Transformation of Nitrogen at Different Stages of Onsite Wastewater Treatment

Rob Potts

Lowe Environmental Impact

What is Nitrogen?

- Nitrogen symbol N, is the chemical element of atomic number seven
- At room temperature, it is a gas and is colourless and odourless.
- It is the fifth most abundant element in the universe.

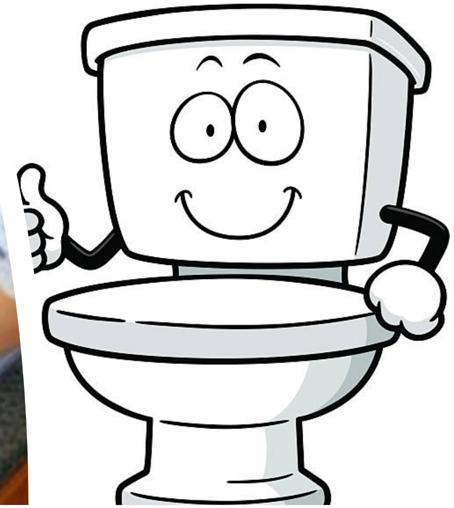
Source of Nitrogen

- Primary source is atmosphere
- Living things - protein
- Rocks, fertiliser, crop residue, organic manure and nitrate salts

Source of Nitrogen in Wastewater

- Kitchen: soap, food particles
- Laundry: detergents, faecal matter
- Bathing: soap, shampoo, oils

commonly known as **Greywater**



- Human waste; urine and faeces commonly known as **Blackwater**

Nitrogen Concentration in Onsite Wastewater

Total Kjeldahl Nitrogen (TKN): 39–82 mg/L (1)

Or 30 – 85 mg/L (2) (Organic N + NH_{3}/NH_{4})

- Ammonium-N (NH_4-N): 4–13 mg/L

- Nitrate-N and nitrite-N (NO_3-N; NO_2-N): <1 mg/L

(1) U.S.EPA (2002) Onsite Wastewater Treatment Systems Manual. EPA/625/R-00/008. Table 4-10.
(2) AS/NZS1547 (2012) Onsite Domestic Wastewater Management

Other Wastewater Characteristics

- pH: 6–9
- Total suspended solids: 155 – 330 mg/L
- Biochemical oxygen demand (BOD_5): 155 – 286 mg/L
- Chemical oxygen demand (COD): 500 – 660 mg/L
- Faecal coliform bacteria: 10^6 – 10^8 CFU/100 mL
- Total P (TP): 6–12 mg/L

Note: On-site wastewater is usually more concentrated than municipal

(1) U.S.EPA (2002) Onsite Wastewater Treatment Systems Manual. EPA/625/R-00/008. Table 3-7.
(2) U.S.EPA (2002) Onsite Wastewater Treatment Systems Manual. EPA/625/R-00/008. Table 4-10.

Key parameters in Nitrogen Removal

- Dissolved oxygen (DO)
- pH
- Temperature
- Alkalinity
- BOD
- COD
- Carbon
- Inhibitors – drugs, disinfectants, etc
- Cover Each of These as All Important to Reduce N

Role of Dissolved Oxygen

- Under anaerobic conditions, organic nitrogen (e.g., in proteins) is decomposed by microorganisms, first into smaller molecules (e.g., amino acids) and then into NH_3 and NH_4:

$$Organic\ N \rightarrow R - NH_2 + CO_2$$
$$R - NH_2 + H_2O \rightarrow NH_3 + NR - OH \rightarrow NH_4^+ + OH^-$$

- Nitrifying bacteria (e.g., Nitrosomonas, Nitrobacter) use DO (aerobic conditions) to convert NH_3 and NH_4 from food to energy:

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O$$
$$2NO_2^- + O_2 \rightarrow 2NO_3^-$$

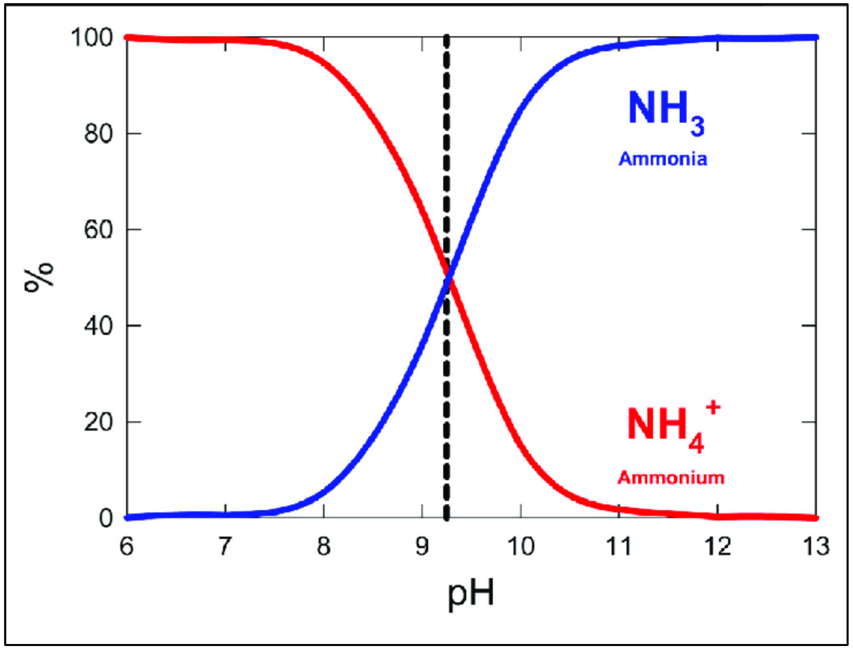
-or-

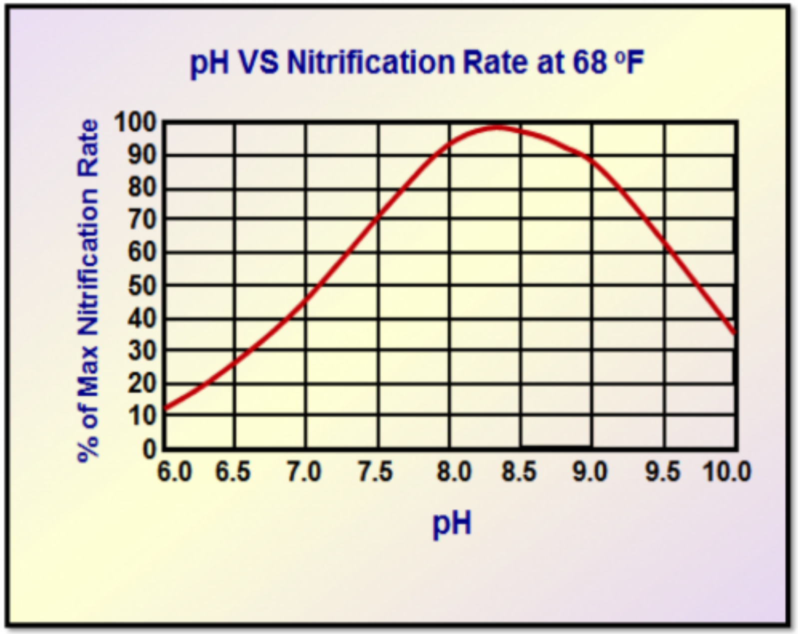
$$NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^-$$
$$2NO_2^- + O_2 \rightarrow NO_3^- + 2H^+ + 2e^-$$

- Denitrification occurs when bacteria scavenge oxygen from NO_3^-, so DO must be depleted (anaerobic/anoxic conditions) for denitrification to occur.

Role of pH

- Controls species of the compounds (NH_3/NH_4^+)
- Limits rate of bacterial growth/nitrification



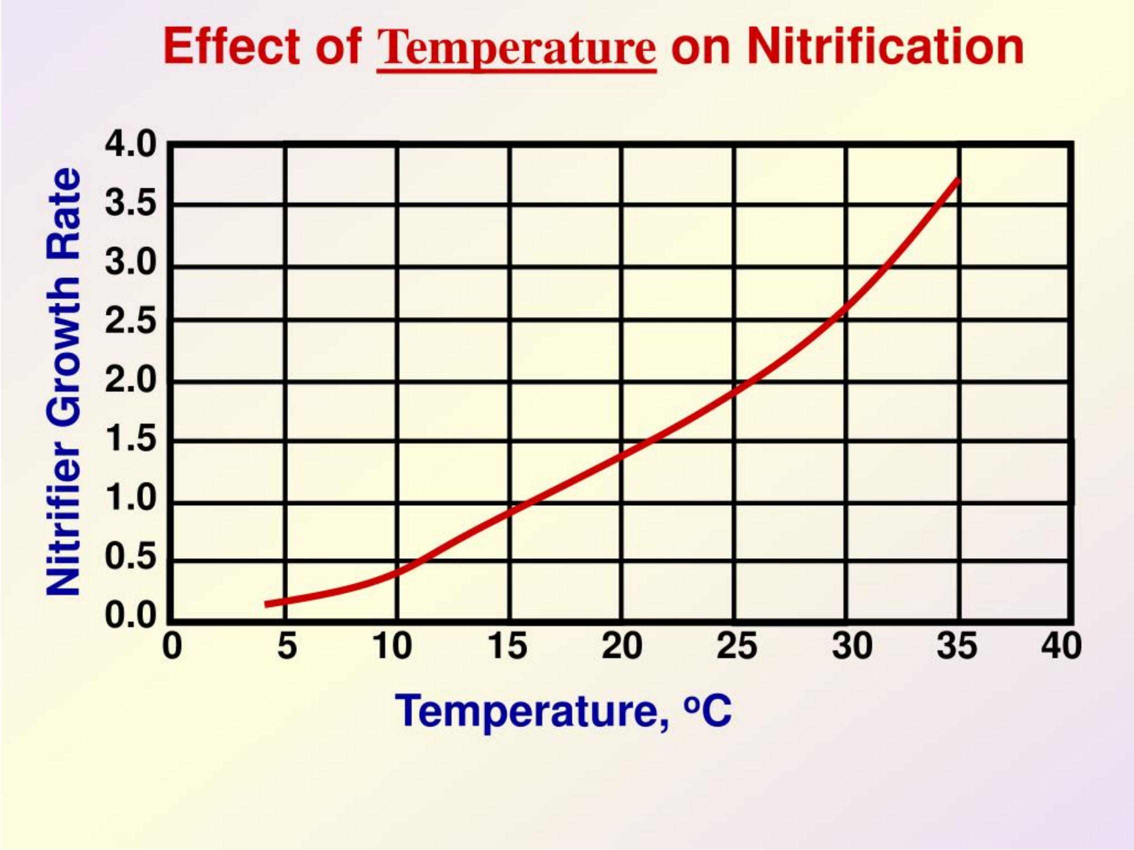


Langenfeld, N., et al (2021) Optimizing Nitrogen Fixation and Recycling for Food Production in Regenerative Life Support Systems. Frontiers in Astronomy and Space Sciences. 8. 10.3389/fspas.2021.699688.

Michigan DoEQ presentation (uploaded 15/10/2014) Nitrification and Denitrification.

Role of Temperature

- Controls the growth rate of nitrifying bacteria.
- Optimum growth at ~38°C
- Potentially low activity in winter



Michigan DoEQ presentation (uploaded 15/10/2014) Nitrification and Denitrification.

Role of Alkalinity

- Buffering capacity of the wastewater (measured in terms of equivalent $CaCO_3$)

$$Acid\ + CaCO_3 \rightarrow H_2O\ + CO_2\ + salt$$

- Indicator of biological activity
- Nitrification processes are acid producing; the oxidation of 1 mg of NH_4 consumes 7.14 mg of alkalinity as $CaCO_3$
- Lack of alkalinity will stop nitrification process
- Denitrification processes are base producing; the reduction of 1 mg of NO_3^- produces 3.57 mg of alkalinity.

Canterbury Alkalinity

Range of values in municipal Water:

District	Low (mg $CaCO_3$/L)	High (mg $CaCO_3$/L)
Kaikoura	75	100
Hurunui	7.2	169
Waimakariri	39	110
CCC		
Selwyn	26	61
Ashburton	12	66
Timaru		
Mackenzie		
Waitaki	(not analysed)	
Waimate	50	122

Typical primary treatment effluent:

NH_4^+: 20 – 60 mg/L[1]

And remember…

$[NH_4] \times 7.14[Alk] \rightarrow NO_3^-$

Typical requirement:

143–428 mg $CaCO_3$/L*

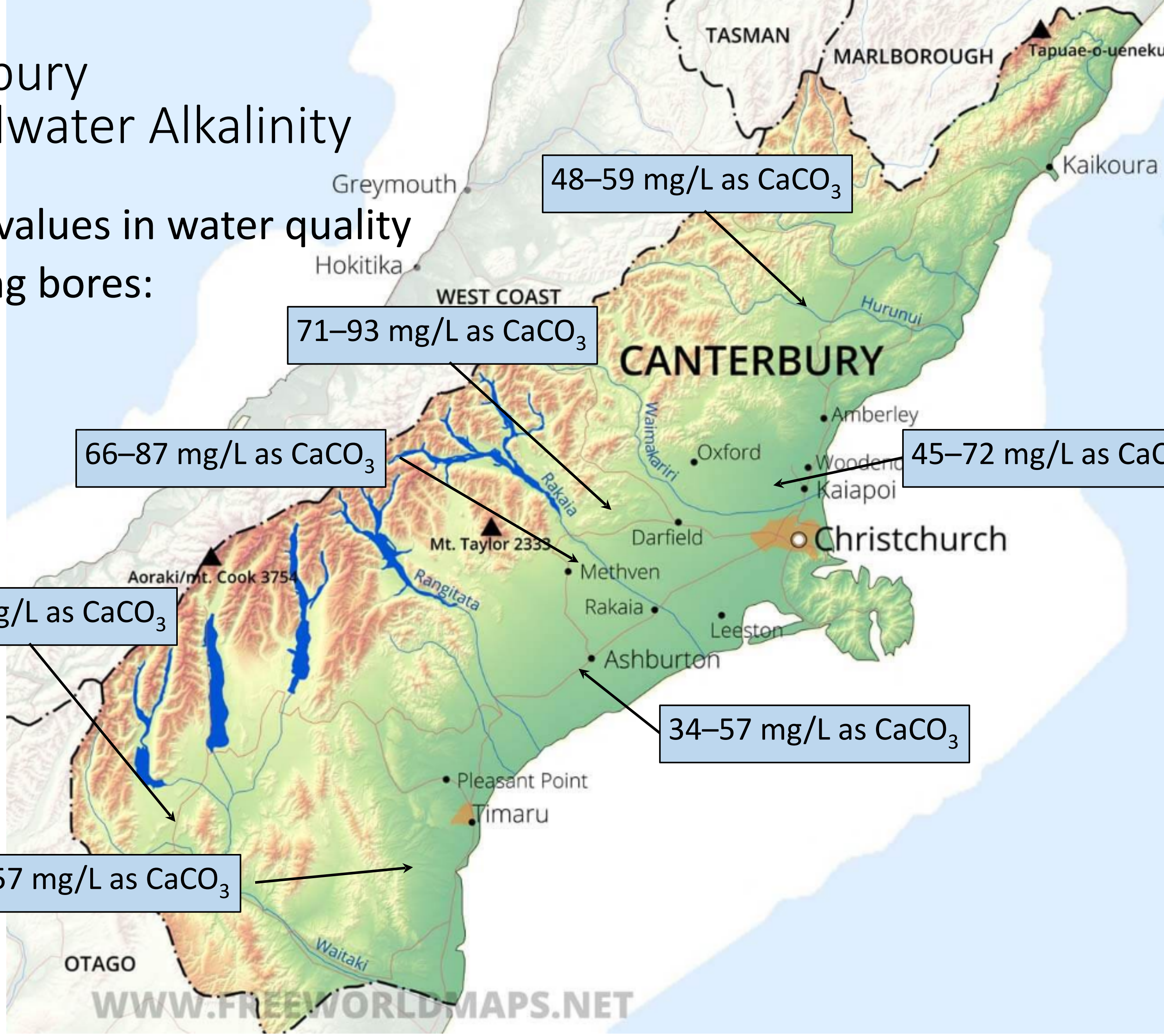
Minimum Req^d> 200 mg/L

*Note that recycled effluent will contribute alkalinity when it denitrifies

(1) Metcalf & Eddy (1991) Wastewater Engineering: Treatment, Disposal, and Reuse. McGraw Hill, Inc. Table 14-7.

Canterbury Groundwater Alkalinity

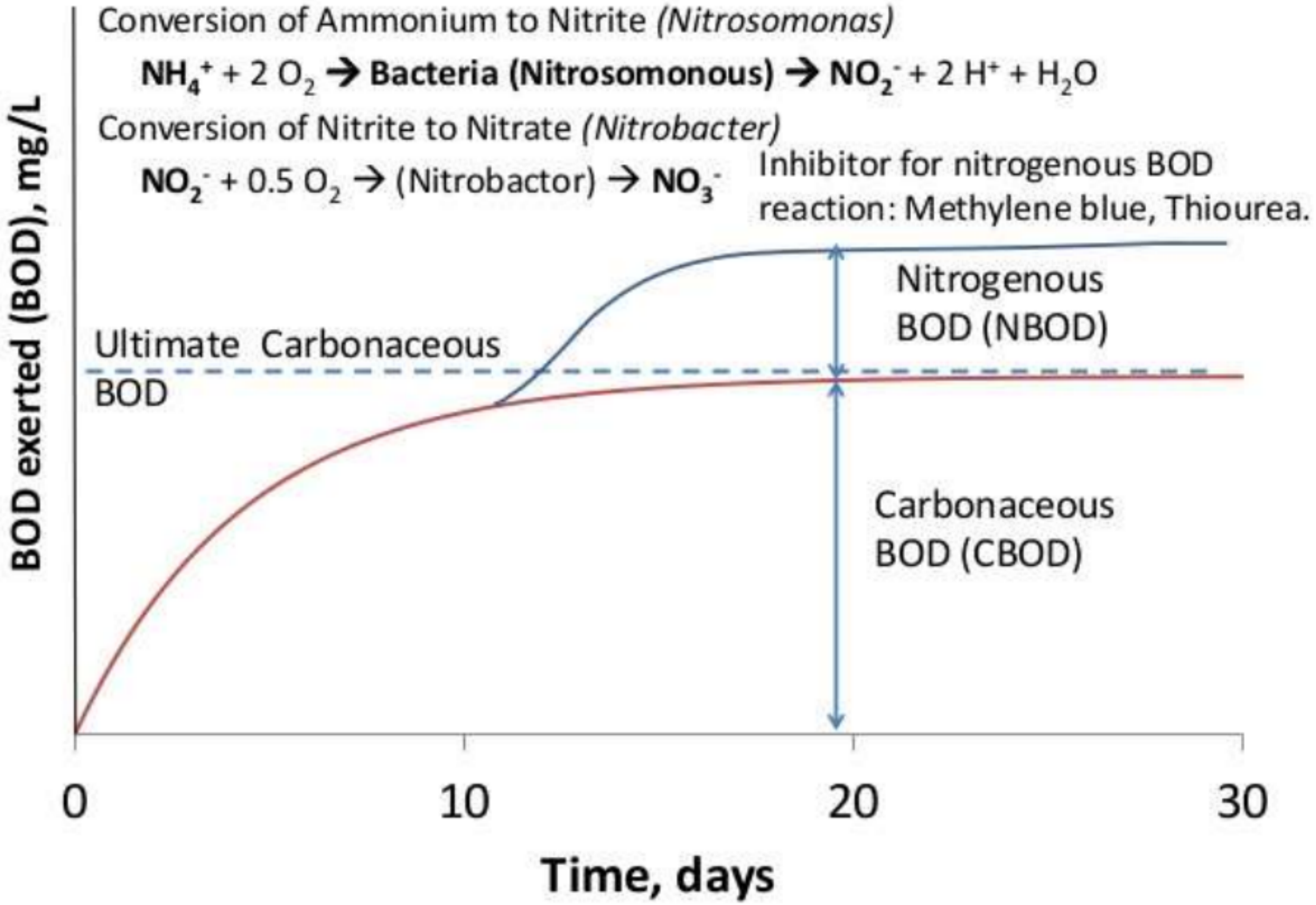
Range of values in water quality monitoring bores:



Role of BOD

- The amount of dissolved oxygen that will be consumed during decomposition
- High BOD will have a depleting effect on receiving waters and on soil DO
- Measures of BOD:
  - BOD_5: measure of the change in DO in a sample across a 5-day period at standard Temp
  - fBOD (filtered, soluble or dissolved BOD): Sample is filtered to remove algae
  - cBOD: measure of the oxidation of carbonaceous sources with nitrifying bacteria inhibited

BOD Cont.....



Conversion of Ammonium to Nitrite (Nitrosomonas)
$NH_4^+ + 2\,O_2 \rightarrow$ Bacteria (Nitrosomonous) $\rightarrow NO_2^- + 2\,H^+ + H_2O$
Conversion of Nitrite to Nitrate (Nitrobacter)
$NO_2^- + 0.5\,O_2 \rightarrow$ (Nitrobactor) $\rightarrow NO_3^-$
Inhibitor for nitrogenous BOD reaction: Methylene blue, Thiourea.
Nitrogenous BOD (NBOD)
Ultimate Carbonaceous BOD
Carbonaceous BOD (CBOD)
BOD exerted (BOD), mg/L
0
10
20
30
Time, days

Role of Carbon

- Denitrifying bacteria require carbon as an electron donor in the reaction:

$$6NO_3^- + 5CH3OH \rightarrow 5CO2 + 3N_2 + 7H_2O + 6OH^-$$

- Biological denitrification requires approximately 1.5 g C for every g of NO_3^-
- C:N of 5, TN reduction 70 – 80%
- C:N of 2 TN reduction 15 – 25%
- The source of carbon can be internal to the natural system e.g., organic matter in the wastewater (need a recycle component), or external e.g., methanol (as above).

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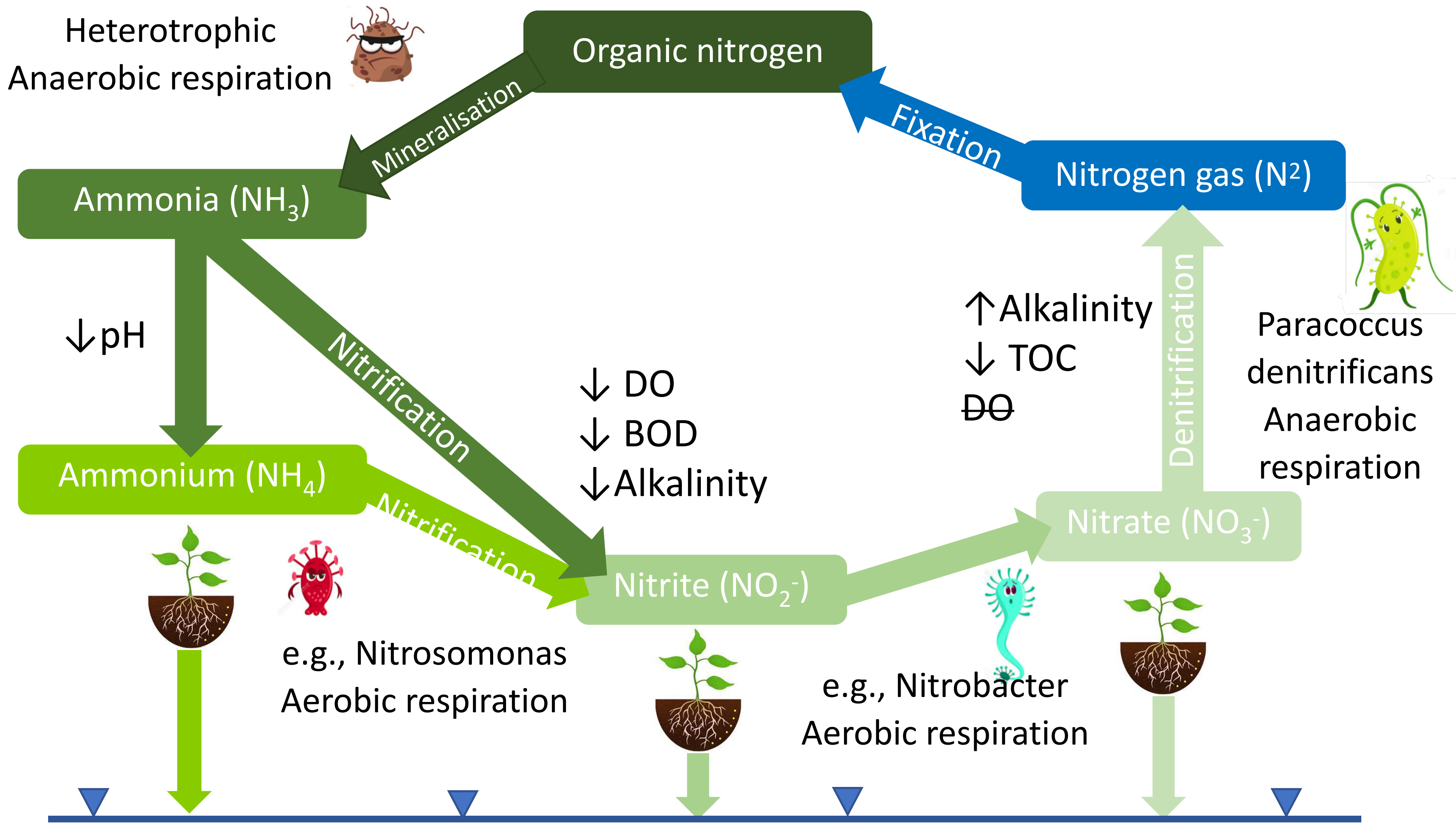
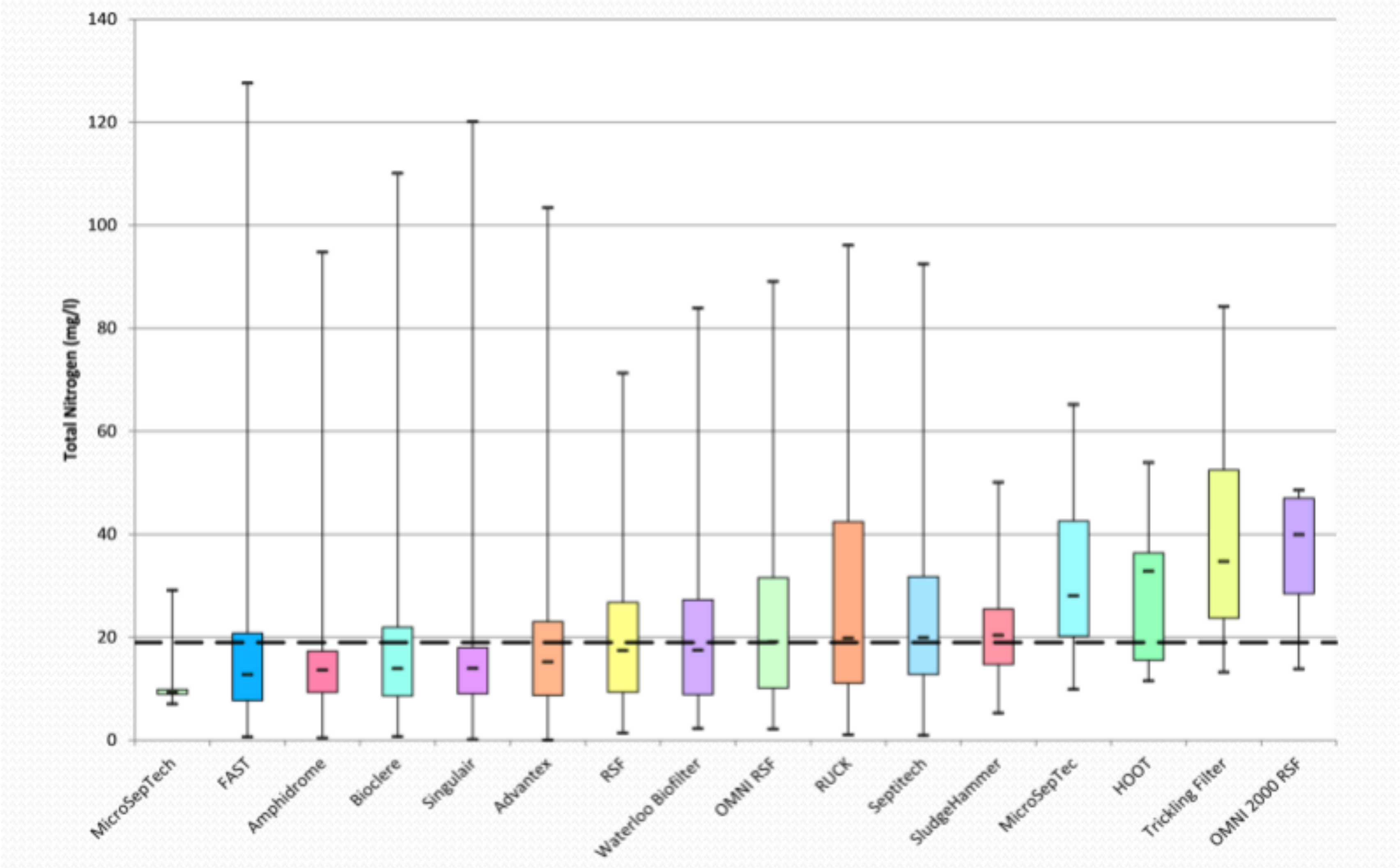
The Nitrogen Cycle



Putting it All Together in OWTS

- Need all those factors working in your favour for your Onsite Wastewater Treatment System (OWTS) to reduce TN – note OWTS cf OWMS
- Variability at Water NZ National Testing Facility with reasonably consistent influent and loading
- Further variability in the field due to people numbers, home or work, diet, hygiene, cleaning products, medication, high/low water use, use of hot or cold water, water source (alkalinity), ambient T
- Next slide shows variability from Barnstable, which is similar to OSET for various suspended growth, fixed film, passive intermittent and recirculation systems

Barnstable County DoH



On-site Wastewater Management Systems (OWMS)

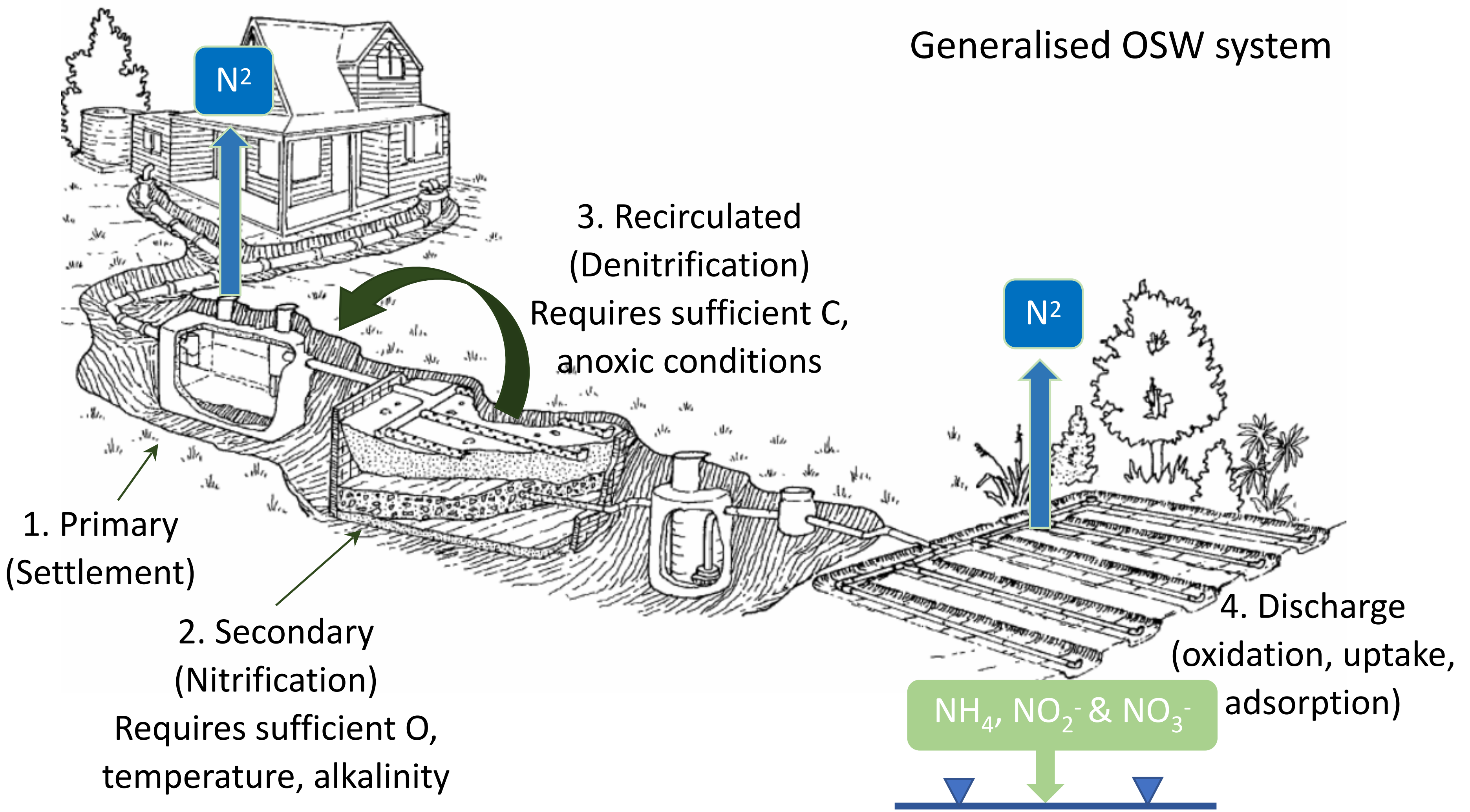


Figure modified from Auckland Regional Council Technical Publication No. 58.

OSW Treatment Options

- Primary (removes solids from effluent)
  - Septic tank/STEP/STEG
- Secondary (generally nitrify effluent, some denitrify)
  - Activated sludge
  - Submerged aerobic fixed film reactor (SAF/SAFF/FAST/IFAS)
  - Passive treatment, e.g. Packed bed reactor, Intermittent sand filter, recirculating sand filter, peat filters
  - Vermiculture
  - Passive Vaulted Trenches/Beds
  - Others
- Tertiary (add-ons) – usually for pathogen removal but also for use in safeguarding drip systems/N reduction
  - Wood chip bioreactors
  - Filtration - Sand filters, disc filtration
  - Land treatment
- Secondary plants need sludge wasting – N can be released from sludge

PRIMARY- Septic Tank

L W E Environmental Impact

- Stand alone option – simple, very little to go wrong
- Sedimentation/Floatation – sludge and scum (FOG)
- Anaerobic digestion of BOD and mineralisation of organic N to NH_3 & NH_4
- Can add effluent filter for < BOD, TSS
- General design principal is maintenance at 1/3 scum, 1/3 sludge, 1/3 daily flow.
- Sludge accumulation 80 L/p/yr – 2 people with 5.4 m^3 tank is 11 yrs for pump out
- Generally first part of Secondary Package OWTS

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Septic Tank Effluent

Component	Concentration Range
Total Suspended Solids, TSS	36 - 85 mg/L
5-Day Biochemical Oxygen Demand, BOD5	118 - 189 mg/L
pH	6.4 – 7.8
Feacal Coliform Bacteria	106 – 107 CFU/100mL
Ammonium-Nitrogen, NH4-N	30 – 50 mg/L
Nitrate-Nitrogen, NO_3-N	0 – 10 mg/L
Total Nitrogen	29.5 – 63.4 mg/L
Total Phosphorus	8.1 – 8.2 mg/L

Sources: EPA Onsite Wastewater Treatment System Manual, 2002, EPA/625/R-00/08 and Crites and Tchobanoglous, Small and Decentralized Wastewater Management Systems, McGraw-Hill, 1998

On-site Secondary Treatment Options

A bit about OSET

- OSET ran in from 2007–2020 and tested close to 50 plants. Performance Certificates of > 70% expired
- Each trial ran for 9 months and used municipal effluent with some I/I issues:
  - TN Influent range 33 – 80, mean 59 mg/L – met test requirements of 20 – 100 mg/L
  - BOD Influent range 55 – 364, mean 209 mg/L, lower than requirements of 150 – 200 mg/L
- Each unit received 1000 L/day of domestic wastewater, with a high load of 2000 L/day in week 36. Later trials were different
- Beginning in week 9, samples were collected in 6-day intervals
- Each system was given a performance rating based on post-treatment mean concentrations :

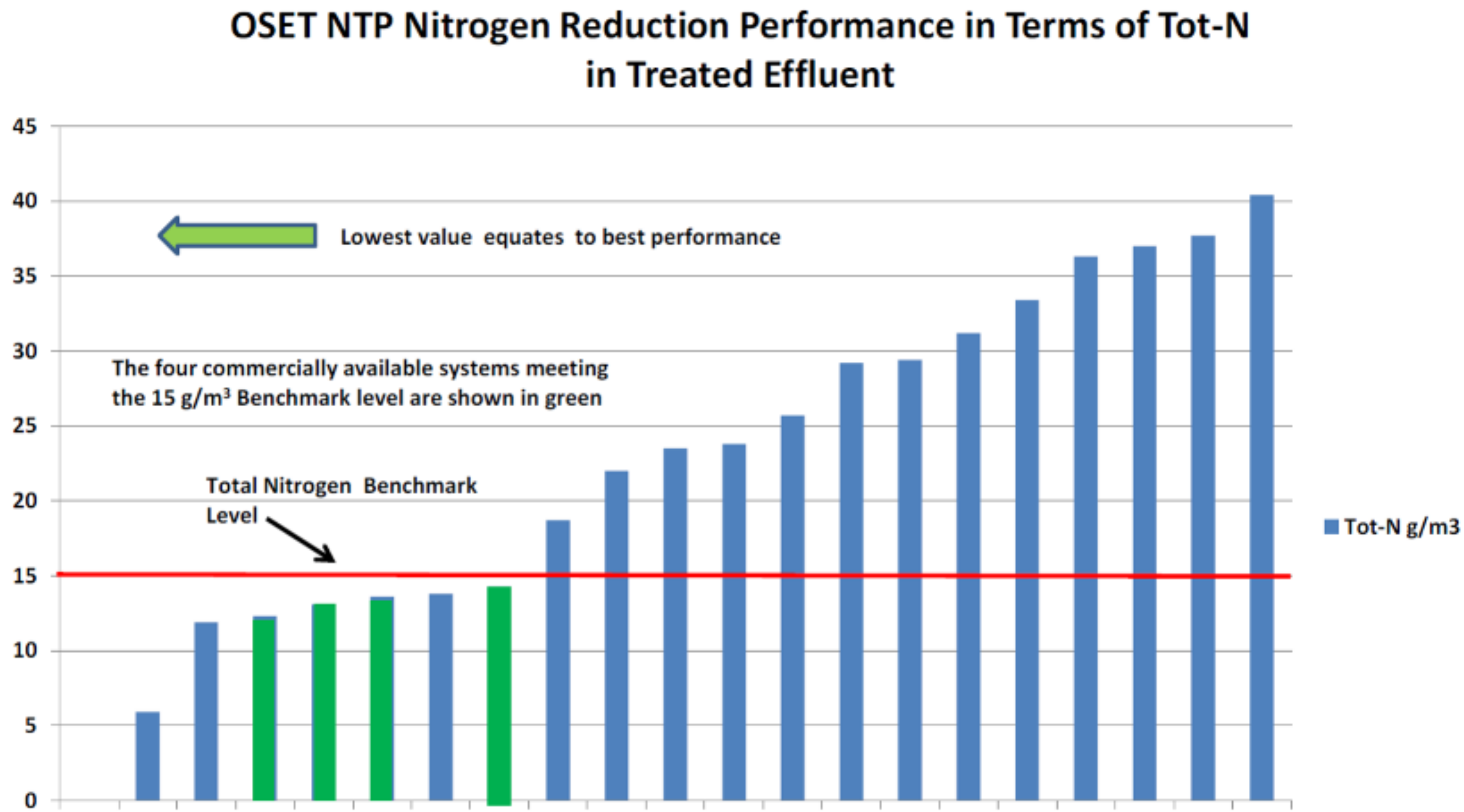
Indicator parameter	Rating				
	A+	A	B	C	D
TN (g/m^3)	<5	<15	<25	<30	≥30
NH_4-N (g/m^3)	<1	<5	<10	<20	≥20

What has been Tested – some x 2

Type	No Tested	Med-avg mg N/L	95%-max mg N/L	Med-min mg N/L
SAF	30	24	53	12
Passive (including Vault Trench)	4	17	47	6
SBR	3	33	47	26
PBR (passive)	6	29	47	12
TF (passive)	2	33	46	26
Vermiculture	4	33	46	22

Results for N from Gunn 2014

OSET Mean Influent 60 mg N/L – most > 50% reduction



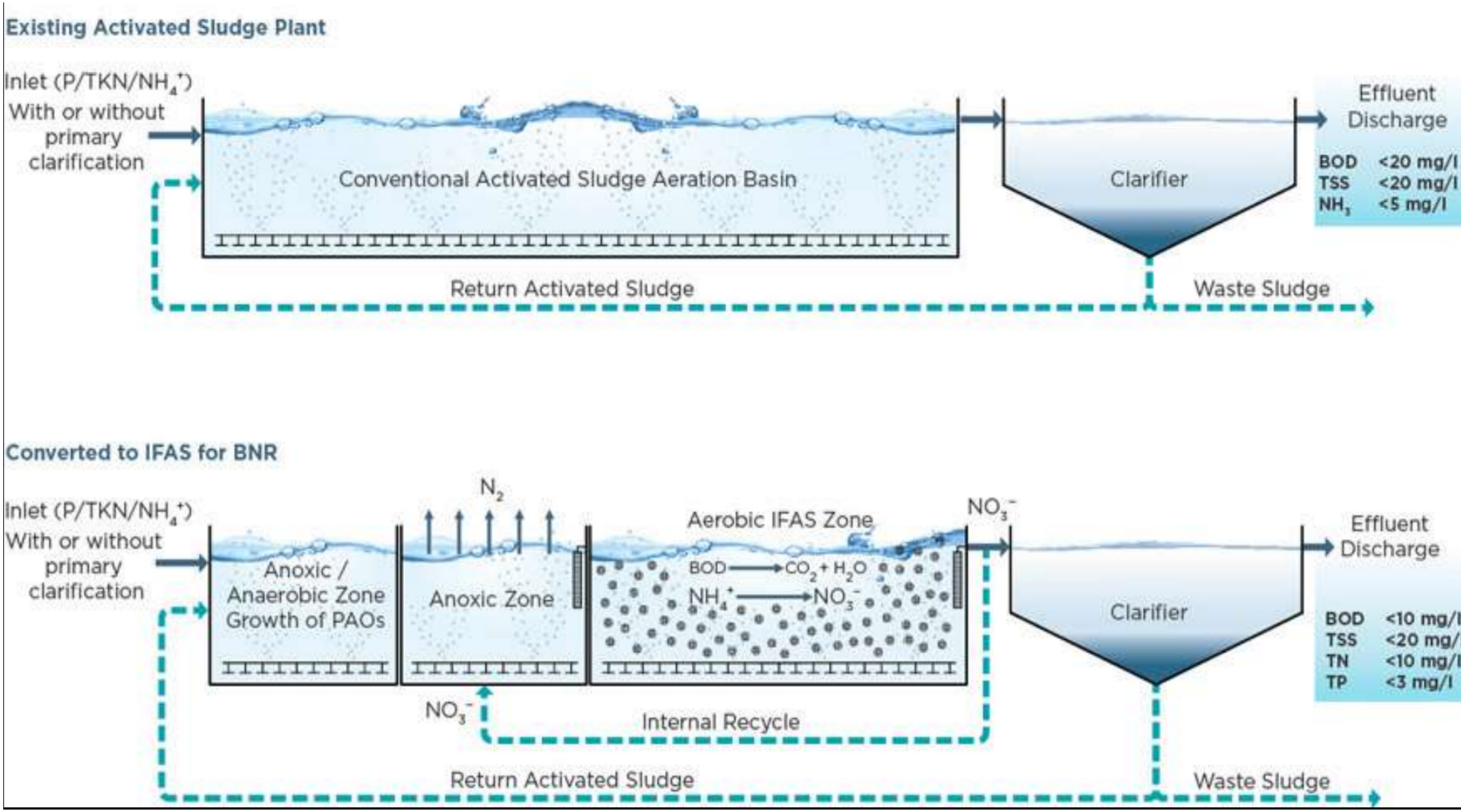
OSET Results Summary

- OSET has been temporarily halted due to influent issues. I consider it is the right place to have it as Rotorua has cold winters. The infrastructure is in-place. Just needs an influent source akin to onsite systems
- The survey undertaken by SWANS-SIG (OWMS-SIG) - the onsite community is keen to see it back
- Some systems failed to meet 1547 criteria (BOD/TSS) and are likely to fail under similar test conditions unless they modify their design
- Results were relatively similar, med 24 – 33 mg/L TN – mean influent 60 mg/L, i.e. 50% reduction achievable
- Lower TN if recycling back to primary 12 - 26 mg/L TN

Activated Sludge Process (ASP)

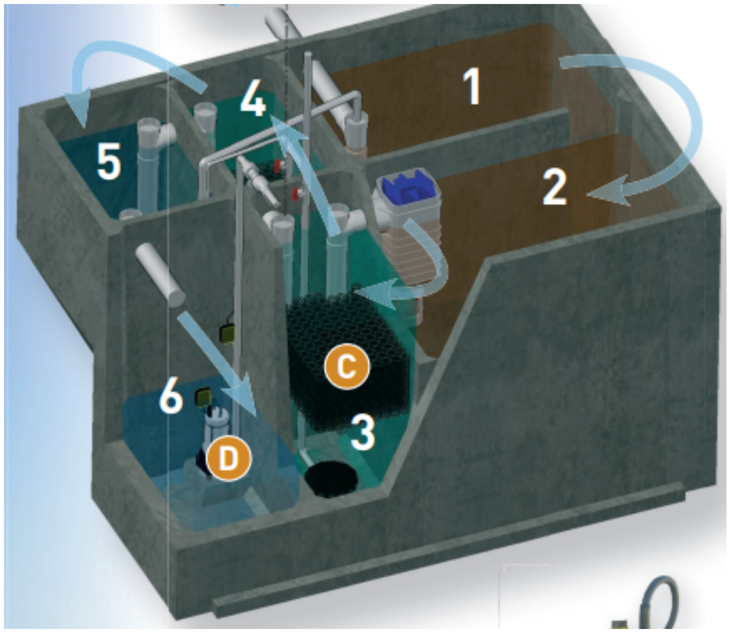
- The activated sludge is a process with high concentration of microorganisms, basically bacteria, protozoa and fungi, which are present as loose clumped mass of fine particles that are kept in suspension by stirring and aeration, with the aim of removing organic matter from wastewater.
- The combination of wastewater and biological mass in the reactor is commonly known as mixed liquor SS and the active microbial mass as mixed liquor volatile S.
- Excess mixed liquor flows into a clarifier and the treated supernatant is either recycled or discharged.
- Clarifier sludge is returned to the reactor (RAS).
- Excess is removed (WAS).

AS vs IFAS



Existing Activated Sludge Plant
Inlet (P/TKN/NH4+)
With or without primary clarification
Conventional Activated Sludge Aeration Basin
Clarifier
Effluent Discharge
BOD <20 mg/l
TSS <20 mg/l
NH3 <5 mg/l
Return Activated Sludge
Waste Sludge
Converted to IFAS for BNR
Inlet (P/TKN/NH4+)
With or without primary clarification
N2
Anoxic / Anaerobic Zone Growth of PAOs
Anoxic Zone
Aerobic IFAS Zone
BOD → CO2 + H2O
NH4+ → NO3-
NO3-
Clarifier
Effluent Discharge
BOD <10 mg/l
TSS <20 mg/l
TN <10 mg/l
TP <3 mg/l
NO3-
Internal Recycle
Return Activated Sludge
Waste Sludge

Submerged Aerobic Fixed Film

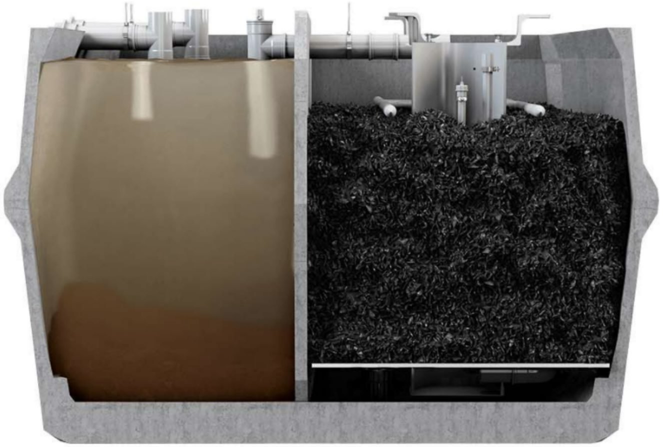


- Effluent passes over microbes on the SAF/SAFF/FAST media
- ~30 units assessed in OSET
  - TN removal variable fn of recycle A (8), B (8), C (6), D (8) ratings
  - NH_4-N removal: A - D rating
- Tend to be extended aeration – High SRT, less sludge - simpler
- Literature:
  - 79% – 94% reduction in NH_3 (1)
  - Max 75% reduction in TN(2)*

* Variable based on airflow rate and recycle

(1) Pahlavanzadeh, S., et al. *Performance and kinetic modelling of an aerated submerged fixed-film bioreactor for BOD and nitrogen removal from municipal wastewater.* Journal of Environmental Chemical Engineering (October 2018) 6 (5): 6154-6164
(2) Forouzesh, M., et al. *Partially aerated submerged fixed-film bioreactor for simultaneous removal of carbon and nutrients from high-strength nitrogen wastewaters: effect of aeration rate and C:N:P ratio.* Water Science & Technology (2017) 76 (4): 877–884.

Passive Treatment Plants



- Effluent is passed through a bed of activated carbon, or other media

  2 assessed in OSET – (1 was aerated so not really passive) and 1 vented

  - TN removal

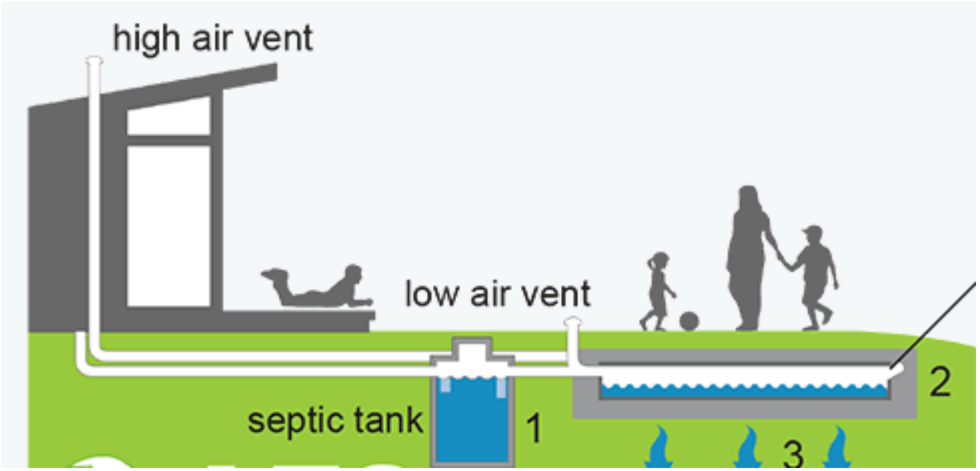
    A (1) B (1)
  - NH_4-N removal: A (2) rating

  Literature:

  - 50% reduction in NH_3 for Activated Carbon[1]

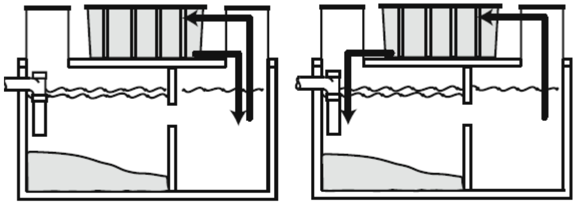
(1) Wang, Q., et al. *Pilot-Scale Biological Activated Carbon Filtration–Ultrafiltration System for Removing Pharmaceutical and Personal Care Products from River Water.* Water (January 2022) 14, 367.

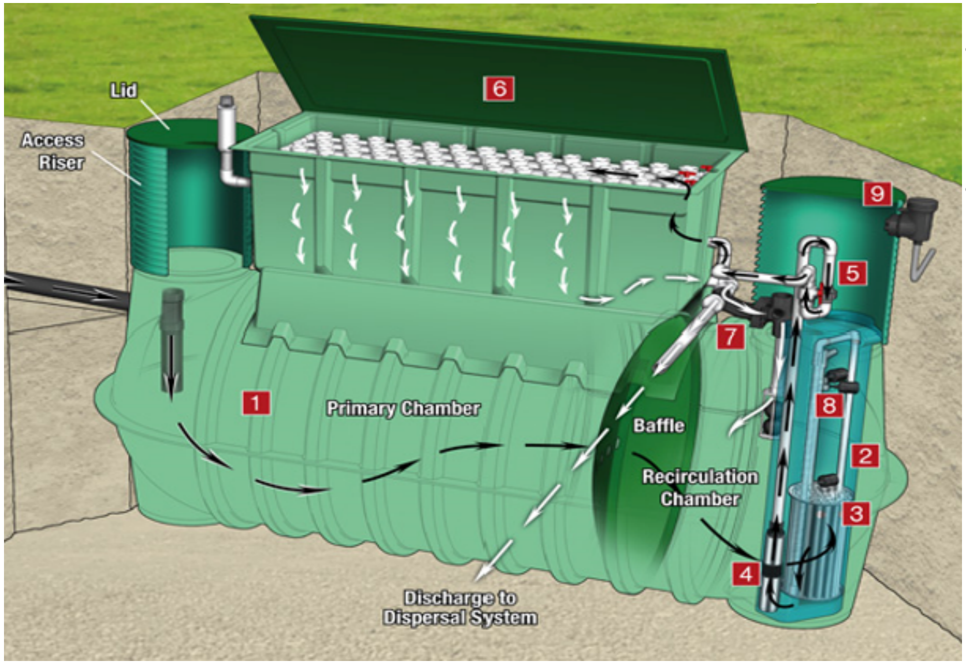
Passive Proprietary Vault Trench



- Engineered piping on a specialty sand bed.
- Aerates and filters effluent, and harbours nitrifying bacteria
- 2 units assessed in OSET
  - TN removal: A and D rating
  - NH_4-N removal: A+ and B rating
- A grade was set up to recycle back to primary, i.e. line trench and pump back to septic tank

Packed Bed Reactors





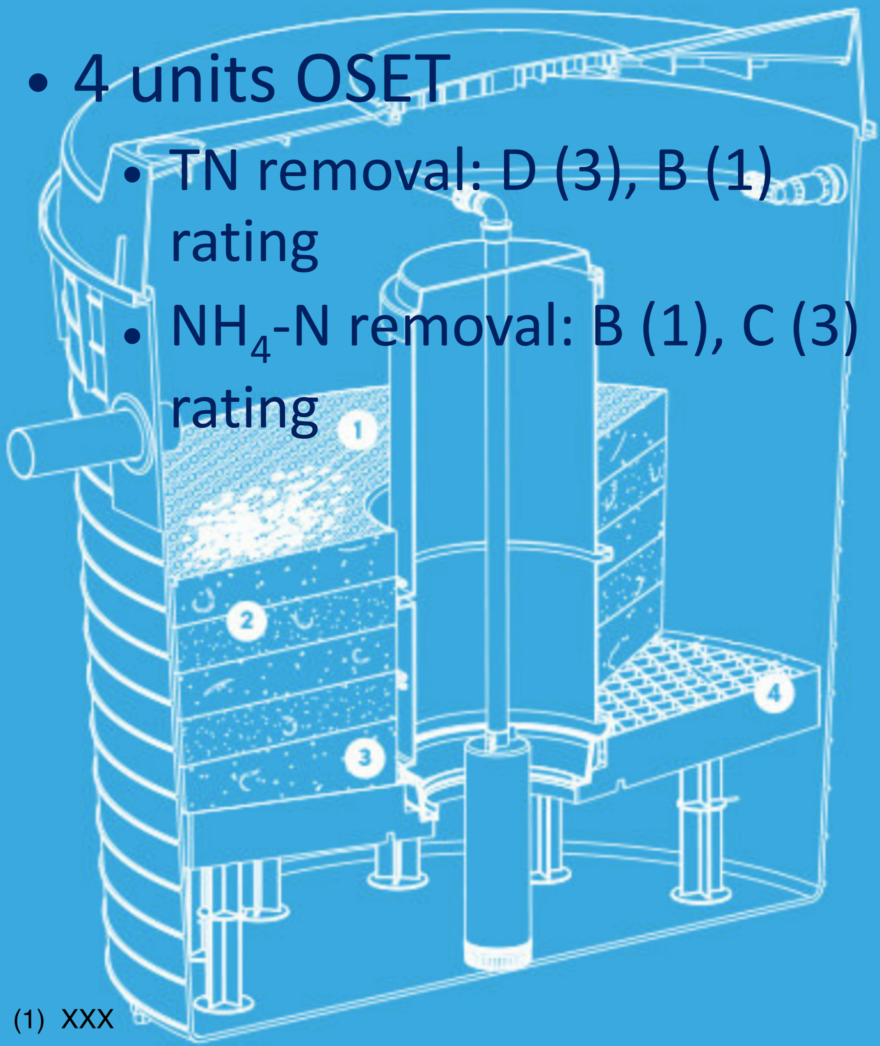
Effluent is recycled through packed bed with textile or similar.

6 units assessed OSET

- A (1), B (1),C (1), D (3)
- A Grade is Mode 3 above recycle to primary
- Unit without Primary recirculation (Mode 1) tested to NSF/ANSI Standard 40:
  - TN removal: 64%
  - NH_3 removal: 96%

Vermiculture Systems

- 4 units OSET
  - TN removal: D (3), B (1) rating
  - NH_4-N removal: B (1), C (3) rating



1
Solid waste is separated from liquid waste. Tiger worms and other micro and macro-organisms convert solids into a liquid and humic material

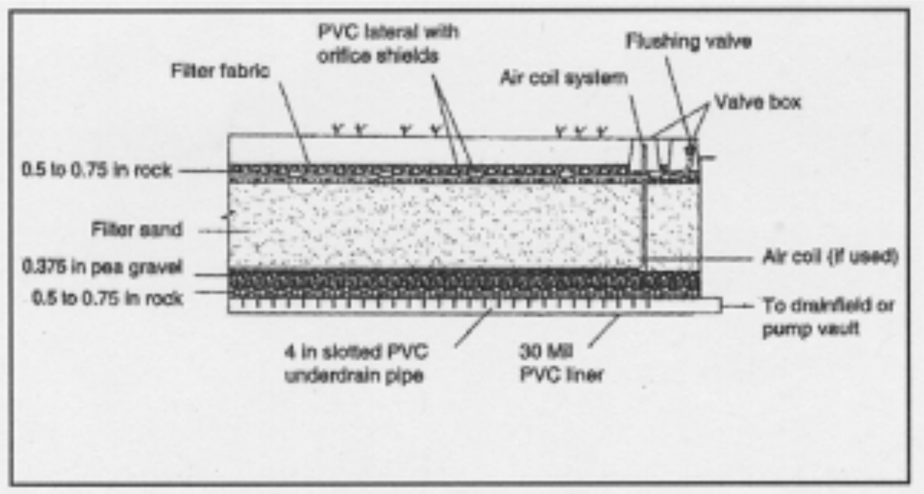
2
Tiger worms live throughout the filter bed naturally aerating it. Wastewater is cleansed by microorganisms as it trickles through the filter bed

3
The internal components of the BioPod can be cleaned-in place if long term accumulation of residual processed waste occurs

4
At the bottom of the filter bed the effluent is now treated and filtered to remove particles >80 microns before it passes into the pump chamber

(1) XXX

TF /Intermittent Sand Filter



- Effluent is passed through a sand bed or other media before being collected and discharged
- 2 TF's assessed in OSET
  - TN C (1), D (1)
  - NH_3 C (2)
- Literature:
  - 40% reduction in TN[1]
  - 90% - 95% reduction in NH_3[1,2]
  - 99% reduction in NH_4-N[3]

(1) Cagle, W. A. & Johnson, L.A., *Onsite Intermittent Sand Filter Systems: A Regulatory/Scientific Approach to Their Study in Placer County, California*. On-Site Wastewater Treatment: Proceedings of the Seventh International Symposium on Individual and Small Community Sewage Systems. Atlanta, Georgia (December 1994)

(2) Sabbah, I., *Intermittent sand filtration for wastewater treatment in rural areas of the Middle East - A pilot study.* Water Science and Technology (February 2003) 48(11-12):147-52

(3) Sievers, D. M. *Pressurized Intermittent Sand Filter With Shallow Disposal Field for a Single Residence in Boone County, Missouri.* On-Site Wastewater Treatment: Proceedings of the Eighth International Symposium on Individual and Small Community Sewage Systems. Orlando, Florida (1998)

SBR

- Example above is 1 available in NZ. It has separate primary, so not true SBR
- Possibly why not A grade as limited denitrification

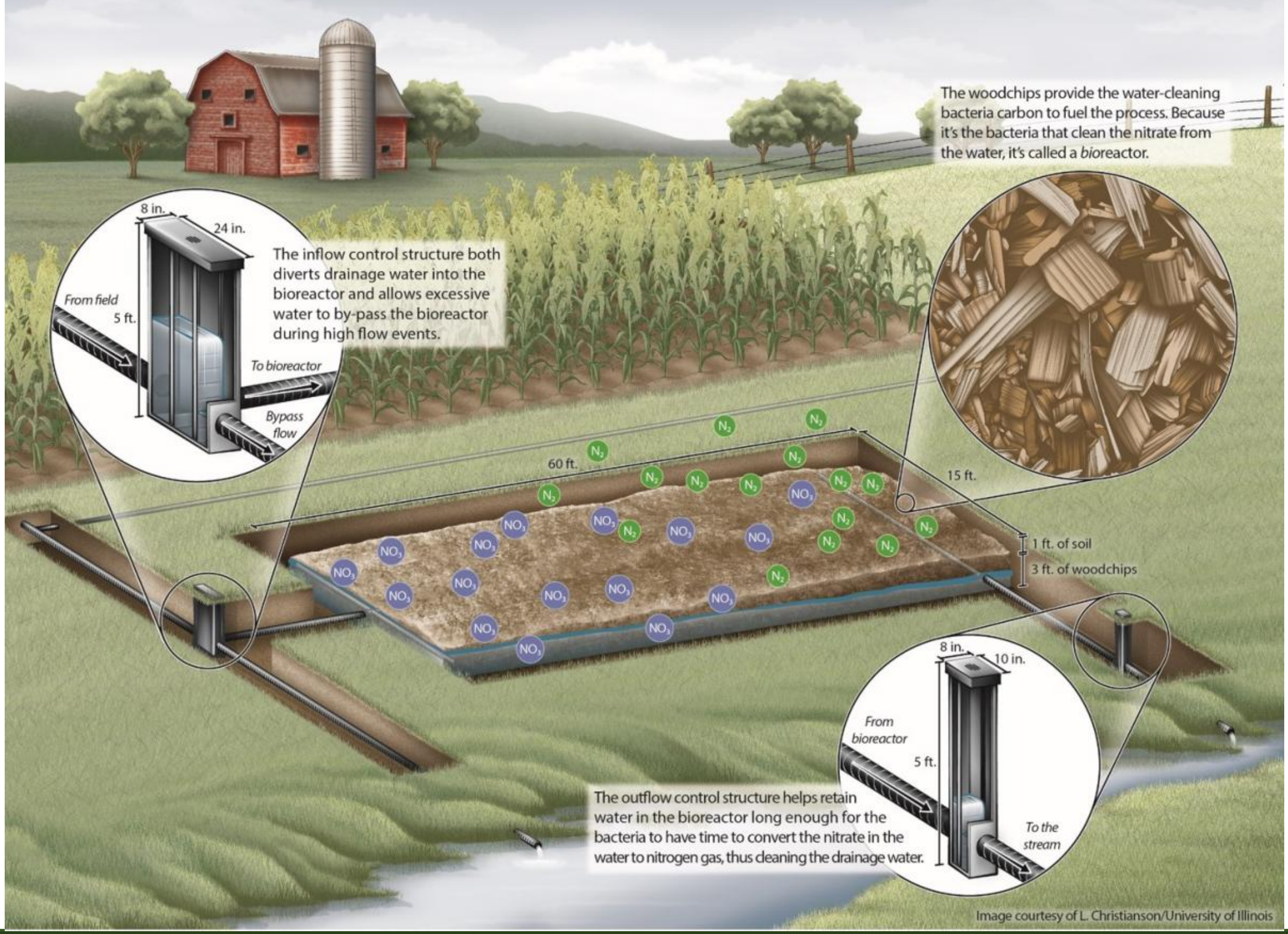
- Effluent is treated in one tank that aerates then settles to allow anoxic
- 3 SBR's assessed in OSET
  - TN C (1), D (2)
  - NH_3 A+ (2), A (1)
- Literature:
  - 84% reduction in TN[1]
  - 91 % reduction in NH_3[1]

1. Pelaz, L., Gomez, A., Letona A., Grralon, G., & Fdz-Polanco, M., Sequencing batch reactor process for the removal of nitrogen from anaerobiclly treated domestic wastewater. Water Science Technology (2018) 77 (6): 1581 – 1590.

Tertiary treatment options

Woodchip Bioreactor

A relatively cheap add-on to a system with nitrified effluent. Can be poly lined pit, with chips/bark submerged

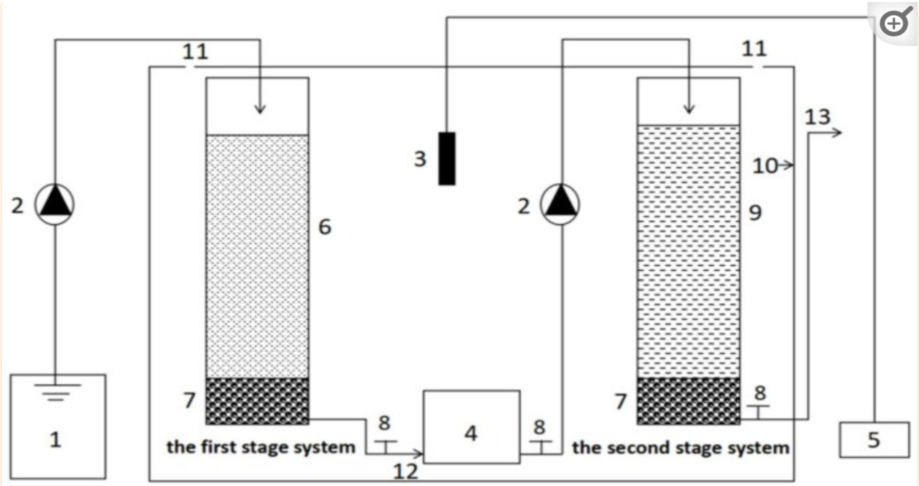


Woodchip Bioreactor

Summary below is 2 years of data following a PBR with about 50% nitrified mainly dealing with black water

	Influent	Following PBR	Following Woodchip	% reduction
Alkalinity	438	53	157	
pH		5	7	
cBOD		6	6	
TSS		16	3	
NH_4-N		34	14	
NOx		48	0.5	99 in BioR
TKN	105	37	15	86 Inf to Eff
TN		83	15	82 in BioR

Tertiary Sand/Glass Filter



- The sand provides a mechanical filtration. Not all sands are equal
- This system provides comfort that driplines are protected
- Reduction in N of nitrified effluent minimal unless set up as anoxic and C added – this can be gravity with submerged sand filter above disposal bed

Most Common – LAS/LTS

Includes: Trenches (Std and Controlled); Beds; Mounds; Irrigation – PCDI, Sub or Surface – usually covered

Are we Designing it Right

- Absolutely not – WHY?
- Constraints of NZ and other Design Standards
- On-site vs Municipal Design Stds
- NZS4404 – 2.5 – 3.5 p/dwelling @ 180 – 250 L/p/d then size conveyance and screens for 2 x WWF and 2.5 x diurnal peak BUT WWTP kinetics designed on DWF, i.e. 2.7 x 200 = 540 L/dwelling/d
- 1547 based on bedrooms and peak flow, e.g. 4 BRs 6/7 people at 200 L/p/d = 1,200 – 1,400 L/d. But water use << 200 L/p/d, more like 100 – 125 L/p/d. The 200 L/p/d is a design flow for sizing LAS and pipework/pumps – not kinetics
- Many OWTS sized for 2,000 L/d but many residences (empty nesters) receives 200 – 250 L/d – it is 8 – 10 x oversized. F:M ratio way out of whack

12 Month Irish Study (1)

LOWE Environmental Impact

The study did not reveal any economies of scale, i.e. less water use per capita for larger households, with range of 60 – 123 L/p/d; weighted average 97 L/p/d

No. of residents	6	4	4	3	5	4

Table 2 – Site characteristics and average total-N loads across research periods.

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Mean flow per capita (L/d)	119	105	82	90	60	123
Biomat length along trenches (m)	11	20	8	0.4	3	4
COD loading per trench (g/d)	72.0	40.2	108.4	12.8	14.1	24.5
Effective hyd. load[a] (L/m^2 d)	24.0	11.7	22.8	373.3	41.7	54.7
Influent total-N to subsoil (g/d)	60.4	28.9	19.6	20.2	18.4	17.8
Total-N after 1 m depth of subsoil (g/d)	25.0	6.8	2.1	15.2	16.7	13.6
Total-N per capita after 1 m depth of subsoil (g/d)	4.17	1.70	0.53	5.07	3.34	3.40

a Per unit area of trench.

(1) Gill, et. Al (2009). Nutrient Loading on Subsoils from On-site Wastewater Effluent, comparing Septic Tank and Secondary Treatment. IWA Water Research 43 pp 2739 - 2749

N Load vs N Concentration

- Literature gives total nitrogen (TN) per person ranging from 8 – 12 g/d, equates to 3 – 4.4 kg/yr. Some USA studies use 5 kg/yr but this allows for 25% homes garbage grinders
- So if TKN in wastewater is only 30 – 80 mg/L, then water use per person is 150 – 200 L/p/d BUT, water use << and TN >>
- Average of STEP tank effluent going to 3 different WWTPS in Central Otago taken over 5 months – this is not Influent but after ST

	Avg	Max	Min
TN	75	123	57

Load vs Concentration Barnstable DoH

Uncertainty in standard leads to compliance enforcement difficulties!

Example 1

A seasonal home typically occupied by two environmentally-conscious retirees. They don't water the lawn, installed water-saving devices, take short showers, &c and have installed an I/A system.

Total Nitrogen numbers come back at 28mg/l, well in exceedance of 19mg/l. Do you press compliance on the owners?

Example 2

A year-round home typically occupied by a family of four. They water the lawn, installed water-saving devices but take long showers, do lots of laundry, have frequent guests and have installed an I/A system.

Total Nitrogen numbers come back at 14mg/l, below 19mg/l, but their water use is through the roof. You'll probably never follow up on this system!

What Does it All Mean

- On-site WW has high strength influent, likely > standards
- Water can be cold, particularly cold wash
- Alkalinity variable depending on source – generally higher in groundwater but low in Canterbury
- OWTS with recycle back to primary provide high C and anoxic to reduce N. Many plants do not do this but could be configured at a lower rated flow capacity, i.e. no recycle can give 20 – 30% reduction and recycle 40 – 75% in TN. OWTS are oversized – will result in poorer performance.
- For various reasons difficult to get good N reduction in small unmanaged plants. Overseas studies suggest an average reduction of 50% (similar to OSET). Overall N reduction will come down to C for denitrification & sludge wasting frequency.
- OWMS includes the soil/plant system. Reliance should be on N LOAD (not concentration) removal from both systems not just end of pipe

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Advice AEE Agricultural Analysis Application Approachable Assessments Assimilation Assistance Biosolids Capability Client Communications Communities Compliance Compost Consents Consultation Contamination Coordinate Council Cultural Current Data Degradation Design Detention Developments Discharges Documentation Drafting E. coli Ecosystems Effects Engagement Environment Equipment Evidence Excellence Experienced Expert Facilitating Farming Feasibility Fieldwork First-flush Fit-for-purpose Flooding Fun Geology Graphs Greywater Groundwater Guidelines Handbag Hazardous Hydraulics Innovation Interpretation Investigation Irrigation Land Landfills Landscape Land-treatment Leaching Lodge Management Metals Microbiology Modelling Monitoring NES Nitrogen Nutrients Onsite Optimisation Organics Overseer Papers Pathogens Phosphorus Plain-english Plans Preparation Presentations Project Quality Relevant Remediation Reports Research Review Sampling Scientific Septage Sludge Soil Solutions Spreadsheets Standpipes Stormwater Strategy Support Surface Water Sustainability Systems Team Testing Timely Treatment Validation Wastewater Water Water-balance Waterways

www.lei.co.nz | Palmerston North Christchurch Wellington | office@lei.co.nz