The potential for nutrients (particularly nitrogen) to degrade the water quality of Whangateau Harbour is a concern for stakeholders. The discharge of treated wastewater from the Omaha Wastewater Treatment Plant (Omaha WWTP) to irrigation blocks on either side of the harbour represents a significant source of nitrogen if it were transported without losses into this high quality receiving water.

Outline of presentation

The overall purpose of this presentation is to

1) Summarise our understanding of processes affecting nitrogen at Omaha using:
   a) Results of field investigations
   b) Model outputs
2) This allowed us to assess the WWTP's nitrogen contribution to Whangateau Harbour

In addition, in this presentation we also:

1) Discuss fate and transport of phosphorus
2) Identify the potential risks of emerging contaminants

Significance of nutrients

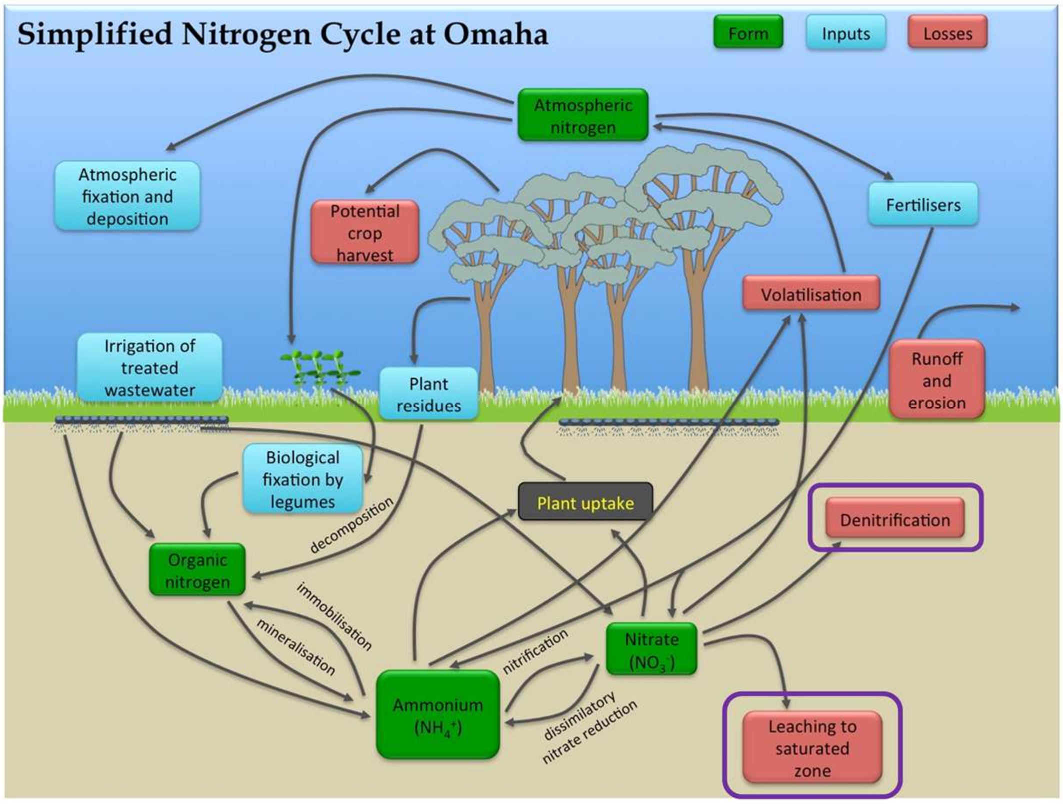
- Wastewater contains nutrients (nitrogen and phosphorus) which can reduce water quality
- In a land irrigation system such as the Omaha WWTP, phosphorus is adsorbed by the soil, but nitrogen can leach through the ground
- Therefore the potential for nitrogen from the Omaha WWTP to degrade water quality in the Whangateau Harbour needed to be understood
- Streamlined Environmental were commissioned to study the fate and transport of irrigated nitrogen from the Omaha WWTP
- To do this we needed to develop a conceptual model of the nitrogen cycle

As part of resource consent applications for continued operation of the WWTP (including the irrigation system), Watercare Services Ltd commissioned a study on the fate and transport of irrigated nitrogen. An initial scoping study (Streamlined Environmental, 2015) showed that there were locations along the likely groundwater path from the irrigation site to the harbour, where denitrification activity (the conversion of nitrate or nitrite to nitrogenous gases) was significant. Hence nitrogen could potentially be lost from the system.

In this follow up study we focussed on nitrogen transformations in soil beneath the irrigation sites. We measured a range of biochemical rates in soil cores with the aim of understanding nitrate loss (denitrification) and nitrate production (nitrification – the conversion of ammonium to nitrate). We also made additional chemical measurements to determine the inorganic nitrogen concentrations in pore water, the amount of readily mineralizable carbon (needed to sustain denitrification), and redox potential (Eh) at the boundary

with the groundwater table. We also commissioned Scion and Turf and Landcare Science Pty Ltd to estimate
nitrogen uptake and immobilization in the eucalypt stand, and golf course, respectively.

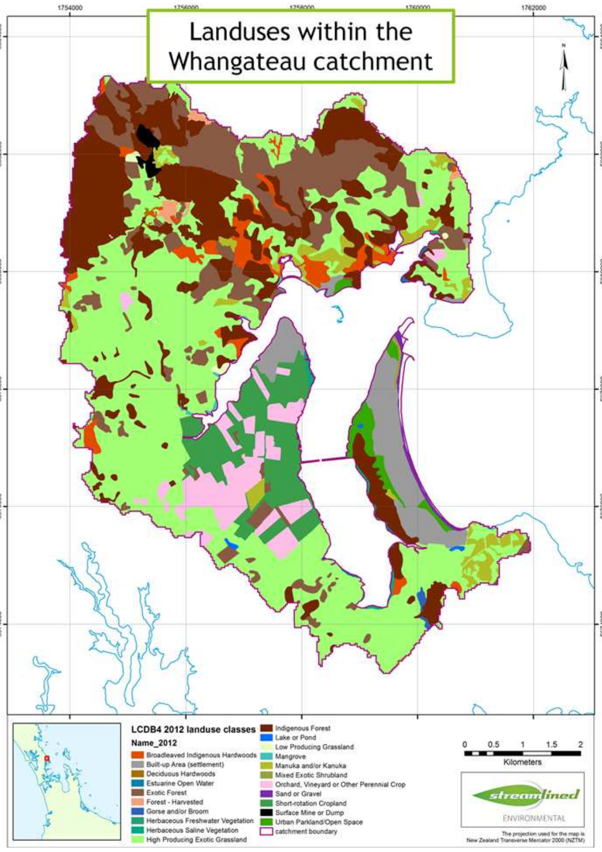
Potential fate of nitrogen from treated wastewater irrigation



This slide shows that potential pathways whereby irrigated nitrogen can be lost from the system and include crop harvest, ammonia volatilisation (conversion to ammonia gas), runoff/erosion, denitrification (conversion to nitrogen gas) and leaching.

For this study we concentrated on the processes of denitrification and leaching (shown in the purple boxes) as the only two ways in which nitrogen can be lost from the 'irrigation site'. This is because
(i) there is either a long term (as is the case with the eucalypts) or no crop harvest (even on the golf course clippings are left to decompose and not removed)
(ii) for ammonia volatilisation to be significant soil pH needs to be alkaline, whereas at both the OBGC and Jones Rd pH is weakly acid, and
(iii) the topography is generally flat and there is no visible indication of tunnel or gully erosion.

Denitrification is the only process whereby nitrogen is completely removed from land and aquatic ecosystems through the end products being nitrogenous gases that are lost to the atmosphere (which is ~78% nitrogen).



Also needed to understand the potential nitrogen inputs to harbour from other sources

Nitrogen sources	Nitrogen (tonnes/year)
Land runoff	26.6
Wastewater irrigation	2.2

In a previous part of our study we estimated the amount of nitrogen entering the Whangateau Harbour from land-based sources. We used the latest landuse data available (LCDB4 2012) and published information on the amount of nitrogen generated from different types of landuse (including beef and sheep, dairy, forestry, native vegetation, urban), which is illustrated in the map. The table shows a much greater nitrogen contribution is likely from runoff from land than from wastewater irrigation.

Information for nitrogen model

- To develop the nitrogen model we needed to understand the following
  - Vegetation uptake (immobilisation)
  - Soil processes
  - Leaching to groundwater

Jones Rd – vegetation uptake

Uptake	Kg N/ha/y
Eucalypts	0-10
Natives	0-10

An estimate of nitrogen uptake by the Eucalyptus forest was needed to inform the nitrogen flow model. This was provided by Scion (Smaill, 2015). We estimated N uptake on the native site (mainly manuka and kanuka) from a recent Lincoln university PhD thesis (Franklin, 2015).

- The Eucalyptus forest at Jones Road is a 10 ha stand (7.6 ha irrigated) of mainly mature *Eucalyptus botryoides* with small numbers of *Acacia melanoxylon* (a N fixer)).
- *A. melanoxylon* is an N-fixing legume and the rate of fixation increases with age.
- Smaill reasoned that when the N-fixing impact of *A. melanoxylon* is considered, the N uptake by the irrigated Eucalyptus forest may be close to 0.
- He concluded that N uptake from the stand is in the range 0-10 kg N/ha/y
- We estimated N uptake from the native site to be similarly low based on the results of N uptake trials on native species conducted by Franklin (2015)

Golf course uptake

Figs 6 & 7. Exposed irrigation pipe (left) and extra growth coinciding with emitters (right).

Figs 1 & 2. Two contrasting soil profiles from the course.

Inputs	Kg N/ha/y
Fertiliser (fairways)	100
Irrigation	128
Total	228

Outputs	Kg N/ha/y
Immobilisation	175
Leaching	53
Total	228

An estimate of nitrogen uptake by the golf course was needed to inform the nitrogen flow model. This was provided by Turf & Landcare Science Pty Ltd, Queensland.

Nitrogen inputs

- Fertiliser N is currently applied to the fairways at a rate of 100 kg N/ha/year in the form of ammonium sulphate.
- A total of 7.5 ha is currently irrigated.
- Typically, 100-200 m3 is irrigated in winter (May to September) and 1000m3 in summer (October to April) holiday period.
- There is no legume content, so the only other N input is assumed to be wastewater irrigation.
- The information provided also indicates that an average of 128kg N/ha/yr is applied to the fairways via the recycled water.
- Therefore, T&LC Science (2015) estimated that ~ 228kg N /ha / yr is applied to the fairways and tees.

Nitrogen loss (outputs)

- T&LC Science (2015) noted that from an agronomic perspective, N removal occurred via two processes: soil immobilisation and leaching through the profile.
- Soil organic matter testing indicated that 2100 kg N/ha is stored in the soil profile, much of which is likely to have accumulated

over the past 12 years of irrigating.

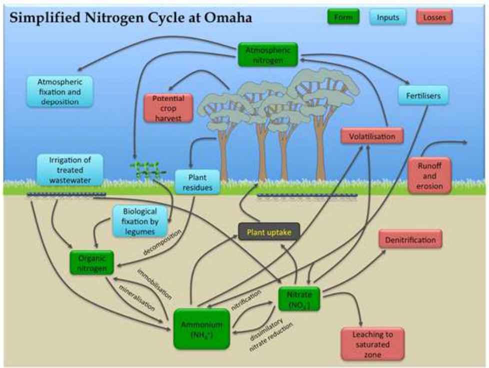
- This indicates that up to 175 kg N/ha/yr could have accumulated in the soil profile, with an estimated 50 kg/ha/yr of N being leached.
- T&LC Science (2015) also noted that because the N removal was related to good turf management, the immobilisation rate was probably sustainable.

Summary of vegetation effectiveness at N uptake

- Very low uptake by vegetation at Jones Road sites
- Quite high uptake by grass on Omaha Beach golf course, which is immobilised in turf

Soil processes

- If nitrogen is not taken up by vegetation, it can still be removed through soil processes before it enters surface water
- To understand the soil processes we measured a number of parameters including:
  - Denitrification enzyme activity (DEA)
  - In situ denitrification rate
  - Short-term Nitrification Activity (SNA)
  - Nitrate (NO3)/ammonia (NH4) concentrations
  - Readily mineralisable carbon (RMC)
  - Loss on ignition (LOI)
  - Dissolved Organic Carbon (DOC)
- Samples were collected from the sites on the following slides



A range of tests (assays) related to denitrification and leaching were undertaken. Field-based tests included the in-situ denitrification or DEA analyses, as well as measurement of nitrate (NO_3) and ammonia (NH_4). Lab-based analyses included RMC and DOC (2 measures of the amount of organic carbon available for bacteria) and SNA.

Denitrification enzyme activity (DEA) is a surrogate indicator of recent denitrification, such as might occur when a high nitrate-containing leachate (from irrigated wastewater) passed through a zone where denitrifying microorganisms were present, and conditions were not limiting to denitrification (i.e. there is sufficient available organic matter to sustain the energy requirements of the denitrifiers, and oxygen is absent). DEA is measured in the lab. **In situ denitrification** is a measure of denitrification occurring in the soil at the time of measurement. It is measured in the field.

Short-term Nitrification Activity (SNA) is an similar type of assay to DEA except that it measures the rate of nitrate production (nitrification) under aerobic conditions by nitrifying bacteria.

Nitrate (NO_3)/ammonia (NH_4) concentrations provide estimates of the pore water concentrations of these N forms. They were used to provide corroborative evidence that the biochemical processes (nitrification and denitrification were occurring.

Available carbon provides the energy for denitrifying microorganisms to grow, and without it significant denitrification is not possible. We used **readily mineralisable carbon (RMC)** to provide an index of carbon availability to denitrifying microorganisms, which we use to explain differences in rates both spatially and with depth. **Loss on ignition (LOI)** was also measured, as it provides an indication of the total carbon reserves in soil or sediment. It provided a definitive and objective measure of the carbon reserves beneath each of the land treatment sites.

DOC (Dissolved Organic Carbon) provides an analogous measurement of carbon availability for denitrification as RMC. It is best suited for water samples or saturated soil samples and so was used on the PDP collected bore site samples.

Golf course soil sampling sites

PDP bore sites

SEL soil sampling sites

Soil samples were collected in two separate field trips; one by Streamlined Environmental (SEL) with assistance from NIWA, and the second by PDP. Soil samples were collected 30 minutes after a 30-minute irrigation event was completed. The samples collected by PDP were within the saturated zone of the sediment profile, whereas samples collected by SEL were at or above the interface between the unsaturated zone and the saturated (groundwater) zone. Duplicate samples were collected from different depths zones (specifically 0 – 200mm, 600-800mm and >1000mm).

Jones Rd soil sampling sites

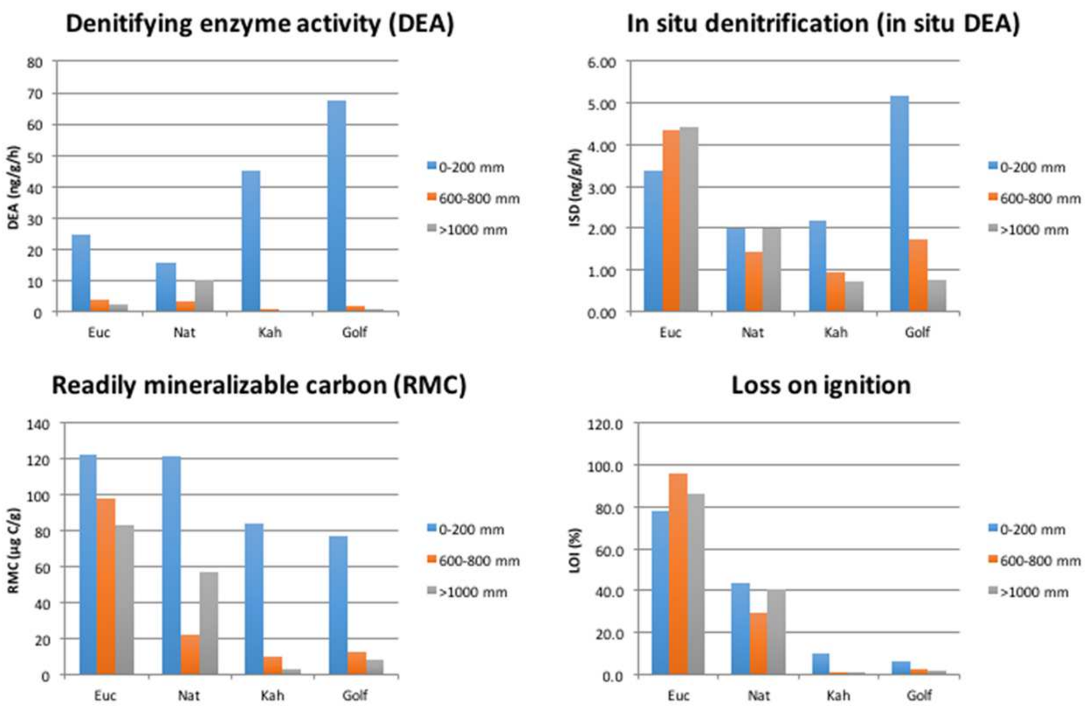
PDP bore sites

SEL soil sampling sites

Summary of results relevant to N loss (denitrification)

Irrigated
EUC = Eucalypt area
NAT = Native block
Golf = Golf Club (OBGC)

Not irrigated
KAH = Kahikitea forest (OTWSR)



From the graphs of Nitrogen Loss (denitrification) measures it can be concluded that:

DEA

- DEA (which is responsive to added nitrate) activities were highest in the surface layers for all landuses with the OBGC (Golf) and OTWSR (Kah) having the highest activities.
- This appears to be related to the high RMC values in the surface layers under these landuses, which provides organic carbon available for use by bacteria.
- The surprisingly high DEA in the surface layer of the OTWSR (Kah) (given there is no treated wastewater present) may indicate the presence of heterotrophic bacteria (that requires carbon), which can denitrify when oxygen is absent (anaerobic conditions) and nitrate is supplied..

In-situ denitrification

- There is consistent denitrification activity in-situ (in situ DEA) throughout the eucalypt cores (ie all depths) (Euc).
- There is similar (but lower) denitrification activity in the native block (Nat), which also has some intermittent peat deposits.
- However, for both the OBGC (Golf) and OTWSR (Kah), higher activities were apparent only at the surface where available

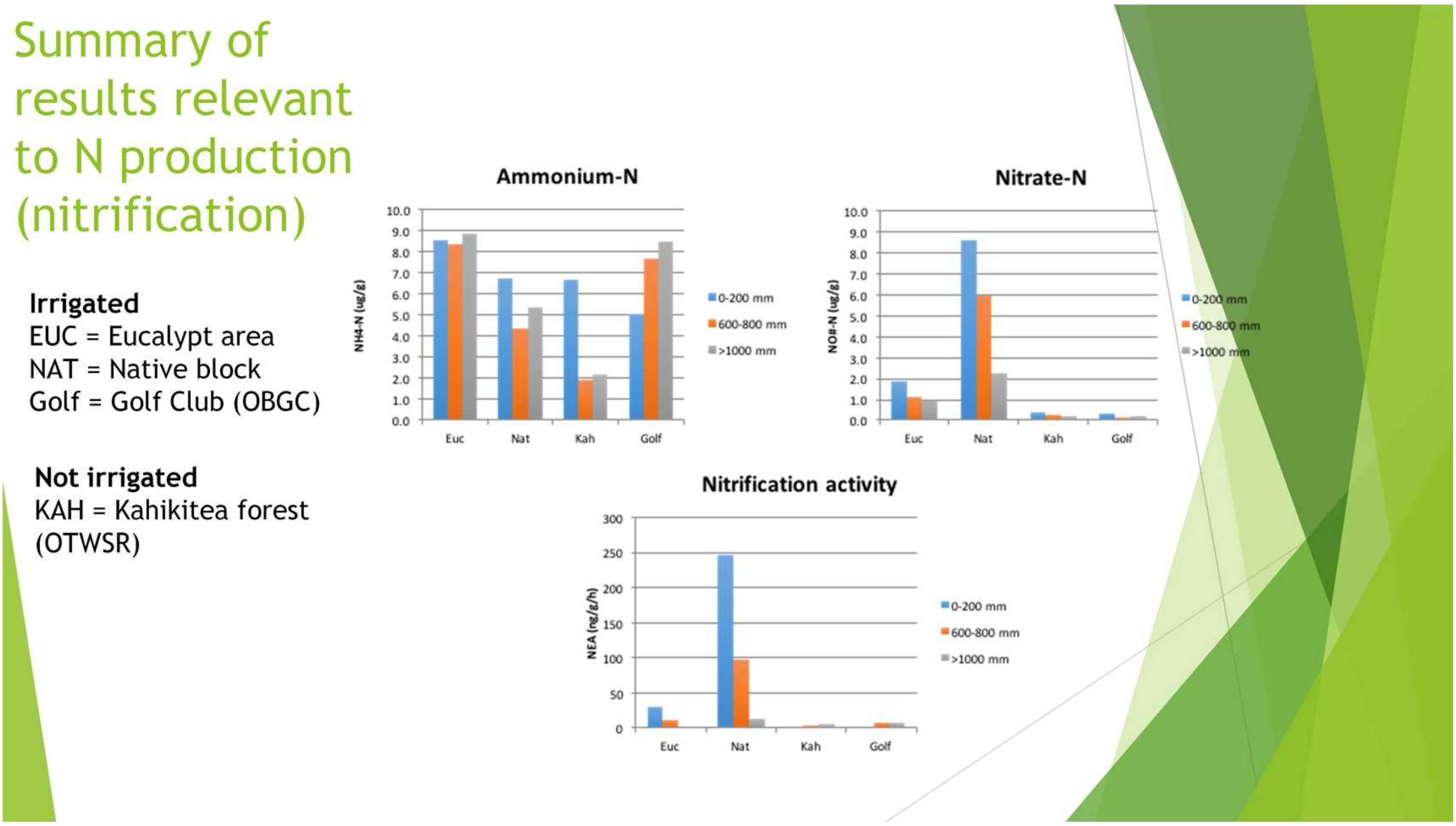
carbon was also high.

RMC

- RMC is relatively high in the surface layers under all landuses.
- Loss on ignition (LOI), which is a surrogate for total carbon, is uniformly high under the eucalypts, which is consistent with the peat substrate
- It is less than half that level in the native plantation, which may be due to the patchy peat distribution (and therefore be a matter of chance in where the cores were taken), or it may reflect a mixing of mineral and peat soils at the time the native plantation was planted.
- LOI is almost absent under both the OTWSR (Kah) and OBGC (Golf) reflecting the mineral soil below the organic-enriched surface layer.

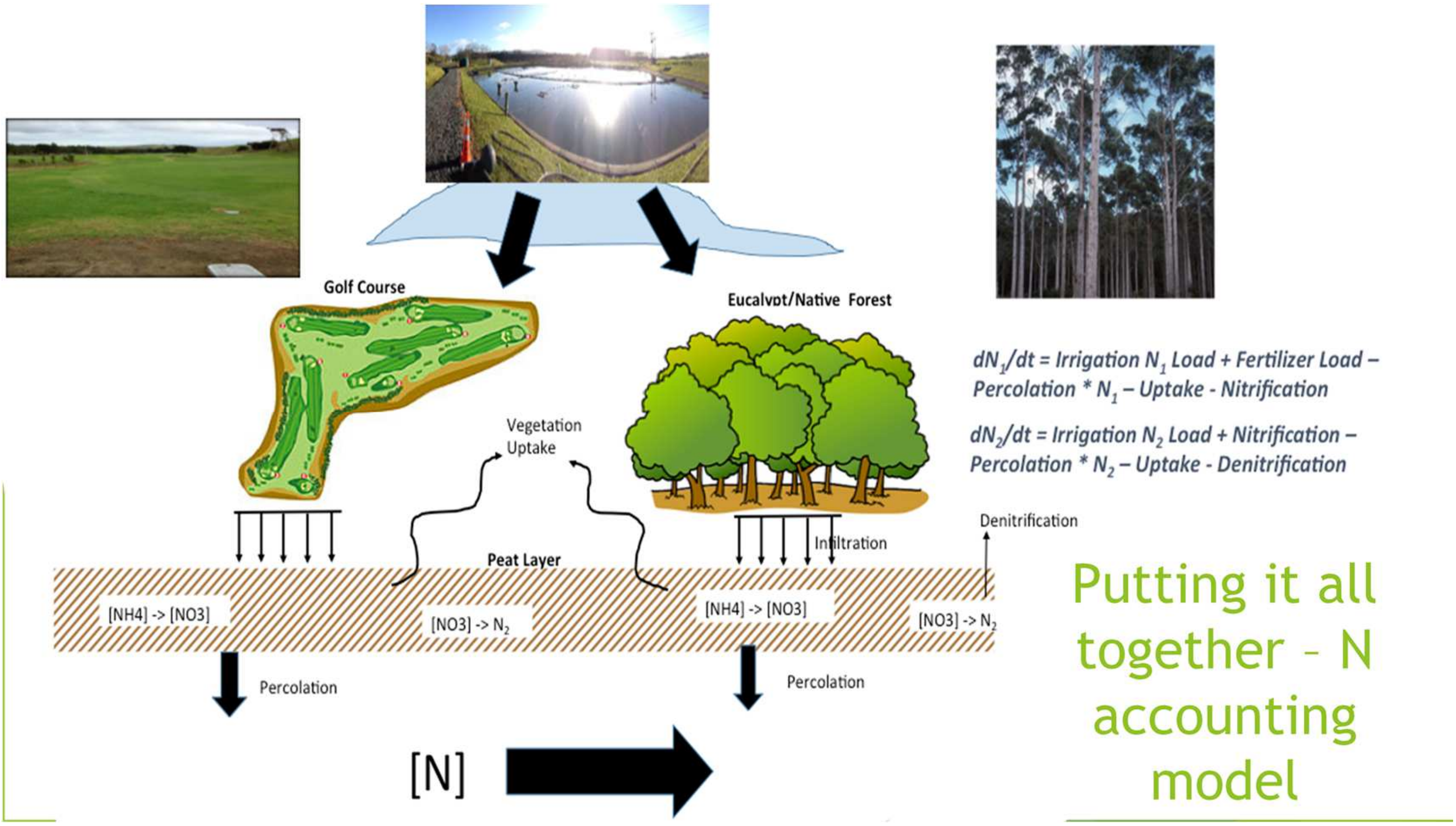
Conclusion

- Whilst in-situ denitrification is highest under the eucalypts they are not orders of magnitude greater than the other landuses
- There appears to be more than enough readily mineralisable carbon to sustain denitrification, so it would appear that something else is limiting.
- There is measureable nitrification activity down to at least 800 mm depth (next slide) and other measurements indicate that oxygen was present.
- It is therefore likely that oxygen is limiting.
- Denitrification clearly is still occurring but it will be limited to anaerobic areas rather than throughout the entire peat matrix.
- However, the depth of the peat means that even though denitrification rate per unit of soil is relatively low, the depth of peat soil is such that nitrate supplied from wastewater and nitrification is removed to low levels. This is confirmed in modelling (see later).



From the graphs of Nitrogen Production (nitrification) measures it can be concluded that:

- There are very high nitrification rates measured in the native block
- Consequently accumulation of nitrate-N also occurs under this landuse down to 1m.
- Significant (but lower than native block) nitrification measured in eucalypts down to 80 cm.
- In contrast, relatively low nitrification activity was measured at OTWSR (Kah) and OBGC (Golf).

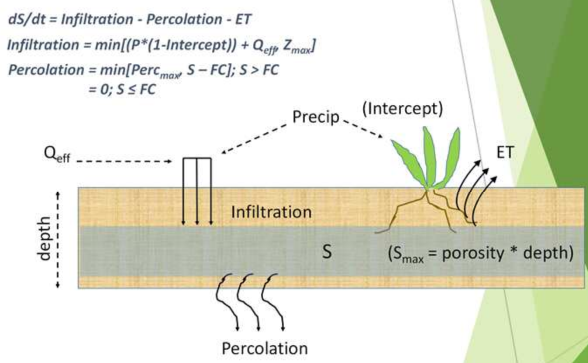


We developed a numerical model to provide for screening level analysis of likely nitrogen (N) flow paths of Omaha WWTP land irrigation water.

- the model should be considered “high level”, with recognized uncertainties associated with both the timing and magnitude of projected nitrogen concentrations and loads in the shallow subsurface.
- The model simulates the application of Omaha WWTP treated wastewater, as irrigation, to multiple land treatment zones.
- The model focuses on the shallow unsaturated subsurface associated with the two primary irrigation areas: Jones Road (divided into separate “Eucalypt” and “Native Block” zones) and the Omaha Golf Course (OBGC, divided into separate “Fairways” and “Dunes” zones).
- Nitrogen fate in the subsurface is simulated as a function of water movement through the unsaturated zone, vegetation uptake, and denitrification and other N loss processes occurring in the subsurface.

Key Model Inputs

- **Hydrogeology of "active" unsaturated (shallow) zone**
  - depth of active layer
  - porosity
  - infiltration and percolation thresholds
  - field capacity and wilting point
- **Dynamic irrigation and meteorology inputs**
  - daily precipitation and evapotranspiration
  - daily irrigation rates
  - extended simulation period: 1967 – 2014
- **Biokinetics**
  - vegetation uptake rate constants
  - nitrification/denitrification rate constants with temperature dependencies



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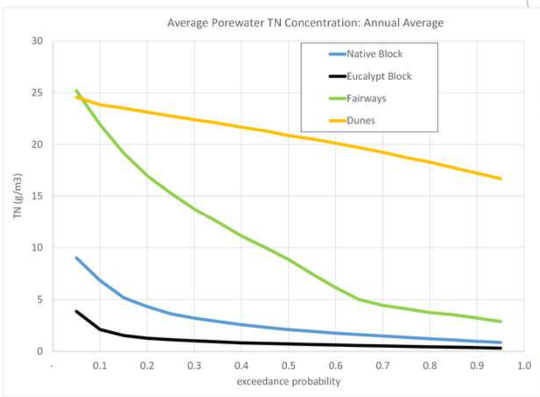
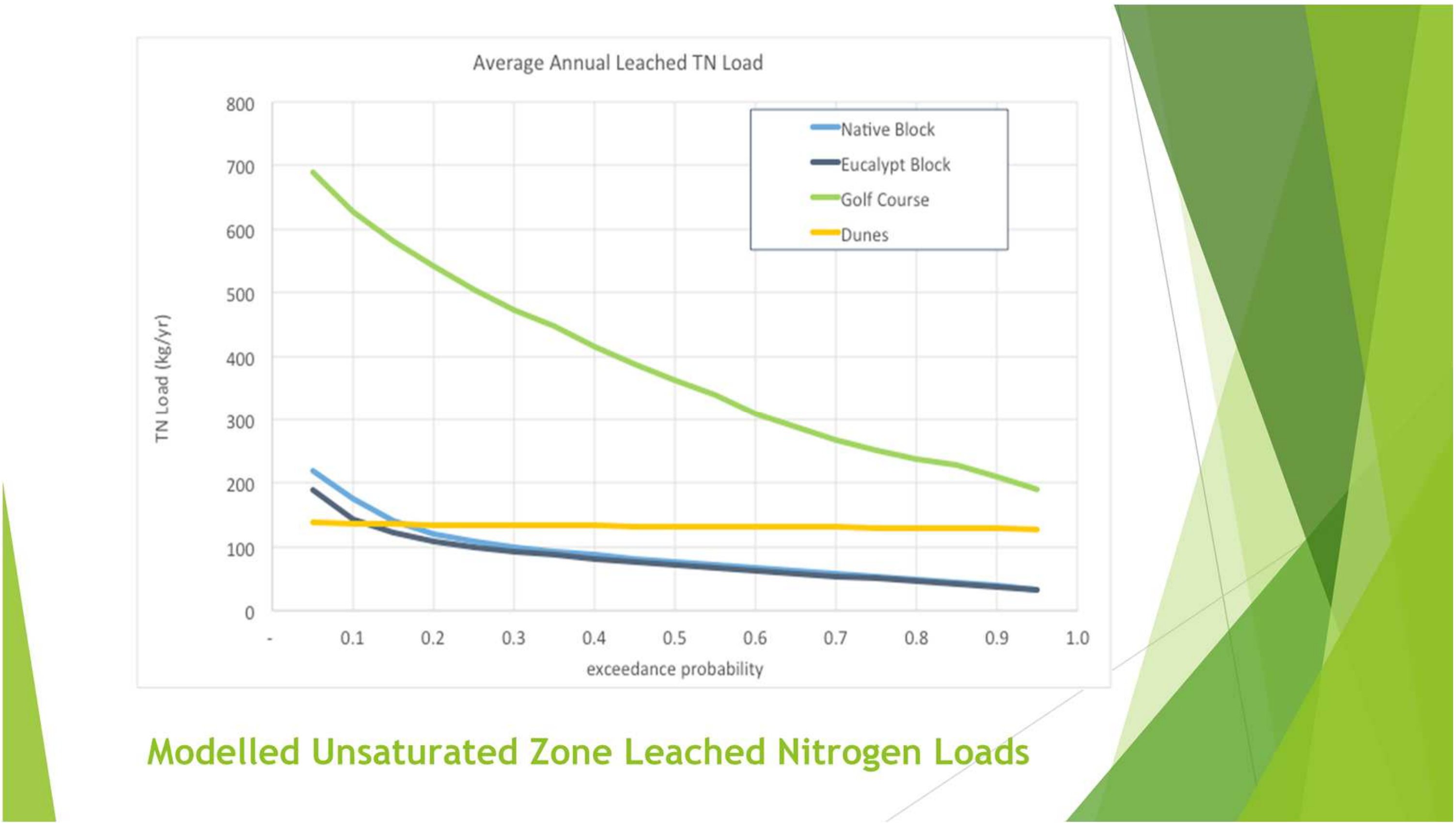
Model Outputs

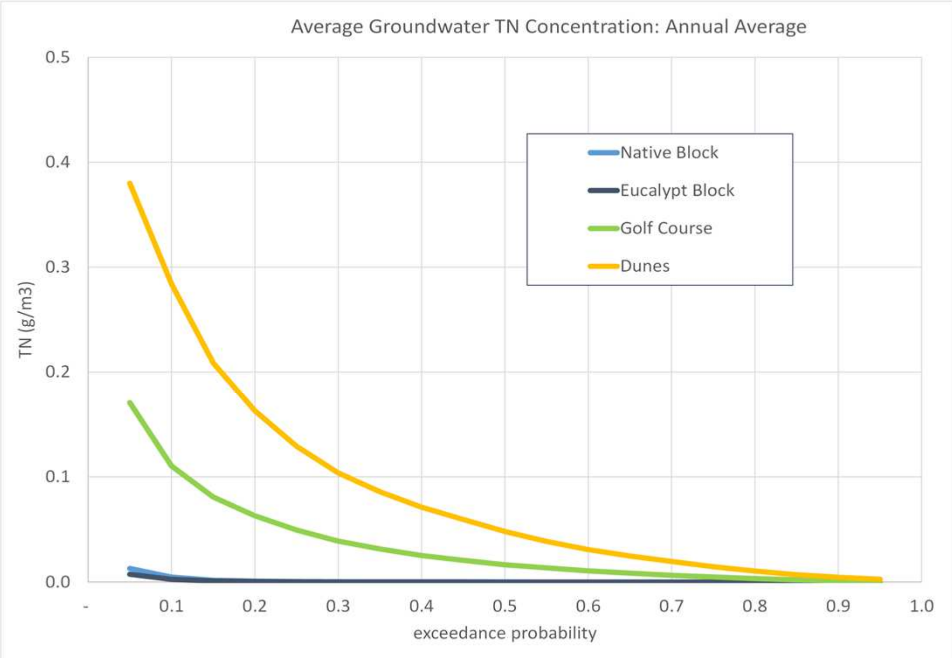
- Porewater NH_4, NO_3, TN concentrations
- Leached N loads (to saturated zone)
- Daily timeseries and statistical summaries
- Nitrogen removal in saturated zone and loads to Harbour



Model output is in the form of daily ammonia-N, nitrate-N, and total-N concentrations in unsaturated zone pore water (the water occupying the spaces between sediment particles) and total nitrogen loads to the deeper (saturated zone) subsurface.

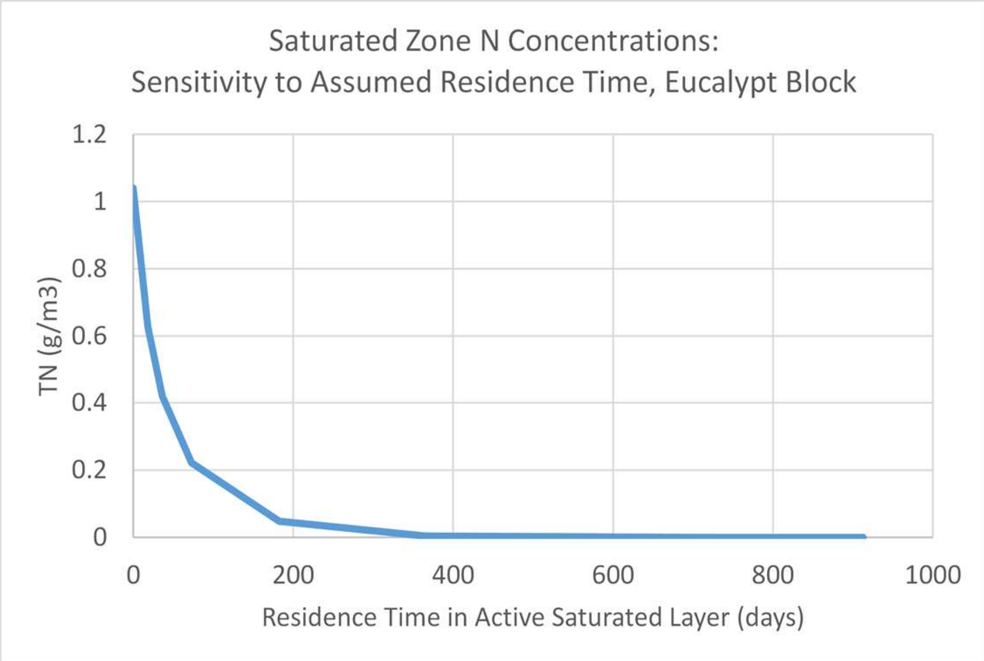


One interprets the graph in terms of likelihood. There is for example a 10% chance (exceedance probability 0.1) that that the TN load from the golf course is > 630 kg/y; a 50% chance that its greater than 370 kg/y, and a 90% chance that it is greater than 200 kg/y. On this basis the native and eucalypt blocks would be predicted to leach approximately the same annual average load from the unsaturated zone, while the golf course would leach the greatest load.



Modelled Saturated Zone Final Nitrogen Concentrations to Whangateau Harbour

Based on the model, there is only a 10% chance (0.1 exceedance probability) that the change in groundwater groundwater concentration from irrigation on the native and eucalypt blocks (Jones Rd side) would be greater than ~0.005 g/m3, whereas on the golf course side there is a 50% chance that the change in groundwater concentration will be greater than ~0.03 g/m3. In other words the groundwater concentration entering the harbour caused by irrigation at Jones Road is expected to be negligible and the change due to irrigation on golf course is only slightly greater.



Sensitivity analysis of effects of residence time on predicted final N concentration

The sensitivity analysis tells us that with a residence time 200 days or greater in saturated peat layers, the N concentrations are predicted to be < 0.05 g/m3. The PDP groundwater modelling studies predict that residence time in these layers is of the order 2-5 years.

Results of nitrogen model

Estimates of nitrogen load from Omaha WWTP (kg N per year)

	Max	Most likely
Irrigated		2200
Leaving unsaturated zone (soil)	1040	655
Entering Harbour (groundwater)	5	0

By way of comparison, the maximum amount of nitrogen predicted to enter the Whangateau Harbour from the Omaha WWTP over a year is roughly equivalent half the amount lost from 1 hectare of grazed pasture (dry stock) over the same period

Key findings

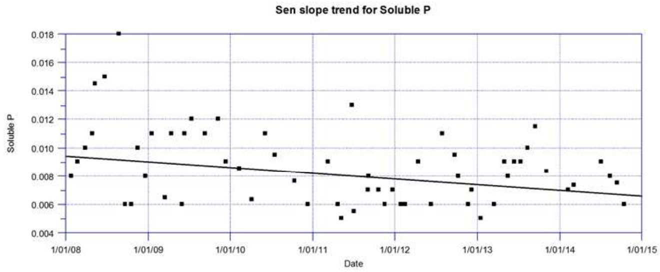
- High denitrification rates in soil mean that nitrogen from Jones Road irrigation is almost entirely removed prior to entering Whangateau Harbour.
- Accordingly, vegetation type at Jones Road is of no practical consequence for nitrogen removal
- There is significant uptake by grass on Omaha Beach Golf Course fairways but not on the dunes.
- The denitrification rates in sands beneath ONGC are low, but N removal will occur in saturated (groundwater) organic sediments
- Overall assessment is that negligible nitrogen from the irrigation will enter the Whangateau Harbour

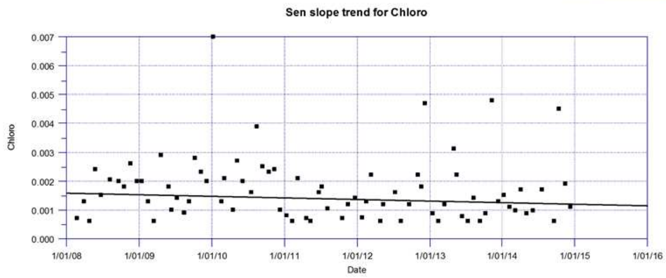
Phosphorus (P) fate and transport

- Literature review and expert judgment only (no phosphorus measurements in our study)
- Mineral soils generally have high ability to take P out of solution (adsorption)
- Peat and sand soils are more complex – wide variation reported in removal rates
- Iron and Aluminium availability is the key – together with the degree of oxidation/reduction (ferric → ferrous mobilises P - puts back in solution)
- Fluctuating water-table in unsaturated soils favours P retention
- Saturated zone (groundwater), provides conditions favourable for P in solution
- Evidence for P retention in estuarine sediments particularly at aerobic interface

Phosphorus fate and transport continued

- Overall – risks of P entering harbour causing algal growth problems very low, AND





- Analysis of P soluble (dissolved) phosphorus from Ti Point since 2008 indicates a significant decline in concentrations over that period.
- There has also been a weak, but significant decline in Chlorophyll a over the same period.
- There is no evidence that phosphorus concentrations in the Harbour are increasing (the opposite if anything) and hence no evidence that leachate from Omaha WWTP is having an adverse effect on the Harbour.

Key findings

- Phosphorus from the Omaha WWTP irrigation is unlikely to enter the Whangateau Harbour
- In any event, phosphorus concentrations in the Whangateau Harbour are declining

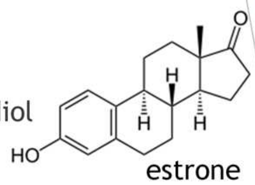
Emerging contaminants (ECs)

- Focused list of 27 ECs measured in Omaha WWTP discharge
  - List chosen by risk assessment procedures to be representative of major EC classes of greatest concern
- Concentrations compared with international literature and environmental risk indicators (ERIs)
  - Concentrations generally low cf. international data
  - 5 (19%) were > ERI – probable ecological risk
  - 5 (19%) were between 10-99% of ERI – possible ecological risk
  - 15 (56%) <10% ERI – unlikely to be an ecological risk
  - 2 (6%) could not be assessed (no ERI)
- For 5 ECs >ERI, maximum dilution required to meet ERI is 10-fold

- Emerging contaminants (ECs) are chemical or microbial agents that are not regulated against.
- They include industrial chemicals, Pharmaceuticals and Personal Care Products, Pesticides, (microbes, nanoparticles…)
- ECs can be manmade or natural
- ECs can be diffuse or point source
- Major diffuse sources are agriculture
- Major point sources are WWTPs & septic tanks
- Highly diverse effects, uses, chemical properties, stability and production
- Effects are generally more long-term or inter-generational than acute
- Uses include industrial, medicines, personal care products, agriculture & horticulture
- Vast numbers and properties
- Many knowledge gaps

Emerging contaminants – assessment of risk

- 5 ECs with probable ecological risk
  - 2 steroid estrogens: estrone (natural) and 17α-ethinyl estradiol (contraceptive pill)
  - 2 insecticides: chlorpyrifos (organophosphate) and permethrin
  - 1 pharmaceutical: diclofenac (Voltarin)
- Greatest dilution needed to comply with ERI is 5 to 10-fold (estrogens and chlorpyrifos)
- Approval for chlorpyrifos recently revoked by EPA, so concentrations will reduce over time
- Attenuation in soils has not been assessed but assuming even conservative transport (ie. no loss) then risk to Whangateau Harbour is probably low (large dilution)



estrone

Key finding

- Emerging contaminants from the irrigation of treated wastewater from the Omaha WWTP currently present a low risk to the Whangateau Harbour
- We recommend periodic reassessment of the risk presented by emerging contaminants