chesapeake Bay Program**
*Science. Restoration. Partnership.*

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## Chesapeake Bay Program

- The Chesapeake Bay Program includes:
  - Signers of the original 1983 Bay Agreement:
    - Maryland
    - Virginia
    - Pennsylvania
    - The District of Columbia
  - EPA - sets Chesapeake Bay water quality limits
  - The U.S. Department of Agriculture
  - Headwater jurisdictions:
    - Delaware
    - New York
    - West Virginia

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## Chesapeake Bay Program

- The Program is led by the Chesapeake Executive Council, which includes:
  - The EPA Administrator
  - Governors of Maryland, Pennsylvania, and Virginia
  - The mayor of the District of Columbia

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## Chesapeake Bay Program

- CBP Agriculture and Wastewater Workgroups
  - Model Bay watershed improvements (since 1985)
- Water quality restoration efforts:
  - Implementing pollution reduction practices on urban and suburban lands
  - Reducing air pollution deposited in the watershed

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## 1987 Chesapeake Bay Agreement

- In a 1987 Chesapeake Bay Agreement:
  - Nutrient water quality targets for 2000 were set (40% less than 1985 conditions)
  - USEPA, MD, VA, DC, PA and the Chesapeake Bay Commission – Signatories to agreement
  - USEPA has the lead on setting water quality standards for the Bay:
    - Based on water quality needs
    - Based on nutrient removal technology available

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## 2000 Chesapeake Bay Agreement

- In a 2000 Chesapeake Bay Agreement:
  - The 40 percent reduction goal would continue beyond 2000 to 2010
  - Signatories would include Delaware, New York, and West Virginia
  - States and DC began planning for nutrient removal at their source – tributary strategies

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## 2010 Chesapeake Bay Agreement

- In a 2010 Chesapeake Bay Watershed Agreement:
  - States and DC committed to meet sector reduction goals
    - Total Maximum Daily Load, or TMDL
    - Waste Load Allocation, or WLA
  - The 40 percent nutrient removal reduction goal would continue beyond 2010 to 2025
    - EPA would review progress by 2017

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## Total Maximum Daily Load (TMDL)

- The 2010 Bay TMDL was prompted by insufficient progress and continued poor water quality in the Chesapeake Bay and its tidal tributaries
- Nutrient load allocations (million pounds/year):

| | 2000 | 2010 TMDL |
|---|---|---|
| Nitrogen | 175 | 186 |
| Phosphorus | 12.8 | 12.5 |

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## Total Maximum Daily Load (TMDL)

- TMDL pollution limits are designed to ensure:
  - Restoration of the Bay and its tidal rivers by 2025
  - Best Management Practices (BMPs) in place by 2017 to meet 60 percent of pollution reductions
- Annual TMDL Bay watershed limits:
  - 185.9 million pounds of nitrogen (excludes tidal water atmospheric deposition of nitrogen)
  - 12.5 million pounds of phosphorus
  - 6.45 billion pounds of sediment



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## Total Maximum Daily Load (TMDL),

- Progress in implementing the Bay Total Maximum Daily Load (TMDL) is tracked by the CBP's "ChesapeakeStat"
- Elements of a TMDL:
  - "Waste load allocations" for point sources
    - Sewage treatment plants
    - Regulated urban stormwater systems
    - Regulated animal feeding operations
  - "Load allocations" for non-point sources
    - Runoff from agricultural lands
    - Non-regulated stormwater from urban/suburban lands



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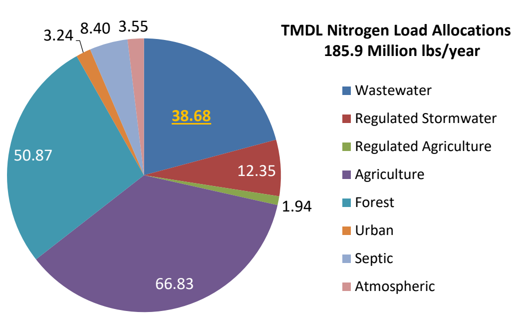
## TMDL Nitrogen Load Allocations



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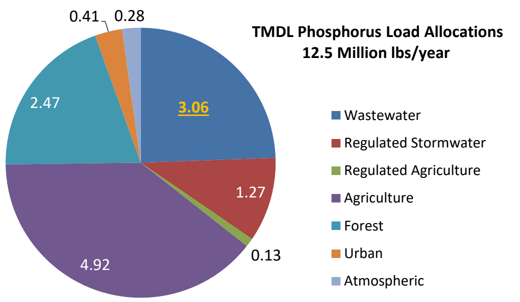
## TMDL Phosphorus Load Allocations



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## Wastewater Sector

2010 Waste Load Allocations (WLAs)

- Nitrogen: 38.7 million pounds/year
- Phosphorus: 3.06 million pounds/year
- Interim target date: 2017 for 60% reductions (from 2010)
- Target date: 2025 for achieving WLAs



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## Wastewater Nutrient Removal

- **Total Phosphorus (TP)** has been removed well in the past
  - Less than 0.3 mg/l TP; even less than 0.1 mg/l
  - **Bay 2010 TMDL Target: Less than 0.3 mg/l TP**
  - 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



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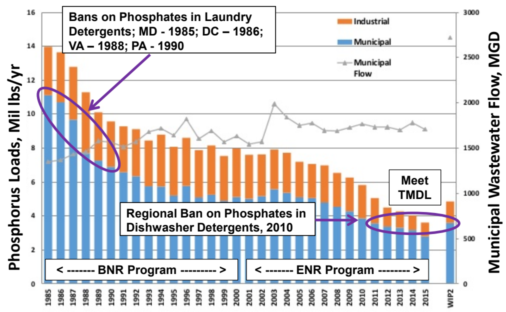
## TP Loadings to the Chesapeake Bay - Wastewater



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## Wastewater 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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## Wastewater Nutrient Removal

- Enhanced (ENR) **Total Nitrogen (TN)** removal is now required:
  - Current 3 to 5 mg/L of TN is not adequate (BNR)
  - **Bay 2010 TMDL Target: Less than 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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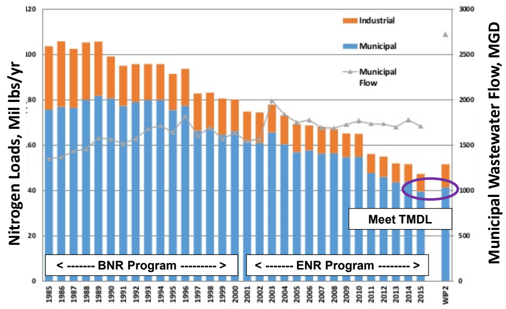
## TN Loadings to the Chesapeake Bay - Wastewater



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## Wastewater Sector

- Wastewater sector nutrient removal goals were met in 2015 because of:
  - BNR upgrades from 1985 – 2000
  - ENR upgrades from 2000 – 2015
- In 2016, EPA announced the wastewater sector's 2025 nutrient removal goals had been effectively met a decade early…!



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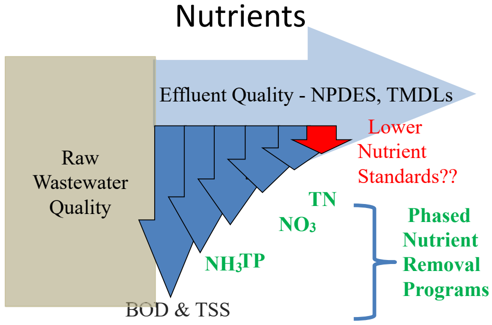
## Future - Role and Impact of Nutrients

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## How will future regulations affect Nutrient Removal Requirements?

Regulatory Challenges:
- Clean Water Act
- Chesapeake Bay Program Regulations
- State Regulations
  - Follow EPA lead
  - Nutrients
  - Sludge
- Local Ordinances

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# Nutrient Removal

Overview

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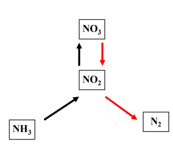
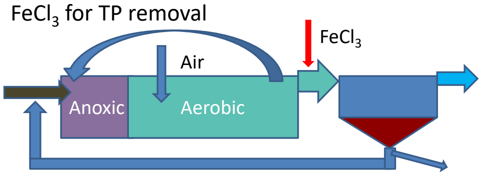
## Nutrient Removal

- Nitrification (*Nitrosomonas* and *Nitrobacter*)
  $NH_3 + O_2 \rightarrow NO_2^- \rightarrow NO_3^-$
- Denitrification
  $NO_3^- + \text{organics} \rightarrow CO_2 + N_2$
- Process adaptation – MLE
- $FeCl_3$ for TP removal

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## Nutrient Removal

- **Why remove Nutrients (nitrogen and phosphorus):**
  - Nutrients contribute to algae growth
  - Excess algae growth (Eutrophication) causes water quality issues:
    - Loss of water clarity
    - Limitation on sunlight penetration
    - Oxygen depletion
    - Fish and marine life die-off
    - Submerged aquatic vegetation (SAV) die-off



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## Historical Overview

- 1920s - 1960s
  - cBOD Removal
  - Nitrification
- 1970s – Chemical addition for phosphorus removal
- 1980s to 2000 – BNR development and application
- Past 20 years – BNR to ENR



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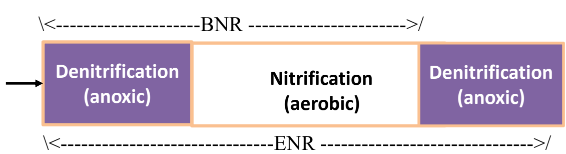
## Common BNR/ENR Configurations




- BNR:
  - Modified Ludzack-Ettinger (MLE)
  - Anaerobic/Anoxic/Oxic (A2O)
  - University of Cape Town Process (UCT)
- ENR:
  - Enhanced MLE/4-stage Bardenpho
  - MLE with Denitrification Filter



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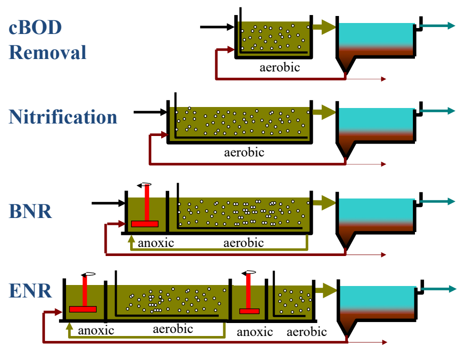
## Evolution of Activated Sludge



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## Nutrient Removal

| Nutrient | Removal Process |
|---|---|
| • Nitrogen | • Nitrification<br>– Ammonia Conversion<br>– $NH_3^+$-N to $NO_3^-$N<br>– Oxygen and alkalinity needed<br>• Denitrification<br>– Nitrate Removal<br>– $NO_3^-$-N to Nitrogen gas ($N_2$)<br>– Carbon source needed |
| • Phosphorus | • Biological Uptake<br>– Conventional<br>– Excess<br>• 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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## Meeting Nutrient Discharge Limits Process Strategies

1. **Multiple barriers for TN removal**
   - Pre-anoxic zone (first stage denitrification)
   - Nitrification – aerobic zone
   - IFAS (enhanced nitrification, optional))
   - Post anoxic zone (second stage denitrification)
   - Denitrification filters (in lieu of post anoxic zone)
2. **Multiple barriers for TP removal**
   - Biological uptake
   - One (maybe two) chemical application points
   - Filtration for TSS (particulate TP) removal

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## Nutrient Removal

Nitrogen

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## Forms of Nitrogen

| FORM | REMOVAL PROCESS |
|---|---|
| • Organic-N | • Converts to ammonia; **a small soluble portion is non-reactive (1.0 mg/l)** |
| • Ammonia(um) ($NH_3$/$NH_4^+$) | • Most abundant form; converts to nitrites/nitrates under aerobic conditions (nitrification) |
| • Nitrite ($NO_2^-$)/Nitrate ($NO_3^-$) | • Converts to $N_2$ under anoxic (no oxygen) conditions (denitrification) |

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## Forms of Nitrogen

- Ammonia(um) ($NH_3/NH_4^+$)
- Organic Nitrogen (Org-N)
- Nitrogen Gas ($N_2$) ↑
- Nitrite ($NO_2^-$)
- Nitrate ($NO_3^-$)

*TKN (Un-oxidized)* — Ammonia(um) and Organic Nitrogen

*$NO_x$ (Oxidized)* — Nitrite and Nitrate

Total Nitrogen (TN) = TKN + $NO_x$

TKN = Total Kjeldahl Nitrogen



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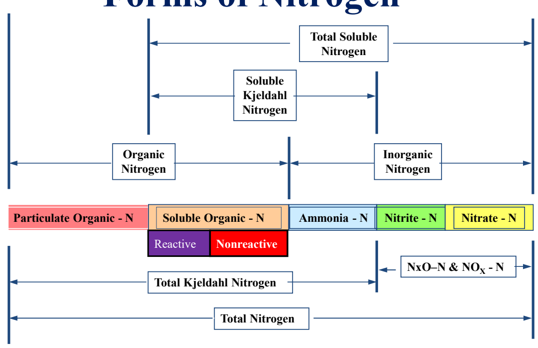
## Forms of Nitrogen



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## Background Uptake

- Physical removal of particulate organic nitrogen
- Conventional biological assimilation of $NH_3$
  - To satisfy biological needs
- Nitrification/Denitrification
  - Aerobic zones
  - Anoxic zones



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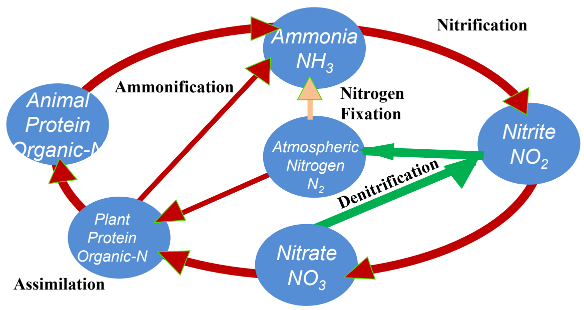
## Simplified Nitrogen Cycle in Nature



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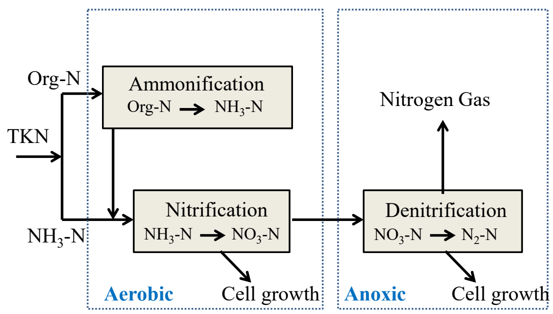
## Nitrification-Denitrification



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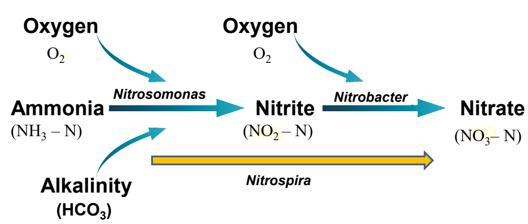
## Nitrification

*The oxidation (as by bacteria) of ammonia and organic nitrogen to nitrites ($NO_2$) and then further oxidation of nitrites to nitrates ($NO_3$).*



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## Nitrification Process Monitoring

- Oxygen requirements:
  - 4.6 mg/mg NH3-N converted
  - Maintain DO in process between 2.0 – 4.0 mg/l
- Alkalinity requirements:
  - 7.1 mg/mg NH3-N converted
  - Maintain alkalinity >70 mg/l $CaCO_3$

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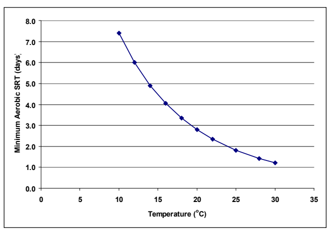
## Nitrification Process Monitoring

- Key Factors:
  - Slow growth requires adequate **aerobic SRT**
  - **DO** typically >2mg/L
  - **pH** 6.5-7.5
  - Target effluent alkalinity of 50 to 75 mg/L as $CaCO_3$




- Overall Reaction:
  - $NH_4^+ + 2\,O_2 \rightarrow NO_3^- + 2H^+ + H_2O$

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## Nitrification Control Parameters

Temperature

- Nitrifiers lose about ½ their activity for each 10ºC temperature drop
- In winter, put additional aeration tanks online, or increase MLSS
- Either action will increase MCRT

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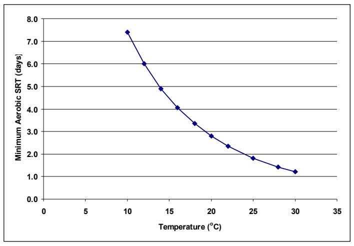
# Nitrification Process Monitoring

- **Key Factor 1**
  - Slow growth requires adequate aerobic SRT
  - **MAINTAIN ADEQUATE SOLIDS INVENTORY**



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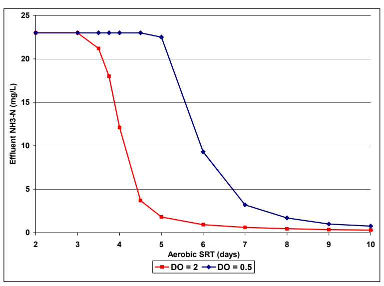
# Nitrification Process Monitoring

- **Key Factor 2**
  - Maintain target DO concentration



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# Importance of Dissolved Oxygen

- Oxygen is sparingly soluble in water
- DO is a growth-limiting substrate
- *Critical oxygen concentration* is about 10% to 50% of DO saturation in water
  - 10% minimum saturation for BOD removal (> 1.0 mg/l DO)
  - 20% minimum saturation for ammonia conversion (> 2.0 mg/l DO)



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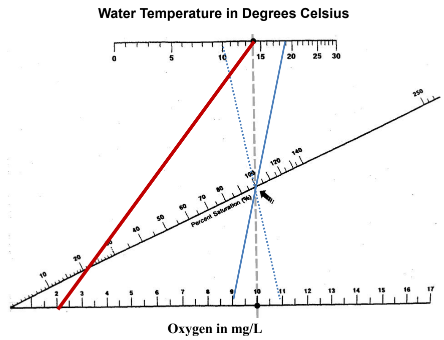
# D.O. - Percent Saturation in Water




Source: Department of Fisheries and Aquatic Sciences, University of Florida



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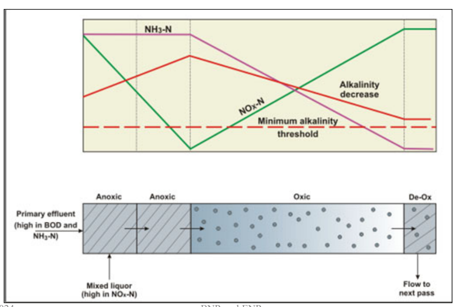
# Nitrification Process Monitoring

- **Key Factors – NH3/NO3, D.O., SRT, and Alkalinity**
  - Maintain target effluent NH3/NO3, DO, and alkalinity



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# Nitrification Problems - Summary

| Possible Causes | Solution |
| --- | --- |
| Insufficient MCRT (target – varies with temperature) | Increase MCRT to establish nitrification by reducing sludge wasting or increasing MLSS levels |
| Insufficient DO in aerator (target - 2.0 mg/l goal) | Increase aeration by adjusting air valves, increasing blower output, or turning on another blower. |
| Insufficient alkalinity (target – NLT 70 mg/l $CaCO_3$) | Add supplemental alkalinity to maintain target $CaCO_3$ concentrations in effluent |
| Chemical inhibition of nitrifiers | Trace source of improper discharge of nitrification inhibitors and eliminate at source |



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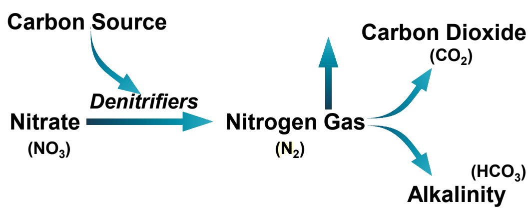
## Denitrification

*Reduction of nitrates or nitrites commonly by bacteria usually resulting in the escape of nitrogen in the air.*



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## Denitrification

Note: (Almost) all nitrates returned to the pre-anoxic zones should be denitrified.

The "goal" $NO_3$-N concentration in the effluent from the last anoxic zone should be between 0 and 0.5 mg/L.



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## Conditions for Denitrification

**No oxygen:**
- **DO less than 0.2 mg/L**
- **No aeration**

**Carbon source:**
- **Primary Effluent**
- **Endogenous**
- **Methanol or other carbon source**

**Mixing:**
- **Submersible mixers**
- **Vertical mixers**



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## Denitrification

- **If effluent nitrate-nitrogen is above the goal:**
  - Verify nitrate recycle pumps are running.
  - Check nitrate recycle pump speed.
  - Verify very low DO in the anoxic zones.
  - Consider if low influent BOD or slowly degradable influent BOD could be inhibiting the process.

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## Keys to Successful Nitrogen Removal

- **Nitrification**
  - Adequate Aerobic SRT – **Keep Solids High!**
  - Adequate D.O./oxygen transfer
  - Adequate Alkalinity/pH
- **Denitrification**
  - **Successful nitrification**
  - Anoxic zones
  - No D.O
  - Carbon

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## Inhibition of Denite Process

- Environmental Conditions
  - pH
  - Temperature
  - **Aerobic Conditions!** Keep DO< 0.2 mg/L
- Insufficient amount of rbCOD (Carbon Substrate).
- Presence of Chemical Inhibitors:
  - Substrates, intermediates, and products of denitrification
  - Synthetic organic chemicals
  - Heavy metals - Hg, Ni, Pb, etc.

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## High DO in the Anoxic Zones

- High DO in the anoxic zones may be more of a problem during the winter because more DO can be absorbed by colder water and biological kinetics are reduced.
- Lower the nitrate recycle rate in the winter if necessary

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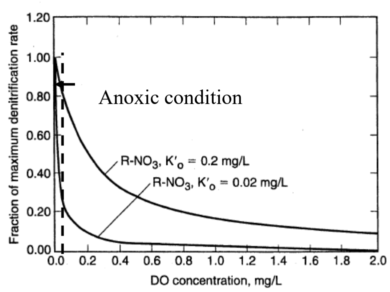
Reduction in rate of Denite as a function of D.O.
(K'o is oxygen inhibition constant)

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## Carbon for Denitrification

- Alcohols
  - Methanol
  - Ethanol
- Glycerol/glycerin – (Biodiesel by-products)
- Acetates - (Acetic acid, sodium acetate)
- Carbohydrates - (Sucrose, sugar water, corn syrup)
- MicroC$^{TM}$ – Carbohydrate (1000), glycerin (2000), alcohol based blends (3000)

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## Nutrient Removal

Phosphorus

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## Forms of Phosphorus

| FORM | REMOVAL PROCESS |
|---|---|
| Organic-P | Converts to orthophosphate form; **a small soluble portion is non-reactive (e.g., 0.05 mg/l)** |
| Condensed Phosphates | Converts to orthophosphate form |
| Orthophosphate | Most abundant form; chemically reactive and consumed by biological growth |

January 2023 TP Removal 119

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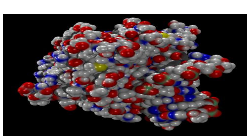
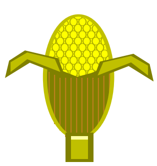
## Sources and Forms of Phosphorus

Organic Phosphorus

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





January 2023 TP Removal 120

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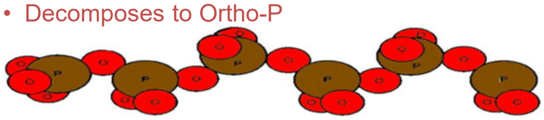
## Sources and Forms of Phosphorus

**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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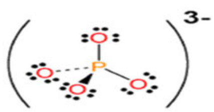
## Sources and Forms of Phosphorus

**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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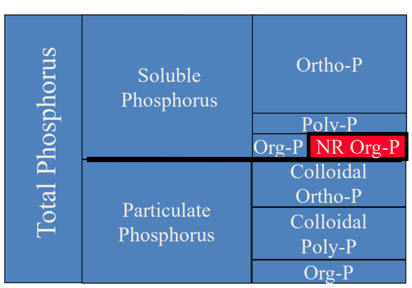
## Forms of Phosphorus



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## Phosphorus Removal at WWTPs

- Physical:
  - Sedimentation and filtration for particulate phosphorus
  - Membrane technologies
- Chemical:
  - Co-precipitation with alkalinity
- 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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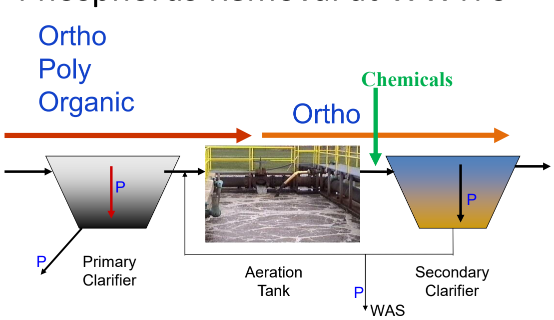
## Phosphorus Removal at WWTPs

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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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## Bans on Phosphorus in Detergents

- **By the mid-1970's, EPA** began advocating bans on detergent phosphates as practical and feasible approaches for reducing phosphorus loadings to the Great Lakes:
  - Bans on phosphates have met with consumer acceptance
  - Nitrilotriacetic acid and other phosphate substitutes have not proved to be a public health problem
  - Bans on phosphates reduce capital and operating costs (Chemical and sludge disposal) at WWTPs

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## Bans on Phosphorus in Detergents

- States along the Great Lakes responded by:
  - Regulating phosphorus in detergents
  - Investing in more effective sewage treatment (e.g. phosphorus removal)
  - Developing and promoting best management practices for agriculture lands(e.g., minimizing surface runoff)

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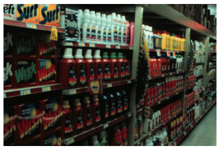
## Phosphate Bans in Detergents

In the mid-1980's, Maryland, Pennsylvania, Virginia, and the District of Columbia instituted bans on phosphates in laundry detergents




Nearly 25 years later, a second regional ban became effective on phosphates in automatic dishwasher detergents

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## Phosphate Bans in Detergents

- Influent phosphorus concentrations to WWTPs were reduce more than 30% after the bans went into effect
- Effluent phosphorus concentrations from WWTPs were reduced more than 50%, after compensating for background uptake of phosphorus

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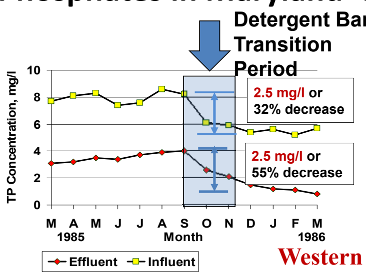
## Ban on Laundry Detergent Phosphates in Maryland -1985




Western Branch WWTP, WSSC

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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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## 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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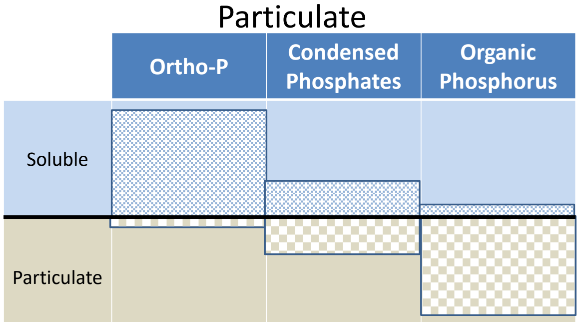
## Phosphorus Forms – Soluble versus Particulate



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## Phosphorus Forms – Soluble versus Particulate

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

January 2023 TP Removal 136

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## Sources and Forms of Phosphorus in Raw Sewage, mg/L

| 1960 | 1980 | Today | |
|---|---|---|---|
| 3 | 3 | 3 | Ortho-P (Human & Food Waste) |
| 0 | 0 | 1 | Ortho-P (Corrosion control) |
| 1 | 1 | 1 | Organic-P (Human & Food Waste) |
| 7 | 4 | 0 | Poly-P (Detergents) |
| 11 | 8 | 5 | Total, typical |

January 2023 TP Removal 137

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## Sources of Phosphorus in Raw Sewage

- 4.0 mg/L from human and food waste
  - 1.1 lbs/cap/year or 1.5 grams/cap/day
  - Prior to development of detergents:
    - Inorganic – 2 to 4 mg/L
    - Organic – 0.5 to 1.5 mg/L
  - Range: 2.5 to 5.5 mg/L, depending on I/I in wastewater sources and non-household contributions (commercial food processing facilities, restaurants, hotels, conference centers, etc.)

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## Sources of Phosphorus in Raw Sewage

- 7.0 mg/L from detergents (before bans)
  - Heavy duty detergents – 12 to 15% P
  - 2.3 lbs/cap/year of P from polyphosphates (2 times more than from human and food waste)
  - Range: 5 to 12 mg/L, depending on percent phosphate content of detergents

January 2023 TP Removal 139

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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)
  - Phosphoric acid, ~ 1 mg/L as $PO_4^{-3}$
  - Sodium hexametaphosphate, ~ 1 mg/L as $PO_4^{-3}$

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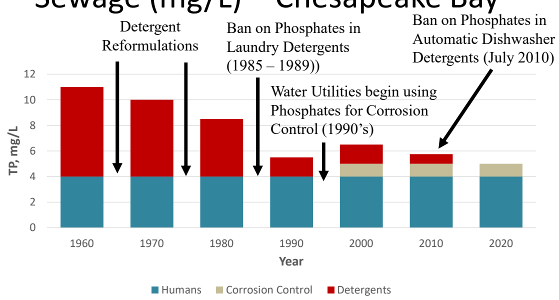
## Trend – Sources of Phosphorus in Raw Sewage (mg/L) – Chesapeake Bay

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## 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 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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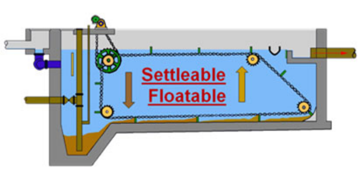
## Removal of Settleable Solids Provides Some Phosphorus Removal

Primary Sedimentation 10 - 30%

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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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## 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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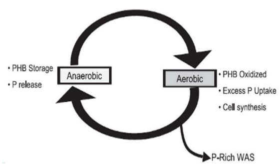
## Enhanced Biological P Removal (EBPR)

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



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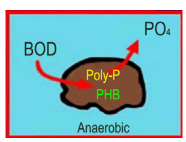
## Enhanced Biological P Removal (EBPR)

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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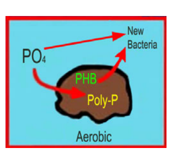
## Enhanced Biological P Removal (EBPR)

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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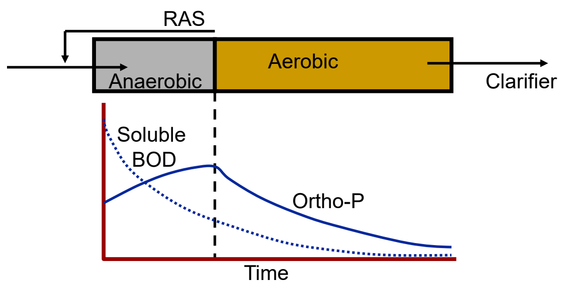
## Enhanced Biological P Removal (EBPR)

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## Phosphorus Removal with Chemicals

**Chemical Reactions** – two mechanisms:

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

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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:
  $\underline{2}Fe + PO_4 + 3OH$ ----> $2FePO_4(OH)_3$ Complex $\downarrow$
  (Mole Ratio = 2.0)

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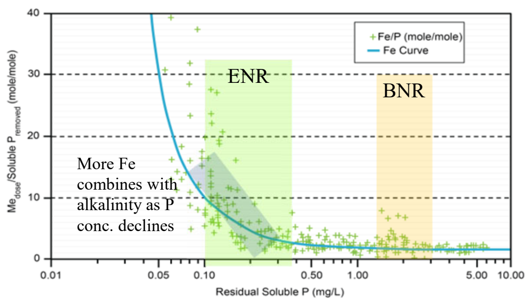
## Chemical Removal of Phosphorus




combines with alkalinity as



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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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## 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 – Effects on pH

- Alum or iron salts will decrease alkalinity and pH, especially at higher dosages
- Lime raises pH
- PACl will not lower alkalinity or pH

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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<br>> 3.0 to reach < 0.25 mg/l P<br>> 5.0 to reach < 0.2 mg/l P<br>>10 to reach < 0.15 mg/l P
    - Dependent on Alkalinity

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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 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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## Effluent Filtration Application

- Assuming that 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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## 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 |



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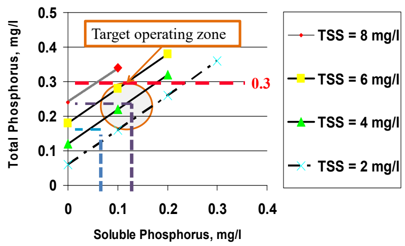
## Effluent TP versus Effluent TSS

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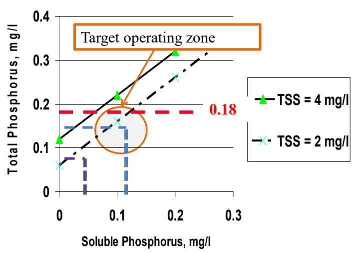
## Effluent TP versus Effluent TSS

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## BNR

Overview

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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” and/or “Post” anoxic zones to already existing nitrification processes for denitrification



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## Typical BNR Configurations

- USEPA model - Sequential BOD removal, Nitrification and Denitrification in separate basins
- South Africa model (MLE) – Modified Ludzack Ettinger process; Denitrification then Nitrification with nitrate recycle
- SBRs - Sequencing Batch Reactors; Nitrification then Denitrification in same basin; no nitrate recycle



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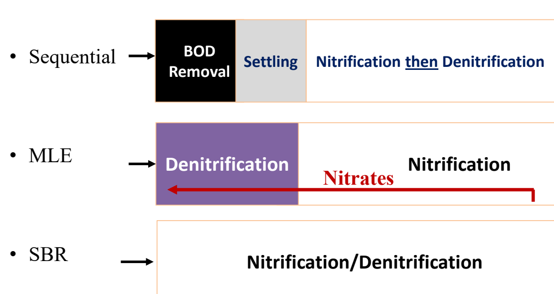
## Typical BNR Configurations



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# BNR Processes

| Process | Nitrogen | Phosphorus | Comments |
|---|---|---|---|
| MLE | Good | None | - Moderate basin volume |
| Enhanced MLE (Bardenpho) | Excellent | None | - Large basin volume<br>- Need for methanol |
| Step Feed | Good | None | - No nitrate recycle |
| SBR | Moderate | Inconsistent | - No nitrate recycle |
| $A^2O$ | Good | Good | - Moderate basin volume<br>- Sensitive to DO in return |
| Modified UCT | Good | Excellent | -Separate anoxic zone for RAS<br>- Several nitrate recycle streams<br>- Increased complexity |
| 5-stage Bardenpho | Excellent | Good | - Larger reactor volume<br>- Need for methanol |
| Oxidation Ditch | Excellent | Good | -Long HRT and SRT<br>- Tight DO controls necessary |

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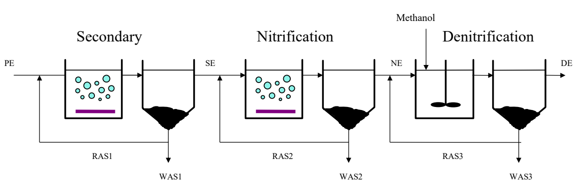
# EPA "Model" for TN Removal

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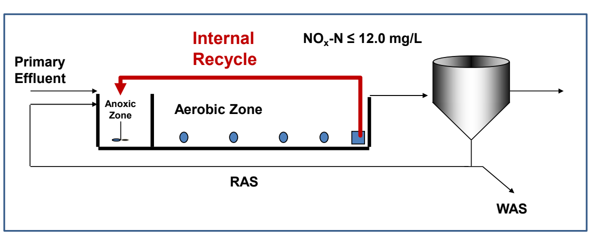
# MLE with Internal Recycle

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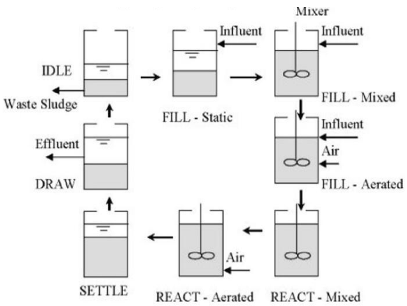
## Sequencing Batch Reactor



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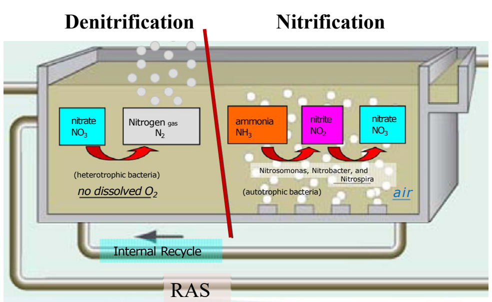
## Biological Nitrogen Removal



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## BNR Program

- BNR Programs in Bay watershed states began removing nutrients in 1985
- 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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# Biological Nutrient Removal (BNR)

- BNR converts/removes Nitrogen (primarily ammonia – $NH_3$) in wastewater to nitrite ($NO_2$), nitrate ($NO_3$), and ultimately nitrogen gas ($N_2$).
- BNR is a two-step process:

  Step 1: Nitrification

  Step 2: Denitrification

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# BNR

- Removes most nitrogen (TN) and 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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# 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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## Milestones

- 1954 Wuhrman proposes 2-stage, aerobic - anoxic process
- 1962 Ludzack and Ettinger proposes 2-stage, anoxic – aerobic process
- 1973 Barnard in South Africa develops the Modified Ludzack-Ettinger process



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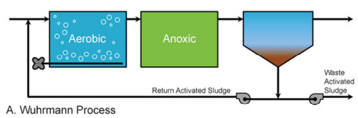
## 2-Stage BNR Process Evolution




1954



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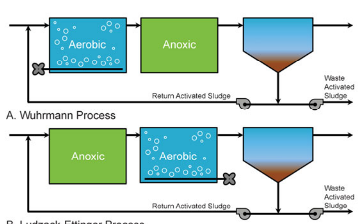
## 2-Stage BNR Process Evolution




1954

1962



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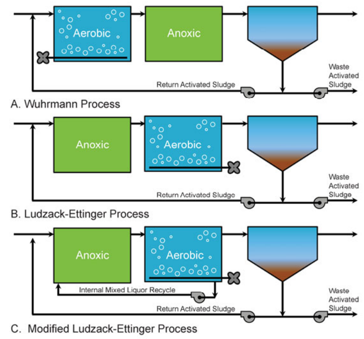
# 2-Stage BNR Process Evolution




1954

1962

1973

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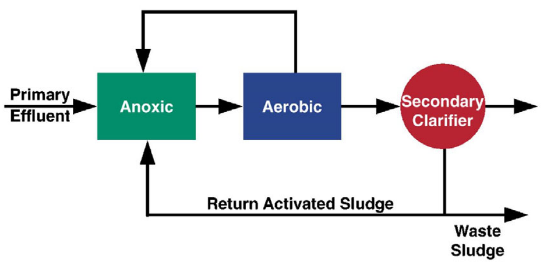
# Modified Ludzack-Ettinger - MLE

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# Milestone

- 1976 Specter patents A/O® and A²/O® processes

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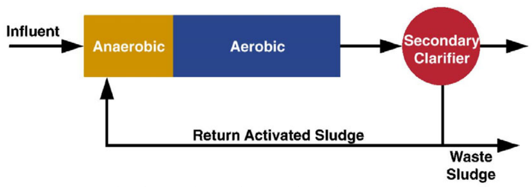
## AO




For biological uptake of phosphorus



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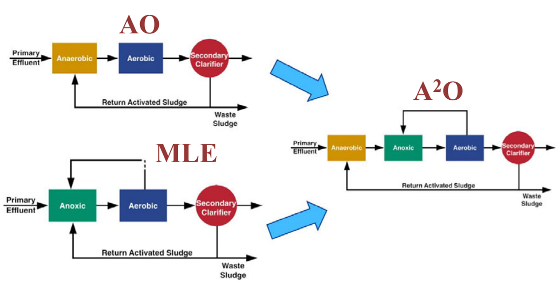
## AO plus MLE = $A^2O$



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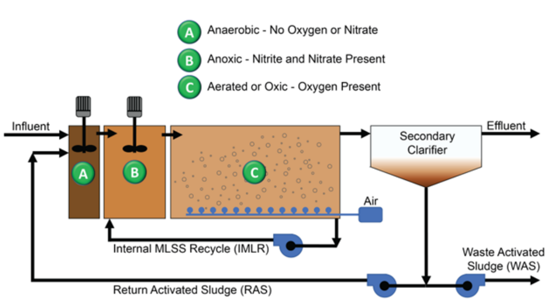
## 3-Stage BNR Process



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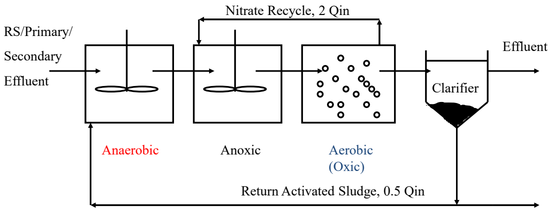
## 3-Stage BNR Process




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



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## Historical View of BNR

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



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## BNR

Process Details



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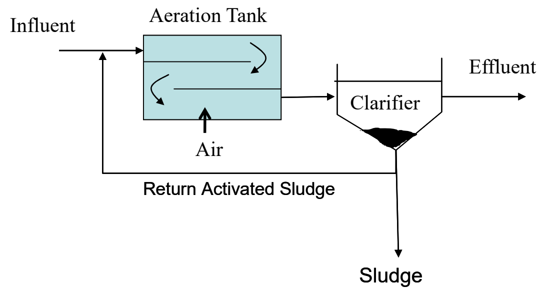
## Typical Activated Sludge Process

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## BNR Processes

- Anaerobic-aerobic (AO)
- Modified Ludzack-Ettinger (MLE)
  - Anoxic-aerobic
- Anaerobic-anoxic-oxic ($A^2O$ and UCT)
- Step feed
- Oxidation ditch

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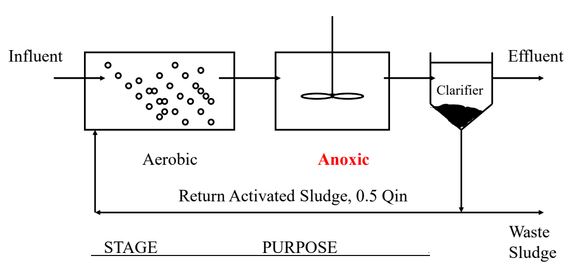
## Two Stage Wuhrmann BNR Process




| STAGE | PURPOSE |
| --- | --- |
| Aerobic (Oxic) | Nitrification |
| Anoxic | Denitrification and Nitrogen gas release |

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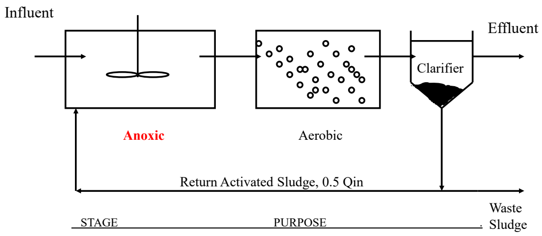
## Two Stage Ludzack-Ettinger BNR Process

Denitrification-Nitrification




| STAGE | PURPOSE |
|---|---|
| Anoxic | BOD Removal, Denitrification, and Nitrogen gas release zone |
| Aerobic (Oxic) | Nitrification zone |



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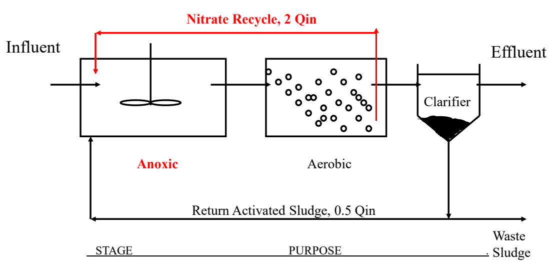
## Modified Ludzack-Ettinger BNR Process

Denitrification-Nitrification with Nitrate Recycle




| STAGE | PURPOSE |
|---|---|
| Anoxic | BOD Removal, Denitrification, and Nitrogen gas release |
| Aerobic (Oxic) | Nitrification zone |



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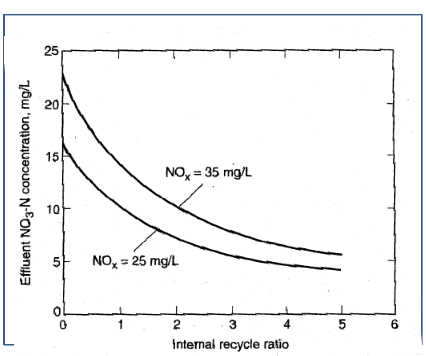
## Impact of Internal Recycle on Effluent TN



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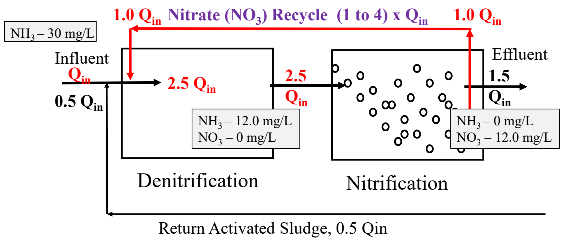
# TN Removal – Example 1




Assume all NO3 returned to Denitrification is converted to $N_2$

Assume all $NH_3$-N is converted to $NO_3$-N in Nitrification.

What is the NH3-N concentration in Denitrification? NH3-N = $\frac{30 \text{ mg/L}}{2.5/1}$ = 12.0 mg/l



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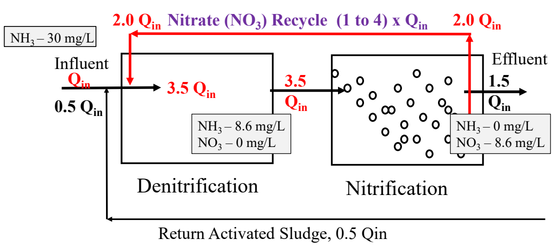
# TN Removal – Example 2




Assume all NO3 returned to Denitrification is converted to $N_2$

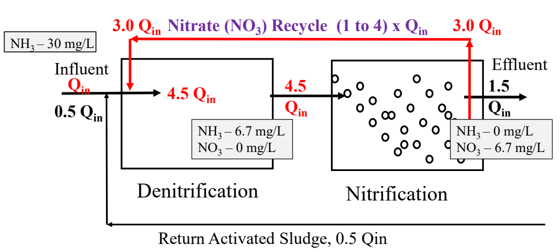
Assume all $NH_3$-N is converted to $NO_3$-N in Nitrification.

What is the NH3-N concentration in Denitrification? NH3-N = $\frac{30 \text{ mg/L}}{3.5/1}$ = 8.6 mg/l



197

# TN Removal – Example 3




Assume all NO3 returned to Denitrification is converted to $N_2$

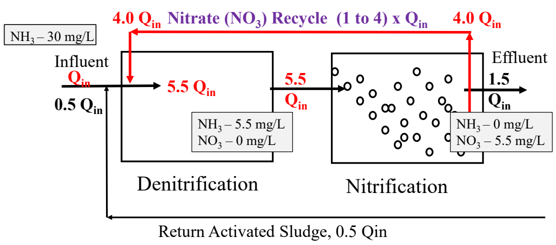
Assume all $NH_3$-N is converted to $NO_3$-N in Nitrification.

What is the NH3-N concentration in Denitrification? NH3-N = $\frac{30 \text{ mg/L}}{4.5/1}$ = 6.7 mg/l



198

## TN Removal – Example 4




Assume all NO3 returned to Denitrification is converted to $N_2$
Assume all $NH_3$-N is converted to $NO_3$-N in Nitrification.
What is the NH3-N concentration in Denitrification? NH3-N = $\frac{30 \text{ mg/L}}{5.5/1}$ = 5.5 mg/l

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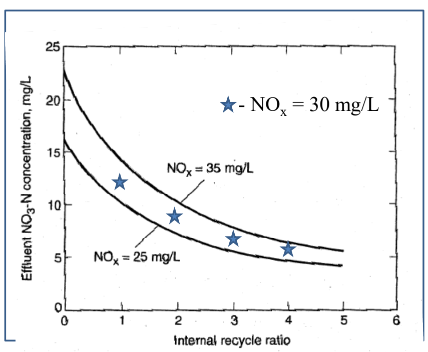
## Impact of Internal Recycle on Effluent TN




January 2024 BNR and ENR 200

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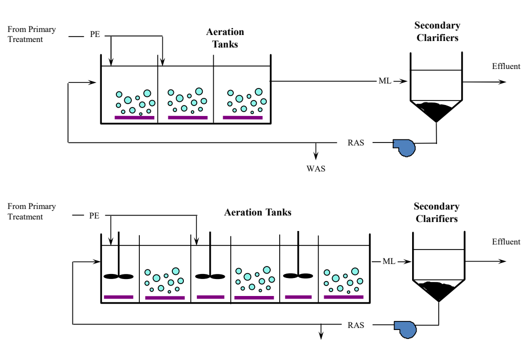
## Step Feed Process

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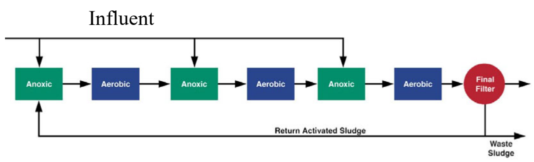
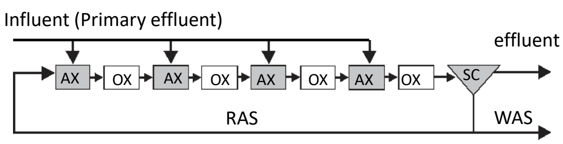
# Step Feed






202

# Step Feed

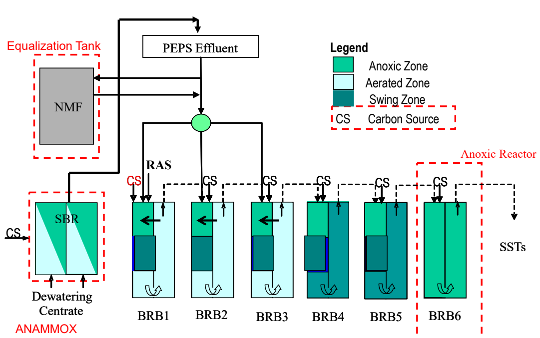



AX – Anoxic zone (denitrification)
OX – Oxic (aerobic) zone (nitrification)
SC – Secondary clarifier (solids separation)
RAS – Return activated sludge
WAS – Waste activated sludge



203

# AlexRenew Step Feed Facility



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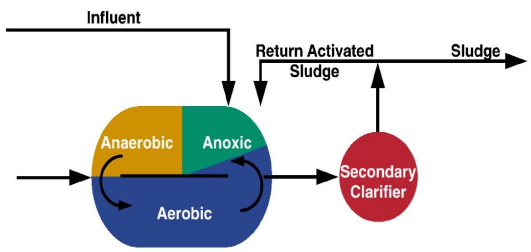
## Oxidation Ditch



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## BNR to ENR

Evolution



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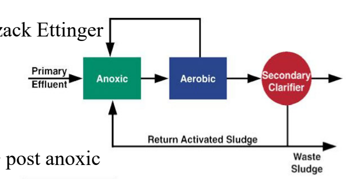
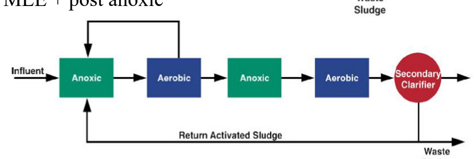
## Example of BNR to ENR

Modified Ludzack Ettinger




MLE + post anoxic



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# Milestones

- 1968 Barth proposes 3-sludge, activated sludge process for nutrient removal
- 1975 Barnard patents Bardenpho® process
- 1980 University of Cape Town (UCT) process developed



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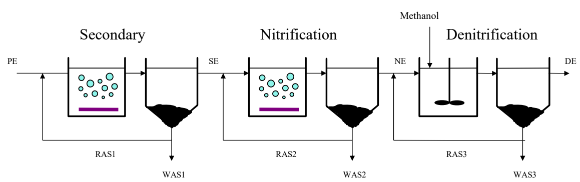
# Three Stage System for BOD and Nitrogen Removal

Post Denitrification w/Methanol




Example: Western Branch WWTP, WSSC 30 MGD



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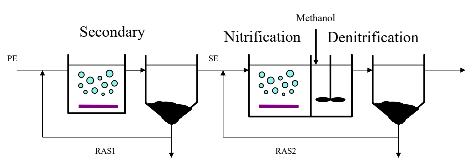
# Two Sludge System for BOD and Nitrogen Removal




Example: Blue Plains, DC Water 370 MGD

Separate denitrification facilities were construction ~ 2015



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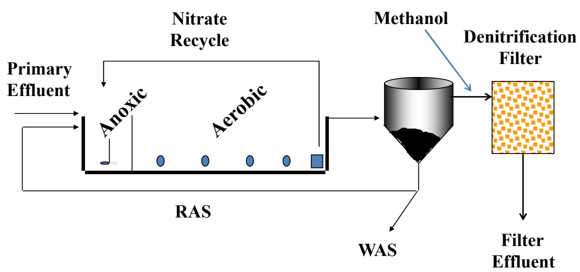
## MLE With Denitrification Filter

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## ENR

Overview

January 2024 BNR and ENR 212

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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

January 2024 BNR and ENR 213

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## ENR Program

- ENR Program began in 2000
- 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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## Enhanced Nutrient Removal

- Over the past two decades, BNR facilities have been upgraded to improve nitrogen removal efficiencies:
  - Post anoxic zones for denitrification
  - Mixed Bed Bio-reactors (MBBR)
  - Fixed film biological filters for nitrification
  - Tertiary denitrification filters

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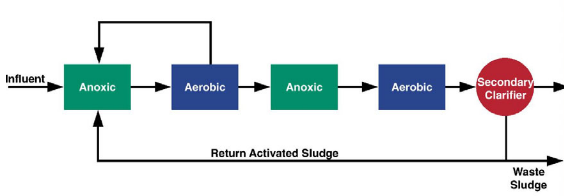
## Bardenpho
(Enhanced Modified Ludzack Ettinger)




January 2024 BNR and ENR 216

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## Enhanced Nutrient Removal

- For WWTPs to upgrade from BNR to ENR, and satisfy new LOT requirements for nitrogen removal, an additional post-denitrification stage is required; for example:
  - MLE + post anoxic
  - MLE + MBBR
  - MLE + Denit Filter
  - Step feed + post anoxic
  - Step feed + MBBR
  - Step feed + Denit Filter

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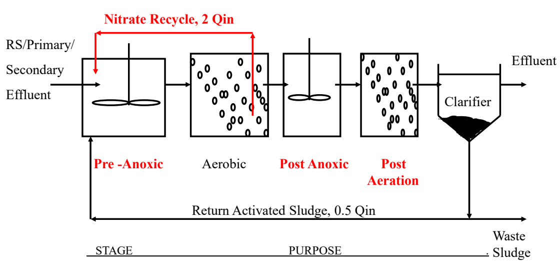
## Enhanced Nutrient Removal Process

With Pre- and Post Denitrification and Aeration




| STAGE | PURPOSE |
|---|---|
| Anoxic | Denitrification and Nitrogen gas release zone |
| Aerobic (Oxic) | Nitrification zone |

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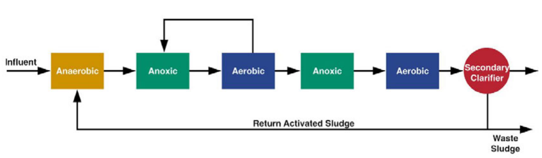
## Modified Bardenpho

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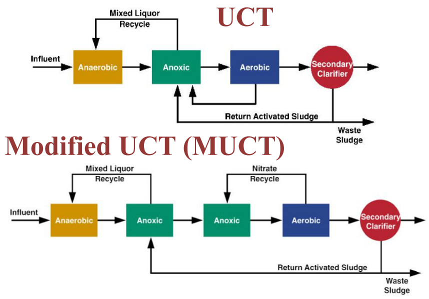
## UCT Processes



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## Denitrification

Note: (Almost) all nitrates entering anoxic zones should be denitrified

The effluent "goal" $NO_3$-N concentration from the last anoxic zone should be between 0 and 0.5 mg/L.



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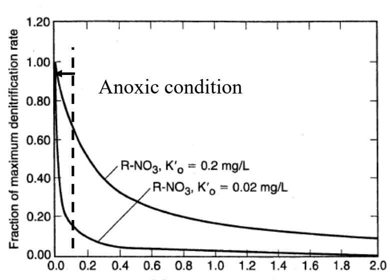
Reduction in rate of Denite as a function of D.O.
(K'o is oxygen inhibition constant)



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## Carbon for Denitrification

- Influent WW Carbon
  - Utilized in anoxic zones
  - Limited carbon available for secondary anoxic zones
- Supplemental Carbon
  - Methanol typically used
    - But requires methylotrophic population!
  - Alternatives to methanol – glycerin, sugars, and proprietary products

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## Carbon for Denitrification

- If using methanol – may not have adequate methylotrophic population
  - Need well controlled anoxic volume
  - Methylotrophs require acclimation time
  - Methylotrophs are believed to be more sensitive to temperature
- Methanol is typically more sensitive to pH and may not be effective in very cold weather
  - Change carbon source – ethanol or glycerin
- Denitrification batch tests
  - Specific denitrification rates (SDNRs) – different carbon sources

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## Other Carbon Sources

- Alcohols
  - Methanol
  - Ethanol
- Glycerol/glycerin – (Biodiesel by-products)
- Acetates - (Acetic acid, sodium acetate)
- Carbohydrates - (Sucrose, sugar water, corn syrup)
- MicroC™ – (Carbohydrate, glycerin, alcohol based blends)

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## Denitrification Problems

| Possible Causes | Solution |
|---|---|
| Not enough nitrates being returned to anoxic zone | Increase nitrate recycle pump speed |
| Not enough BOD entering anoxic zone | - Bypass primary clarifiers, or<br>- Add supplemental carbon (for example, methanol) to anoxic zone |
| BOD entering the anoxic zone breaks down too slowly | Add readily available carbon source such as methanol to anoxic zone or increase the anoxic zone hydraulic retention time |
| High DO in the anoxic zone | Try to limit backmixing of air from the aerobic zones or decreasing the DO in the AT influent. Decrease nitrate recycle rate if necessary. |



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## Fixed Film Processes

Nutrient Removal



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## Fixed Film Processes

- cBOD Removal
  - TF – Trickling Filters
  - RBC – Rotating Biological Contactor
- Nitrification
  - BAF – Biological Aerated Filter
  - IFAS – Integrated Fixed-Film Activated Sludge
  - MBBR – Moving Bed Biofilm Reactor
- Denitrification
  - Denit Filter
    - Down flow
    - Up flow



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## Fixed Film Processes

| cBOD Removal | Nitrification | Denitrification |
|---|---|---|
| – TF<br>– RBC<br>– BAF | – TF & RBCs<br>– BAF<br>– IFAS<br>– MBBR | – Denit Filters<br>– MBBR (w/o $O_2$)<br>– BAF (w/o $O_2$) |

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## Fixed Film Processes

**What can fixed film (a.k.a. attached growth) processes do?**

1. ***Remove Nutrients***
   - **Phosphorus**
   - **Nitrogen**
2. **Remove BOD:**
   - **Dissolved organic solids**
3. **Remove TSS:**
   - **Suspended particulate solids**
   - **Suspended organic solids**

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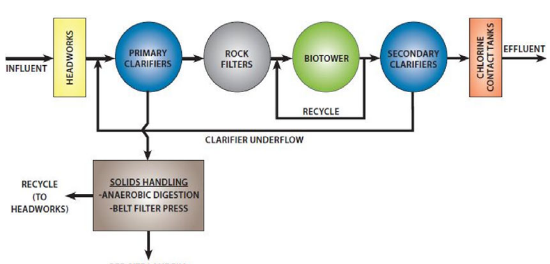
## Process Configuration

### Nitrification

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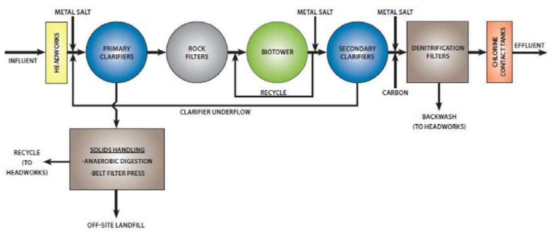
## Process Configuration
ENR with Denitrification Filters

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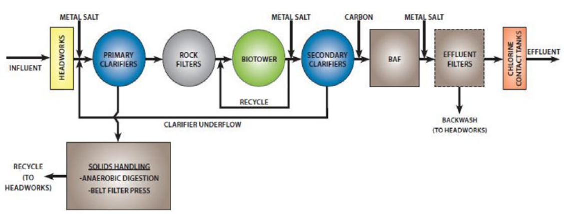
## Process Configuration
ENR with Denit-BAF and Effluent Filters

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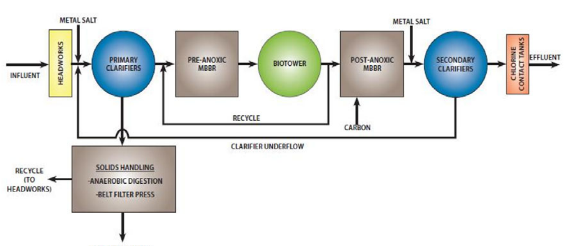
## Process Configuration
ENR with Pre- and Post-anoxic MBBR

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## Fixed Film Nitrification

IFAS and MBBR



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## Why Use An IFAS Process ?

- Increase capacity without more tanks
- Achieve nitrogen removal in tank, which could not otherwise totally nitrify and denitrify



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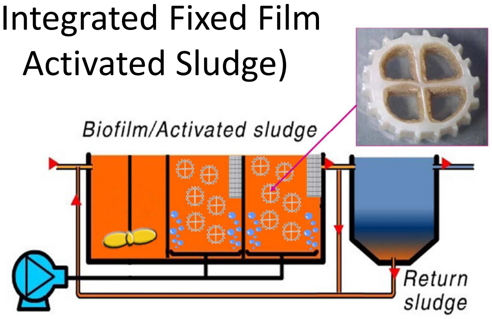
## IFAS (Integrated Fixed Film Activated Sludge)



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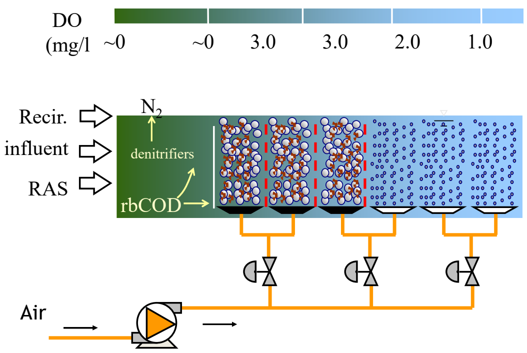
# IFAS LAYOUT

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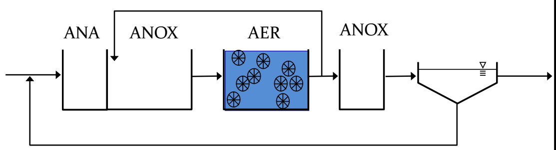
# IFAS in Nutrient Removal




Typically an upgrade to implement BNR or increase Nitrification capacity at existing plants.



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# Benefits of IFAS Processes

- Increase total solids inventory without increasing solids loading to clarifier
- Minimize effects of solids washout under high hydraulic loadings
- Avoid cost of construction of new tanks
- Decrease required recycle rates



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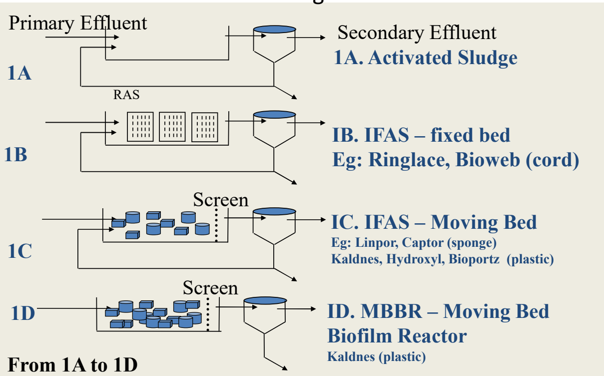
## Plant Configurations




**From 1A to 1D**

***Clarifier size requirements decrease; Operating MLSS HRT requirements decrease; Biofilm surface area increases***

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## Types of IFAS Systems

**Fixed**
- **Rope**
- **Plastic**

**Free**
- **Sponge**
- **Plastic**




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## Free Floating Media - Plastic

**Hydroxyl**




January 2024 BNR and ENR

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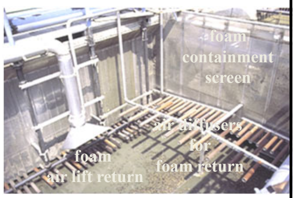
## Free Floating Media - Sponge




**Lotepro – Linpor Process**



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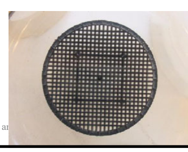
## Plastic Media (Kaldnes)

| | | K1 | K2 | K3 | Model O | Biofilm Chip |
|---|---|---|---|---|---|---|
| Length | (mm) | 7.2 | 15 | 9 | 50 | 2 |
| Diameter | (mm) | 9.1 | 15 | 25 | 60 | 47 |
| Specific Surface Area | (m2/m3) | 500 | 350 | 480 | 94.5 | 1,200 |



K3

Model O



Biofilm Chip



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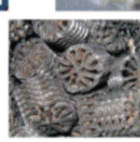
## Integrated Fixed Film Activated Sludge System

- Media held in Aeration Basins to provide attached growth for Nitrifying biomass
- Typical Floating and Fixed IFAS Media
  - Kaldnes (plastic)
  - Linpor (sponge)
  - Ringlace (cord)





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## Fixed Film Nitrification

Biological Aerated Filter - BAF

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## Submerged BAFs

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## Submerged BAFs

- Biofor® - Up flow filter (Infilco Degremont)
  - Aerated, fixed bed
  - Dense granular clay media
  - "Sinking" media; 3 mm diameter for nitrification
- Biostyr® - Up flow filter (Veolia Water/Kruger)
  - Aerated, packed bed
  - Media less dense than water held in place by a screen
  - "Floating" media; 3 mm diameter for nitrification

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## Submerged BAFs

- GFK%yjhmstqtl~%|fx%gfxji%ts%ymj%uwnshnuqj%tk%gntknqywfynts
- Y~unhfqq~%tujwfyji%fx%fs%zu2kqt|%rtij
- R jinf%hfs%gj%jnymjw%ijsxjw%ymfs%|fyjw%yt%ln{j%xzspjs%rjinf%tw%qjxx%ijsxj%ymfs%|fyjw%yt%uwtizhj%kqtfynsl%rjinf
- GFKx%htrgnsj%gntqtlnhfq%ywjfyrjsy%fsi%frrtsnf2snywtljs%fsi%xtqnix%wjrt{fq%ns%tsj%wjfhytw%zsny
- Fhhzrzqfyji%xtqnix%fwj%wjrt{ji%kwtr%ymj%GFKx%ymwtzlm%gfhp|fxmnsl

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## Submerged BAFs

| Type of BAF | Applied volumetric loading, kg/m$^3$·d (lb/d/1000 cu ft) | Hydraulic loading, m$^3$/m$^2$·h (gpm/sq ft) | Removal efficiency, % |
|---|---|---|---|
| Upflow sunken or floating media, backwashing[1,2] | BOD: 1.5 – 6 (94 – 370)<br>TSS: 0.8 – 3.5 (50 – 220) | 3 – 16 (1.2 – 6.6) | BOD: 65 – 90%<br>TSS: 65 – 90% |
| Upflow, sunken media [3] | 10 | | |
| Upflow, floating media [3] | 8 | | |
| Submerged, non-backwashing[4] | BOD: 0.8 – 1.5 (50 – 94) @ 20°C | 2 – 12 (0.8 – 5) @ 20°C | BOD: 85 – 95% |
| Patapsco ($NH_3$) | 44 | 3.4 | |

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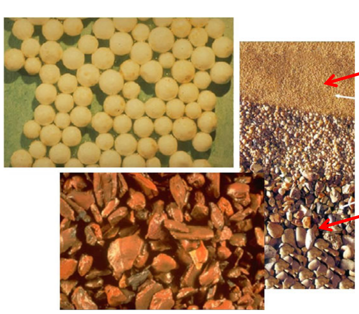
## BAF Media



Fine material
- Good filtration
- Large, specific surface area

Coarse material
- Less clogging

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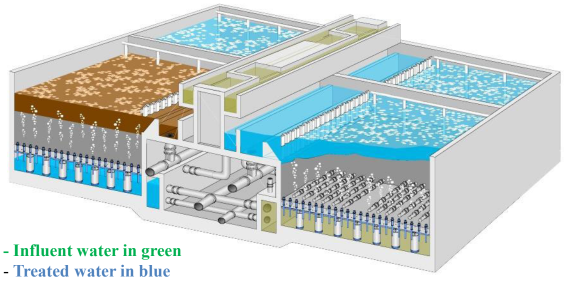
## BIOFOR® Process View with One Cell in Backwash



- Influent water in green
- Treated water in blue
- Process air and air scour bubbles in white



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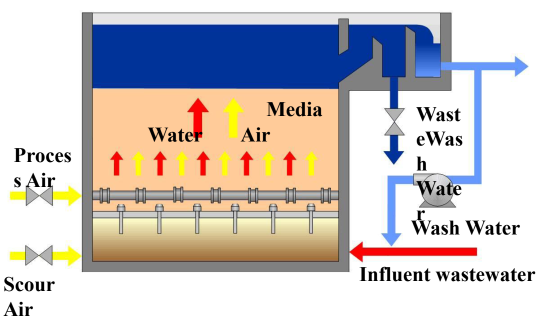
## BIOFOR® Sequences



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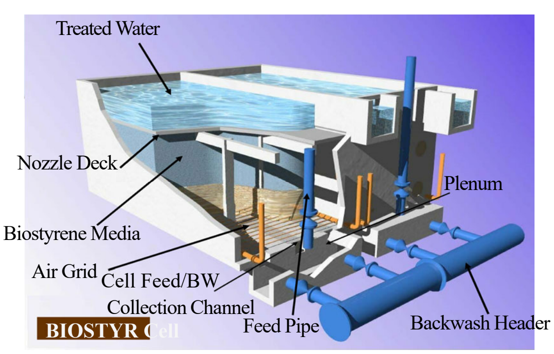
## BIOSTYR® Process



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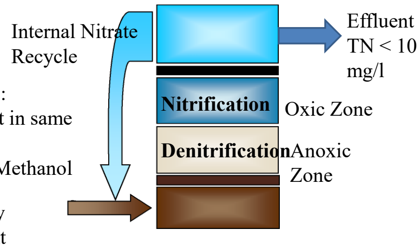
## BIOSTYR® Process




Advantages:
1. Nit/Denit in same cell
2. Reduce Methanol feed



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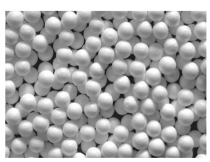
## BIOSTYR® Media

- Bead diameter: 3.3 - 5.0 mm
- Clean bed porosity: 0.35 - 0.40 (void space as a fraction of total media bed volume)
- Bead density: 2.5 -3.1 lb/ft3
- Good uniformity coefficient (<1.25)
- Compatible with development of biological film





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## Denitrification

Denit Filters



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# Denit Filters

- Down Flow Denit Filters
  - Tetra Denite® System (Severn Trent)
  - Elimi-Nite® System (Leopold)
  - Davco Denitrification® System (Siemens)
- Up Flow Denit Filters
  - DynaSand® Filter (Parkson)
  - Astrasand® Filter (Paques/Siemens)
- Up Flow Fluidized Bed (Envirex)

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The TETRA® Denite® system from Severn Trent Services removes nitrate-nitrogen and suspended solids in a single step. It is used as a tertiary process on effluents from wastewater treatment plants. TETRA was recently awarded a contract to supply their TETRA® Denite® system for use at the Baltimore City Patapsco WWTP.

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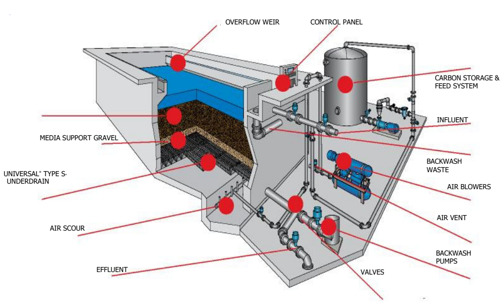
# Leopold® elimi-NITE® Denitrification System

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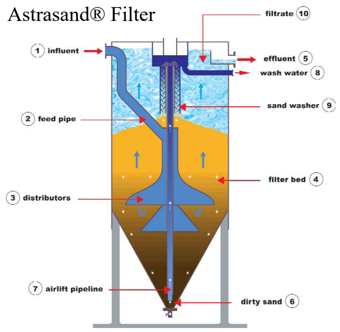
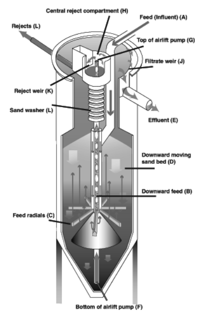
# Up Flow Denit Filters

Astrasand® Filter




DynaSand® Filter



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**Comparison of Denitrification Filter Manufacturers and Equipment ***

| Manufacturer/ filter | Severn Trent Services/ TETRA® Denite® | F. B. Leopold/ elimi-NITE | USFilter/Davco | Parkson/ DynaSand | Paques and Siemens/ Astrasand |
|---|---|---|---|---|---|
| **Flow regime** | Downflow | Downflow | Downflow | Upflow | Upflow |
| **Under drain** | T-block; concrete-filled, HDPE jacket | Universal Type S HDPE block | Pipe lateral; or Multiblock HDPE block | None required | None required |
| **Air header arrangement** | SS box header; laterals beneath underdrain | SS header across filter; laterals | SS air header; 2-inch laterals | Vertical air lift | Vertical air lift |
| **Media** | 18 inches graded gravel 6 ft of 6 × 9 mesh silica sand: uniformity coefficient - 1.35, 0.8 minimum Sphericity | 15 inches graded gravel 6 ft of 6 × 12 mesh sand | 2 layers support gravel, 6 ft of 6 × 9 mesh sand | 1.35 to 1.45 mm subround media or 1.55 to 1.65 mm subangular media with uniformity coefficient of 1.3 to 1.6; 6.6-ft bed depth | 1.2 to 1.4 mm sand, 6.6-ft bed depth |
| **Nitrogen-release cycle** | Initiated by headloss or time-controlled cycle; Speed Bump controls | Initiated by headloss or time-controlled cycle | Initiated by headloss or time-controlled cycle | None required | None required |
| **Backwash water and air requirement** | 6 gal/min·ft$^2$); 5 scfm/ft$^2$ | 6 gal/min·ft$^2$ 5 scfm/ft$^2$) | 10 gal/min·ft$^2$); 5 scfm/ft$^2$) | Continuous through air lift and sand washer | Continuous through air lift and sand washer |

* Source – Severn Trent



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**Summary of Design Guidance for Denitrification Filters ***

| Source | Hydraulic loading rate (gal/min·ft$^2$) | Mass loading rate (lb NO3-N per ft$^3$/d) |
|---|---|---|
| *Manual: Nitrogen Control* (U.S. Environmental Protection Agency, 1993) | 1 to 2, 30 minutes empty bed contact time | 0.018 to 0.1 |
| *Biological and Chemical Systems for Nutrient Removal, Special Publication* (Water Environment Federation, 1998) | | **0.015 to 0.2 depending on temperature** |
| *Wastewater Engineering, Treatment and Reuse* (Metcalf & Eddy, 2003) | **1 to 2 at 20°C** | **0.087 to 0.112 at 20°C** |
| | 0.5 to 1.5 at 10°C | 0.05 to 0.075 at 10°C |
| Severn Trent Services TETRA®Denite® | <3 at average flow; <7.5 peak hydraulic with one cell out of service | Determine using process model |
| F.B. Leopold | 1 to 2 | 0.07 |
| USFilter/Davco | 2 | NA |
| Parkson | 4.5 | 0.015 to 0.12 |
| Paques/Siemens | 4.1 | 0.13 |

* Source – Severn Trent



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## Solids Handling Side Streams

Nutrient Removal Systems

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## What are Sidestreams

- Any process flow resulting from the treatment of biosolids 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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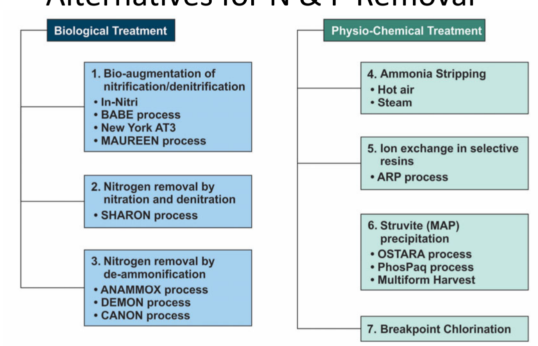
## Common Side-stream Treatment Alternatives for N & P Removal

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## Why consider side-stream treatment?

- Concentrated nutrient load
- Usually economical when sidestreams 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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## Nitrogen Removal

- Bioaugmentation
  - In-Nitri
  - BABE
  - NYC AT-3
  - MAUREEN
- Nitritation/Denitritation
  - SHARON
  - STRASS
- Nitritation/Deammonification
  - ANAMMOX
  - DEMON
  - CLEAR Green
  - ANITA Mox



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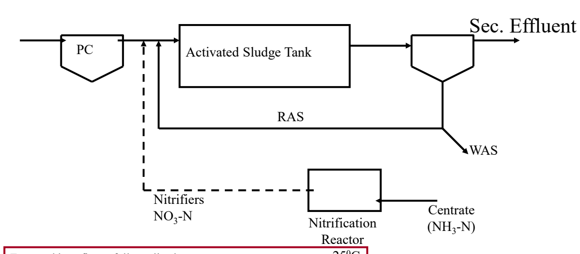
## InNitri Process was the first bioaugmentation scheme




Expected benefit not fully realized
- Temperature change
- Poor capture of recycle stream nitrifiers
- Predation
- Change in total dissolved solids content –osmotic pressure



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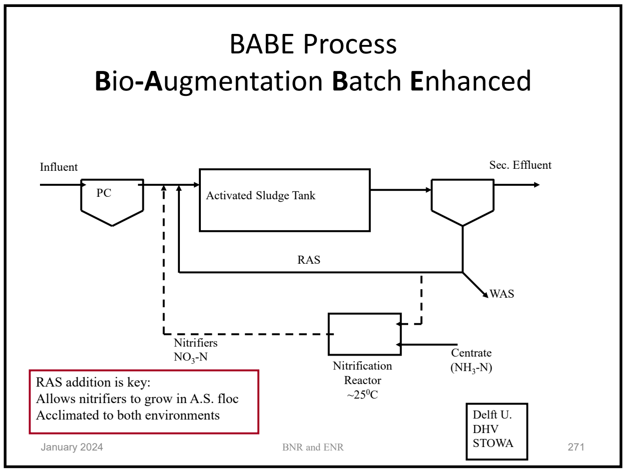
BABE Process
Bio-Augmentation Batch Enhanced
Influent
PC
Activated Sludge Tank
Sec. Effluent
RAS
WAS
Nitrifiers
NO3-N
Nitrification
Reactor
~25°C
Centrate
(NH3-N)
RAS addition is key:
Allows nitrifiers to grow in A.S. floc
Acclimated to both environments
Delft U.
DHV
STOWA
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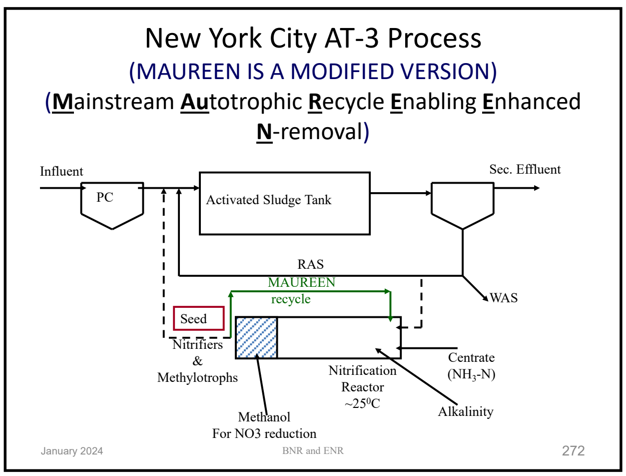
New York City AT-3 Process
(MAUREEN IS A MODIFIED VERSION)
(Mainstream Autotrophic Recycle Enabling Enhanced N-removal)
Influent
PC
Activated Sludge Tank
Sec. Effluent
RAS
WAS
MAUREEN
recycle
Seed
Nitrifiers
&
Methylotrophs
Nitrification
Reactor
~25°C
Centrate
(NH3-N)
Alkalinity
Methanol
For NO3 reduction
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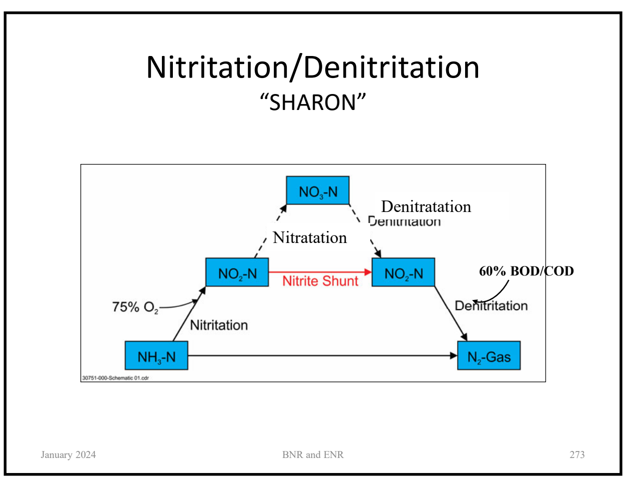
Nitritation/Denitritation
"SHARON"
NO3-N
Denitratation
Nitratation
NO2-N
Nitrite Shunt
NO2-N
60% BOD/COD
75% O2
Denitritation
Nitritation
NH3-N
N2-Gas
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BNR and ENR
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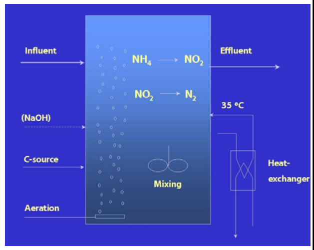
## SHARON

- *SHARON™ Process* (Single reactor system for high ammonium removal over nitrite)
  - provides separate biological centrate nitrification and denitrification
- 85% to 90% Total Nitrogen Removal
- Denitrifies from nitrite, nitrate prevented from forming
- Provides a 25% reduction in O2 and a 40% reduction in Carbon requirements



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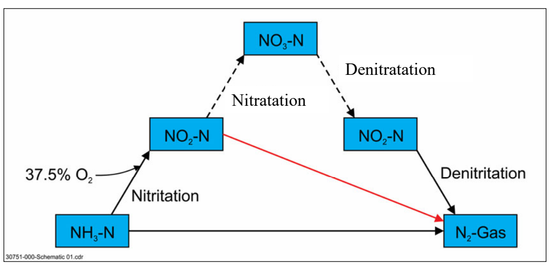
## Nitritation/Deammonification
"ANAMMOX"



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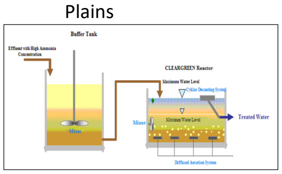
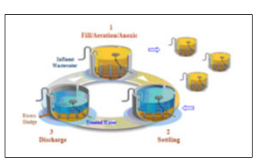
## SBR-type Anammox Process: Cyclic Low Energy Ammonia Removal (CLEAR)GREEN™

- Three 8-hour Cycles per day
- Pilot finished in Paris, France
- Currently being piloted at Hampton Roads and Blue Plains





*Images Courtesy of IDI*



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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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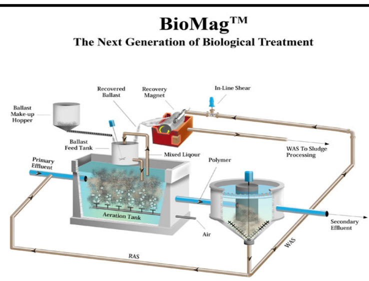


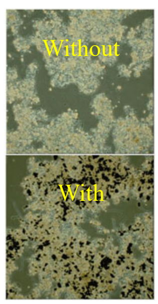


Cambridge Water Technology's BioMag Process® uses Magnetite ($Fe_3O_4$) as a flocculation aid to improve settling characteristics of activated sludge. With a specific gravity of 5.2 and a strong affinity for biological solids, magnetite can significantly decrease SVI's and increase MLSS settling rates to handle higher flows. Enhanced nutrient removals, especially phosphorus, are possible.



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## Side Stream 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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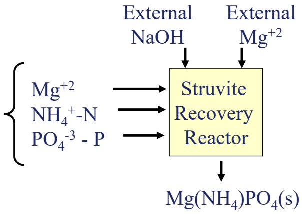
# How Struvite Precipitation Works

- 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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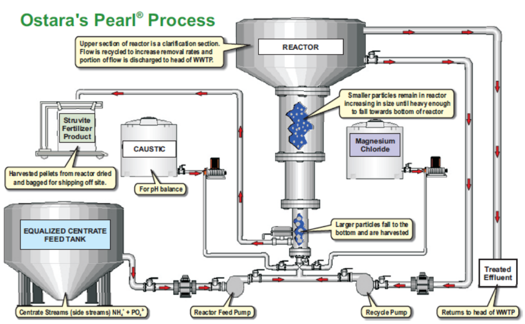
# Schematic of Ostara Process

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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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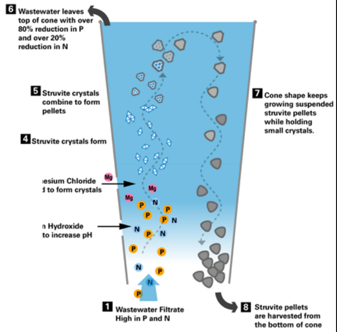
## Multiform Harvest

- 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)




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## Summary

Helpful Hints - Final Comments



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## Helpful Hints

- Consider multiple “barriers” for TP and TN removal, e.g. post anoxic zone
- Nitrification is “Key” to the success of BNR/ENR processes when removing TN
- Nitrify completely – $NH_3$ < 0.1 mg/L; no $NO_2^-$
- Maintain < 0.2 mg/L D.O. in denitrification process to maximize denitrificatiion rate
- Allow for excess chemical addition (5 – 7 mole ratio) to meet TP levels < 0.18 mg/?

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## Final Comments

- Many possible causes for poor nutrient removal performance
- Important to determine cause and act quickly to maintain chemical and biological processes
- Basic troubleshooting approaches are universal.
- Sidestream treatment can significantly reduce TP and TN loadings to mainstream process.

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Questions?

Jan 2019 Aeration of BNR/ENR Processes 288

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Post Test:

https://form.jotform.com/202865093580156

# Thank You

Ed Jones
Maryland Center for Environmental Training
College of Southern Maryland
La Plata, MD

"Anyone who can solve the problems of water will be worthy of two Nobel prizes – one for peace and one for science."

- John F. Kennedy

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