Applying treated municipal wastewater to a forested catchment: Modelling effects on stream discharge, sediment and nutrient loads

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Background

- The use of forested areas for wastewater irrigation has been increasingly adopted for tertiary treatment in inland cities.

- The Soil and Water Assessment Tool (SWAT) has been used to evaluate impacts of alternative land management practices.

- Few studies have applied the hourly routing algorithm in SWAT to simulate nutrient fluxes, or to evaluate forestry irrigation.

Wastewater disposal at Nipawin, Canada
Photo: SaskWater

Wastewater disposal at Penn State, US
Photo: Matthew Laposata
Objectives

• Evaluate the effectiveness of a Land Treatment System (LTS) for nutrient removal from treated wastewater

• Examine and simulate (with SWAT) long–term (10–year) effects of treated wastewater irrigation, forestry harvesting, and altered rainfall on LTS

• Run scenarios to provide information on the effects of different management strategies for wastewater irrigation
Study area

Lake Rotorua
80 km²

Rotorua wastewater treatment plant: 21,000 m³ d⁻¹

Whakarewarewa forest: 193 ha; 14 blocks
Lake Rotorua

Puarenga Stream

Waipa Stream

Kaituna rain gauge

Waipa D/S Hydrometric Station

Red Stag rain gauge

Catchment boundary (16 km²)

Spray irrigated blocks (*Pinus radiata*)

Native forest (10%)

*Pinus radiata* (80%)

Mixed woody (6%)

Non-grazed grass (4%)

Rotorua Airport Weather Station

Summary of SWAT setup

- Digital Elevation Model
- Meteorological records
- Atmospheric deposition
- Soil parameterization
- Land use classification
- Plant growth
- Management schedules
- Point sources (e.g. spring)
- Monitoring station
- Hydrologic forcing data:
  - Hourly rainfall
- **Hourly rainfall/infiltration** (Green and Ampt, 1911)/hourly routing algorithm
Management schedule setup

- Each block was assumed to be planted and mature at the start of the modelling period.
- Pine harvesting operations were configured by the harvesting date.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Specification</th>
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</thead>
<tbody>
<tr>
<td>IRR_AMT</td>
<td>Depth of irrigation water applied on HRU</td>
<td>Daily irrigation volume</td>
</tr>
<tr>
<td>IRR_SQ</td>
<td>Surface runoff ratio (fraction)</td>
<td>Web–based Hydrograph Analysis Tool</td>
</tr>
<tr>
<td>IRR_SC</td>
<td>Irrigation source</td>
<td>Outside of the catchment</td>
</tr>
<tr>
<td>FRT_KG</td>
<td>Amount of fertilizer applied to HRU (kg ha(^{-1}))</td>
<td>Contaminants in the wastewater</td>
</tr>
<tr>
<td>FRT_SURFACE</td>
<td>Fraction of fertilizer applied to top 10 mm of the soil</td>
<td>Web–based Hydrograph Analysis Tool</td>
</tr>
</tbody>
</table>
Challenges

• The complexity of irrigation operations
  ✓ Multiple blocks were configured with daily input for up to three operations (irrigation, fertiliser application and tree harvesting) for a period of 10 years

• Limited consideration in hourly routing algorithm of modelling nutrient transport
Apply daily fertilizer (kg) onto each forested block which covers numerous HRUs.

Operate a 10-year daily management schedule.

Simulate sediment load using hourly routing algorithm.

Simulate inorganic P bound to sediment.

Constrain values of parameters for hydrolysis rate within the default range.

Implement:
- `sched_mgt.f`
- `fert.f`
- `soil_write.f`
- `allocate_parms.f`
- `iopera`
- `rthsed.f`
- `rtout.f`
- `route.f`
- `ysed.f`
- `paped.f`
- `route.f`
- `ysed.f`
- `soil_chem.f`
- `psed.f`
- `enrsb.f`
- `solp.f`
- `orgn.f`
Sampling measurements: Weekly average

- Total Kjeldahl nitrogen (NH$_4$–N + ORGN)
- Ammonium–nitrogen (NH$_4$–N)
- Nitrate–nitrogen (NO$_3$–N)
- Total nitrogen (TN)
- Dissolved reactive phosphorus (DRP)
- Total phosphorus (TP)
- Total phosphorus (DRP + ORGP)
- Suspended sediment (SS)
- Discharge (Q)
Modelled vs. measured weekly mean discharge

Rainfall (mm d$^{-1}$)

Weekly average rainfall
Simulated Q
Measured Q

Judgement from Moriasi et al. (2007)

$R^2 = 0.81$ (very good)
$NSE = -0.25$ (unsatisfactory)

$R^2 = 0.83$ (very good)
$NSE = 0.51$ (satisfactory)
Modelled vs. measured weekly mean suspended solids

Calibration

Validation

$R^2 = 0.43$ (unsatisfactory)

$NSE = 0.16$ (unsatisfactory)

$R^2 = 0.54$ (satisfactory)

$NSE = 0.28$ (unsatisfactory)

Judgement from Moriasi et al. (2007)
Modelled vs. measured weekly mean total phosphorus

- Measured TP load
- Simulated TP load
- TP in wastewater
- Number of harvest blocks

Judgement from Moriasi et al. (2007)

- Calibration: $R^2 = 0.48$ (unsatisfactory)  $NSE = -0.2$ (unsatisfactory)
- Validation: $R^2 = 0.52$ (satisfactory)  $NSE = 0.07$ (unsatisfactory)
Modelled vs. measured weekly mean total nitrogen

- Simulated TN load
- Measured TN load
- TN in wastewater

Judgement from Moriasi et al. (2007)

- $R^2 = 0.7$ (very good)
- $NSE = 0.25$ (unsatisfactory)

- $R^2 = 0.8$ (very good)
- $NSE = 0.54$ (satisfactory)
# Irrigation scenarios

<table>
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<tr>
<th>Scenario</th>
<th>Specification</th>
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<tr>
<td>(i) Increasing irrigated area</td>
<td>Wastewater applied evenly on two blocks, four blocks, or eight blocks on the same soil type</td>
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<tr>
<td>(ii) Avoiding irrigation during high rainfall</td>
<td>Irrigation during ‘wet’ days with rainfall &gt; 20 mm d(^{-1}) shifted to the first subsequent dry day</td>
</tr>
<tr>
<td>(iii) Weekly irrigation frequency</td>
<td>Total weekly wastewater was irrigated on the first day of a week and no irrigation was undertaken on the remaining days in that week</td>
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<tr>
<td>(iv) Irrigation removal</td>
<td>Irrigation removed for the period 2007–2012</td>
</tr>
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</table>
Annual mean TN load deviation from current irrigation schedule

Deviation of annual mean TN load (%)

- Wet days removal
- Weekly irrigation after 2007
Comparison of simulated Waipa Stream nitrate load with and without (after 2007) wastewater irrigation.
Conclusions

• LTS was highly effective for TP removal but made much lesser contribution to TN removal

• Harvesting operations and extreme high rainfall appeared to result in peaks in SS and TP simulations

• Scenario simulations indicated:
  – avoiding irrigation during high rainfall events could increase nutrient leaching
  – daily irrigation frequency could be more effective in removing TN than less frequent irrigation
  – removing irrigation could rapidly reduce NO$_3$–N to earlier background levels

Photo: Hemo Spring, Rotorua, New Zealand
Future work

- To predict TN and TP load attenuation effects for Lake Rotorua: wastewater irrigation may cease by 2019
- To predict effects of future climate on stream loads and Lake Rotorua
- To consider groundwater processes and lag times in more detail
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