Risk-Based Decision Analysis in Ground Water Quality Management

Jagath Kaluarachchi
Professor
Civil and Environmental Engineering
Utah State University

Background

- Ground water is an important natural resource providing valuable water supply to most users.
- Even in abundance supply, poor ground water quality is of limited use.
- Ground water quality is typically affected by **land use activities** producing both ***point and non-point source pollution.***
- Impacts of poor ground water quality include public health effects to economic damages.

Non-Point Source Pollution

- Common pollutants include ***heavy metals, nitrogen, and organic chemicals***.

- Common chemicals used in agricultural activities are
  - nitrogen in fertilizers
  - pesticides, insecticides, and herbicides

- Unlike on-site remediation with point-sources, best management practices (BMPs) are implemented to minimize non-point source pollution.

Nitrate in Ground Water

- Nitrate is commonly found in ground water in background concentrations of 1 to 5 ppm.
- Excessive nitrate concentration in ground water above 10 ppm (as N) can cause health impacts including the potential for cancer.
- Heavy nitrate concentrations in ground water is found due to ***nitrogen-rich fertilizer and septic systems***.
- Nitrate is a concern in agro-well areas of Sri Lanka including northern and eastern coastal aquifer regions.

Research Questions

- What is the spatial distribution of sustainable on-ground N loading to maintain public health in a system of agricultural watersheds?
- Which BMPs should be considered to reduce nitrate pollution in ground water if loadings are high?
- What are the individual economic costs incurred due to the adoption of each BMP?
- What is the tradeoff between competing environmental and economic goals in adopting BMPs and how to prioritize the BMPs accordingly?

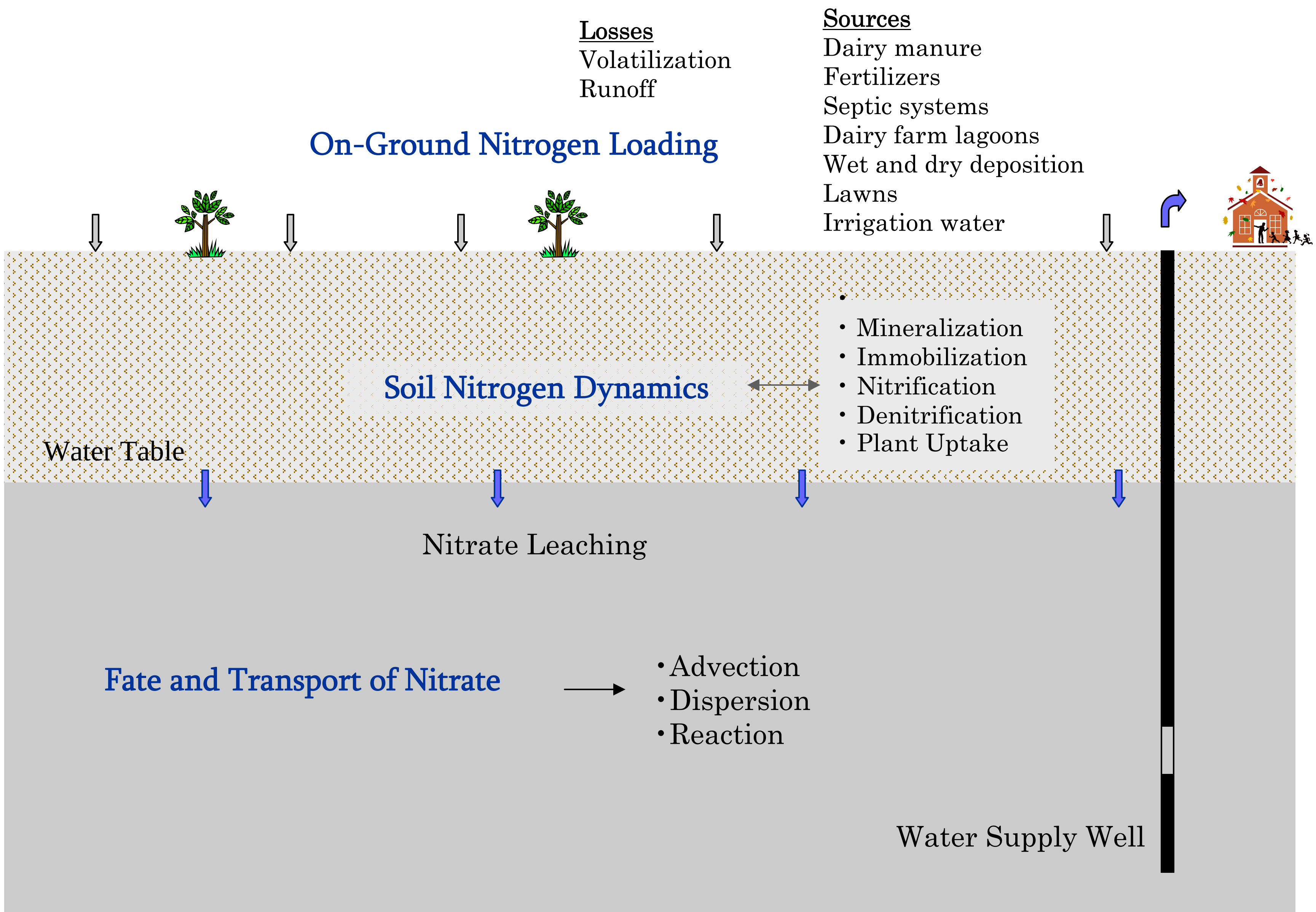
Management Options

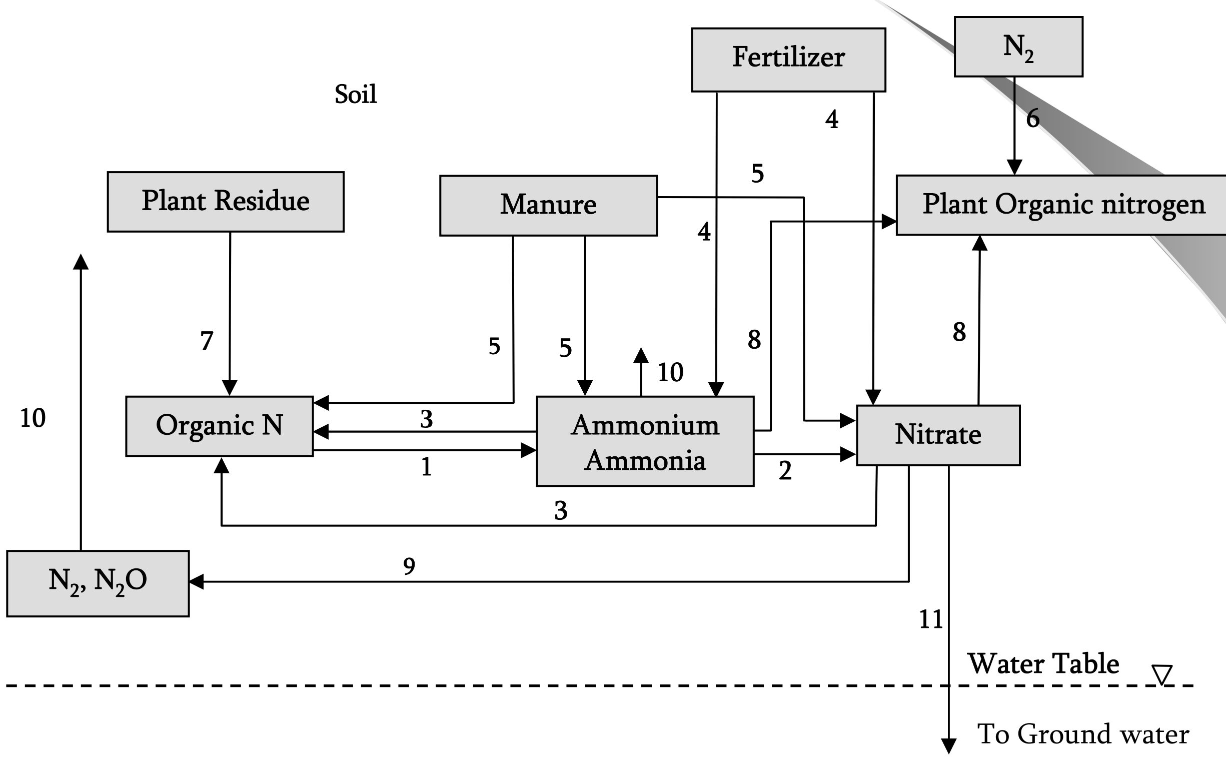
- **Change of land use practices**
  - *Manure application*
  - *Fertilizer application*
  - Crop rotation
  - Better designed septic systems

- **Change of land use**
  - Agricultural to residential
  - Agricultural to industrial

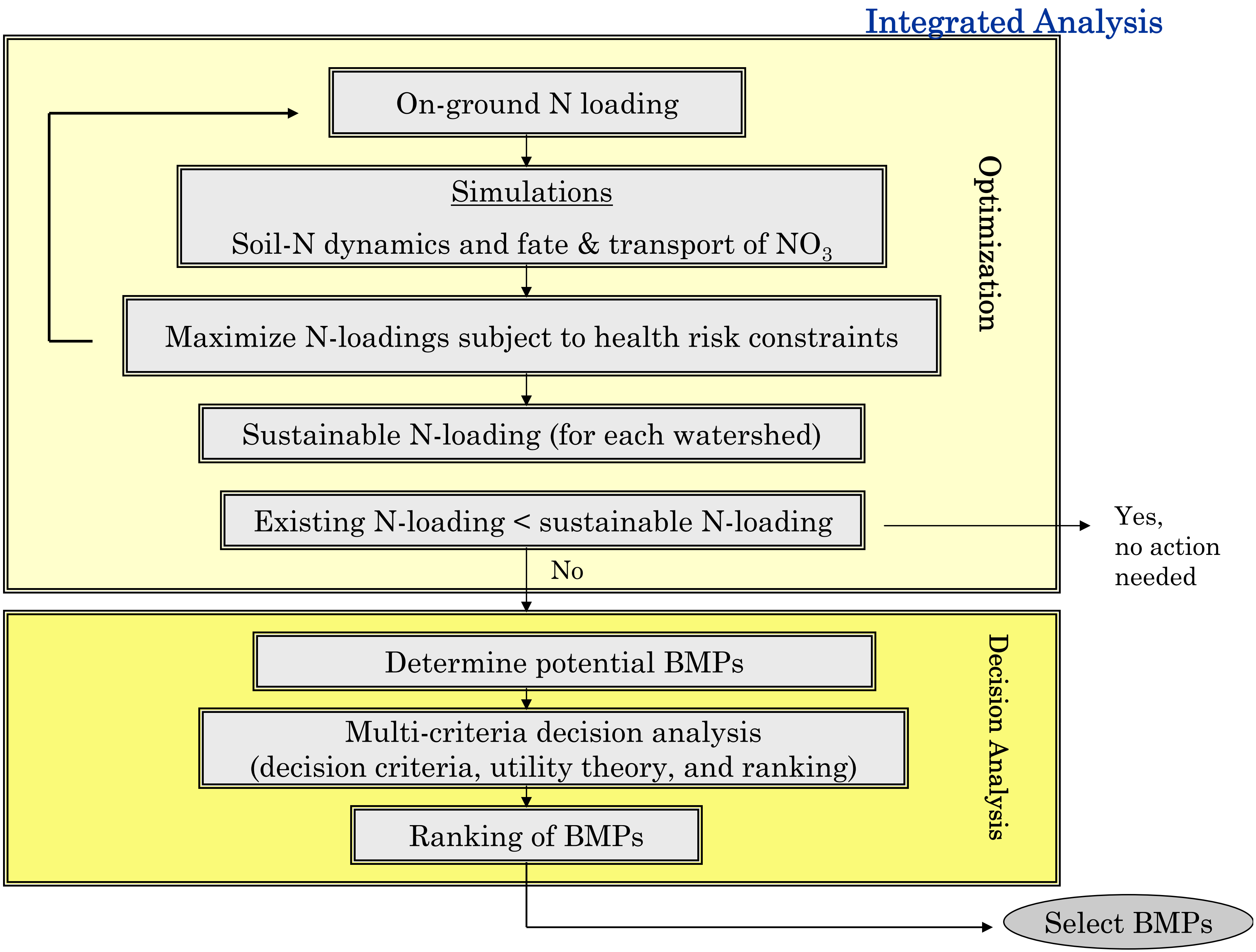
Conceptualization and Model Development

Conceptual Model



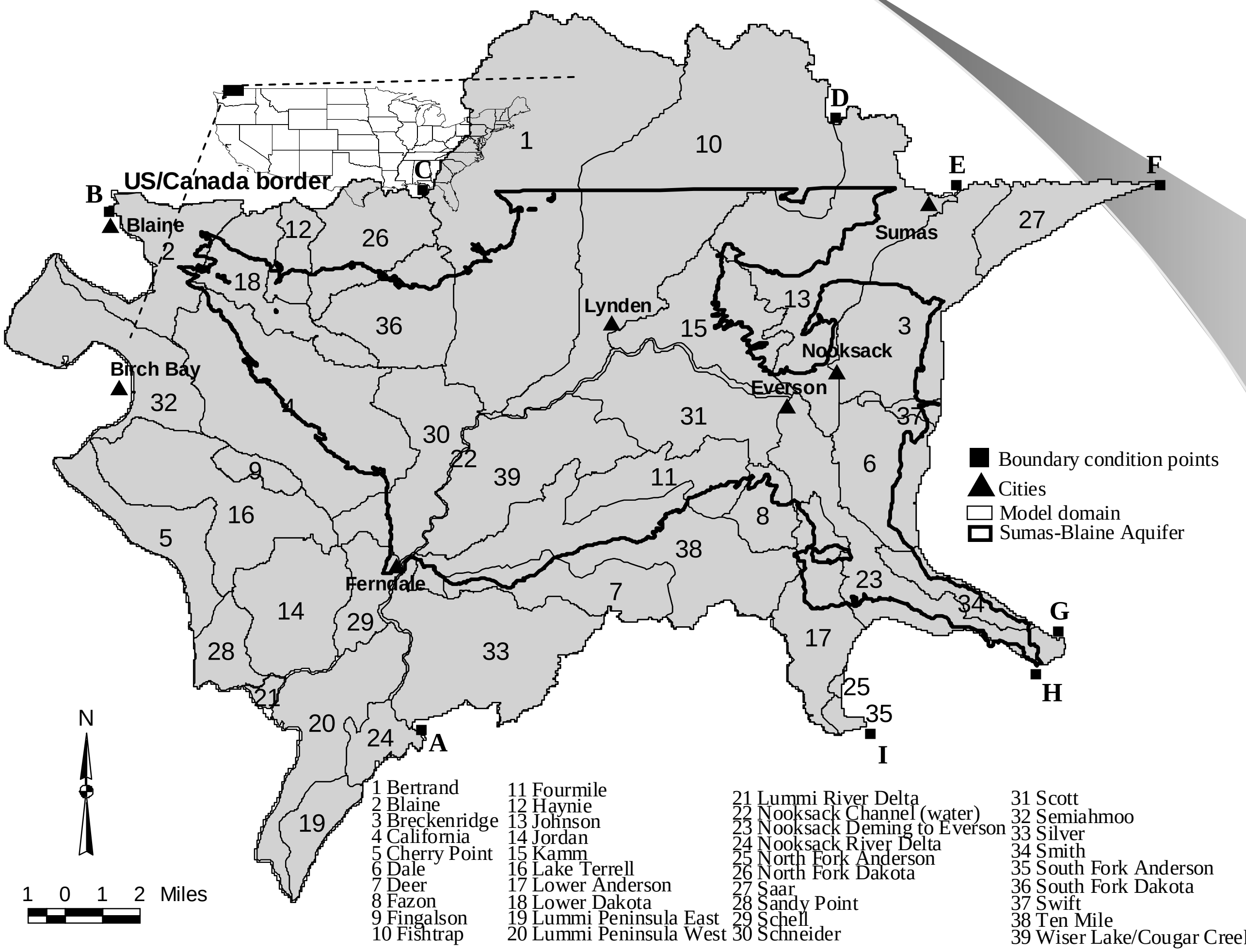


1. Mineralization
2. Nitrification
3. Immobilization
4. Fertilization
5. Manure Application
6. N Fixation
7. Crop Residue
8. Plant Uptake
9. Denitrification
10. Volatilization
11. Leaching


Integrated Analysis
On-ground N loading
Simulations
Soil-N dynamics and fate & transport of NO_3
Maximize N-loadings subject to health risk constraints
Sustainable N-loading (for each watershed)
Existing N-loading < sustainable N-loading
Yes, no action needed
No
Optimization
Determine potential BMPs
Multi-criteria decision analysis
(decision criteria, utility theory, and ranking)
Ranking of BMPs
Decision Analysis
Select BMPs

Demonstration Example

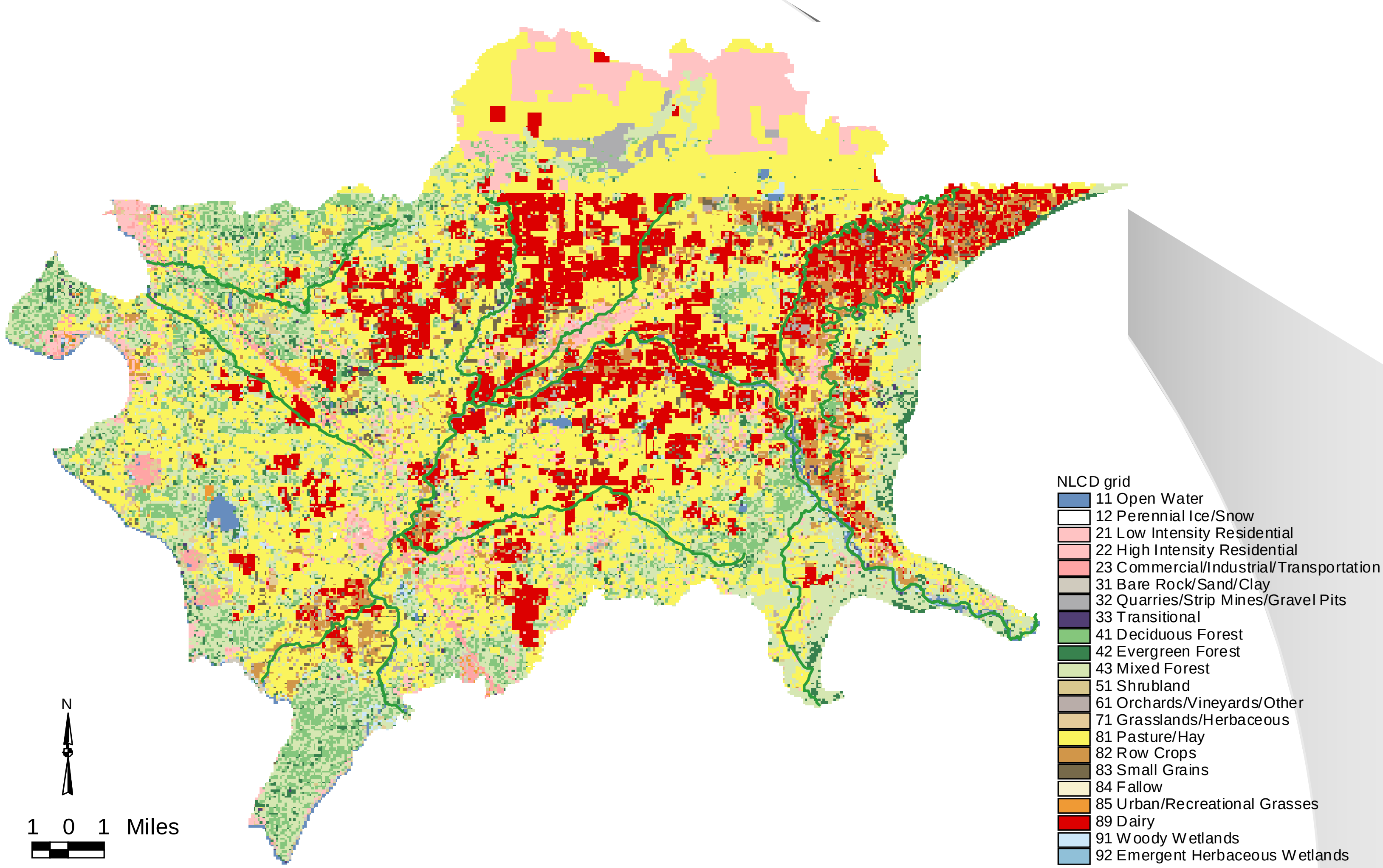
Sumas-Blaine Aquifer, WA



Background

- Area of 963 square km
- Mostly agriculture but scattered residential and industrial activities.
- Serious nitrate contamination over the past two decades; sometimes more than 150 ppm.
- Low water table and high vulnerability to nitrate leaching.
- Heavy agricultural activities
  - 8^{th} in the US for dairy production
  - 5^{th} in the world for raspberry production

Land Cover Classification
(NLCD from the USGS)



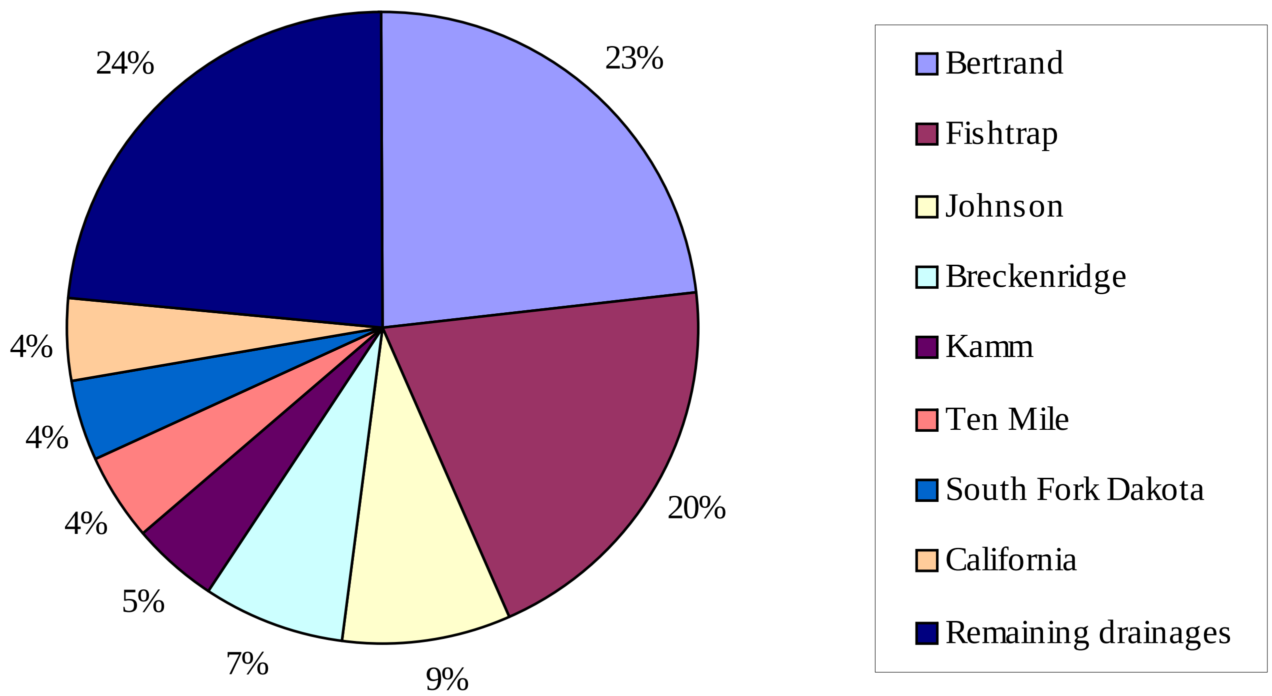
Selected Results

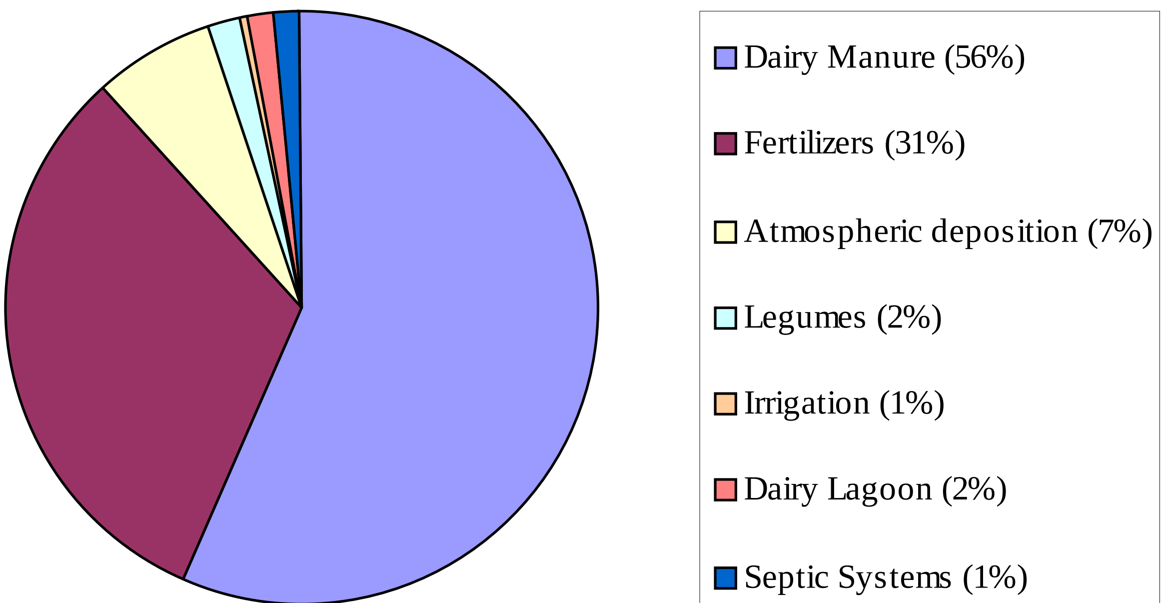
NLCD class	Dairy manure	Wet deposition	Dry deposition (regional)	Dry deposition (dairy)	Irrigation	Fertilizer	Lawns	Legumes
Low Intensity Residential		•	•				•	
High Intensity Residential		•	•				•	
Commercial/Industrial/Transportation								
Bare Rock/Sand/Clay		•	•					
Quarries/Strip Mines/Gravel Pits		•	•					
Transitional		•	•		•	•		
Deciduous Forest		•	•					
Evergreen Forest		•	•					
Mixed Forest		•	•					
Shrubland		•	•					
Orchards/Vineyards/Other		•	•		•	•		
Grasslands/Herbaceous		•	•		•	•		
Pasture/Hay		•	•		•	•		•
Row Crops		•	•		•	•		
Small Grains		•	•		•	•		
Fallow		•	•		•	•		
Urban/Recreational/Grasses		•	•				•	
Dairy Farms	•	•	•	•	•			
Woody Wetlands		•	•					
Emergent Herbaceous Wetlands		•	•					

Simulation Models

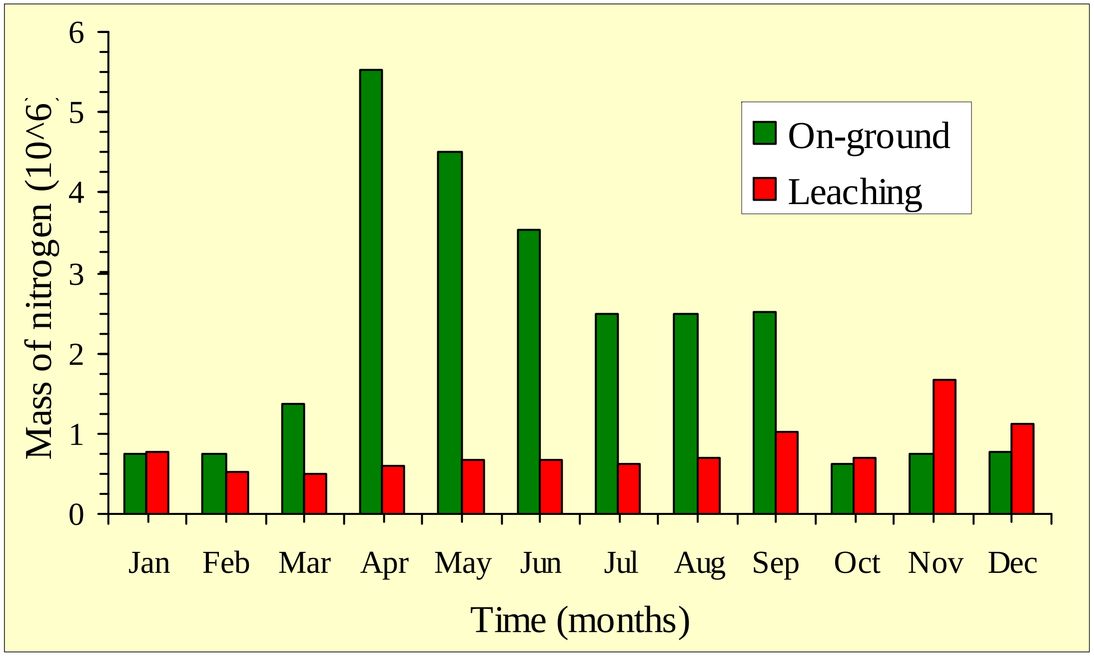
- On-ground loading of N
  - actual land use information
- Soil-N transformations
  - in-house model similar to the NLEAP
- Flow in ground water
  - MODFLOW
- Fate and transport in ground water
  - MT3D
- Optimization
  - Genetic algorithm combined with artificial neural network
- Multi-criteria decision analysis
  - Importance order of criteria method

On-ground N Loading

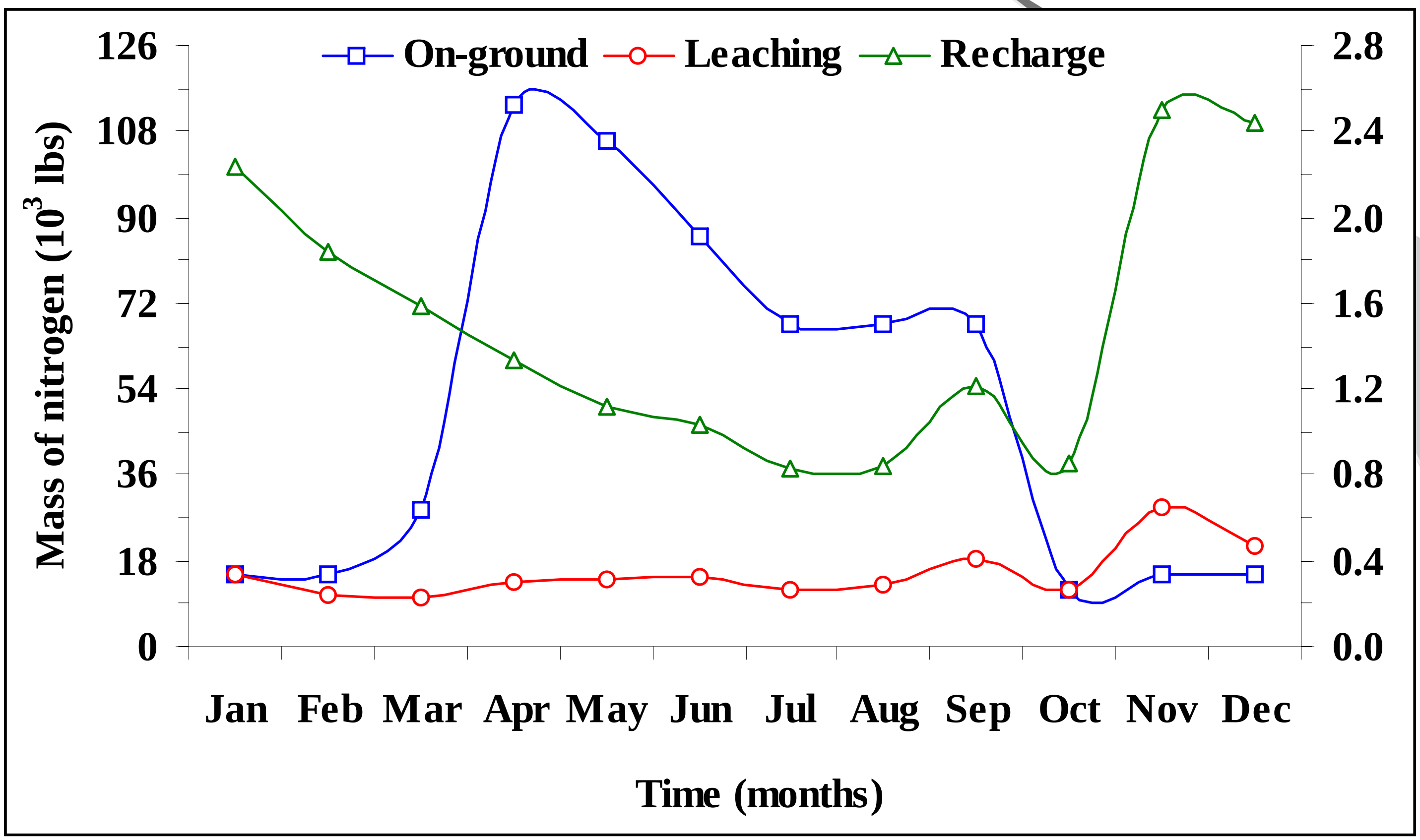



Dairy Manure (56%)
Fertilizers (31%)
Atmospheric deposition (7%)
Legumes (2%)
Irrigation (1%)
Dairy Lagoon (2%)
Septic Systems (1%)

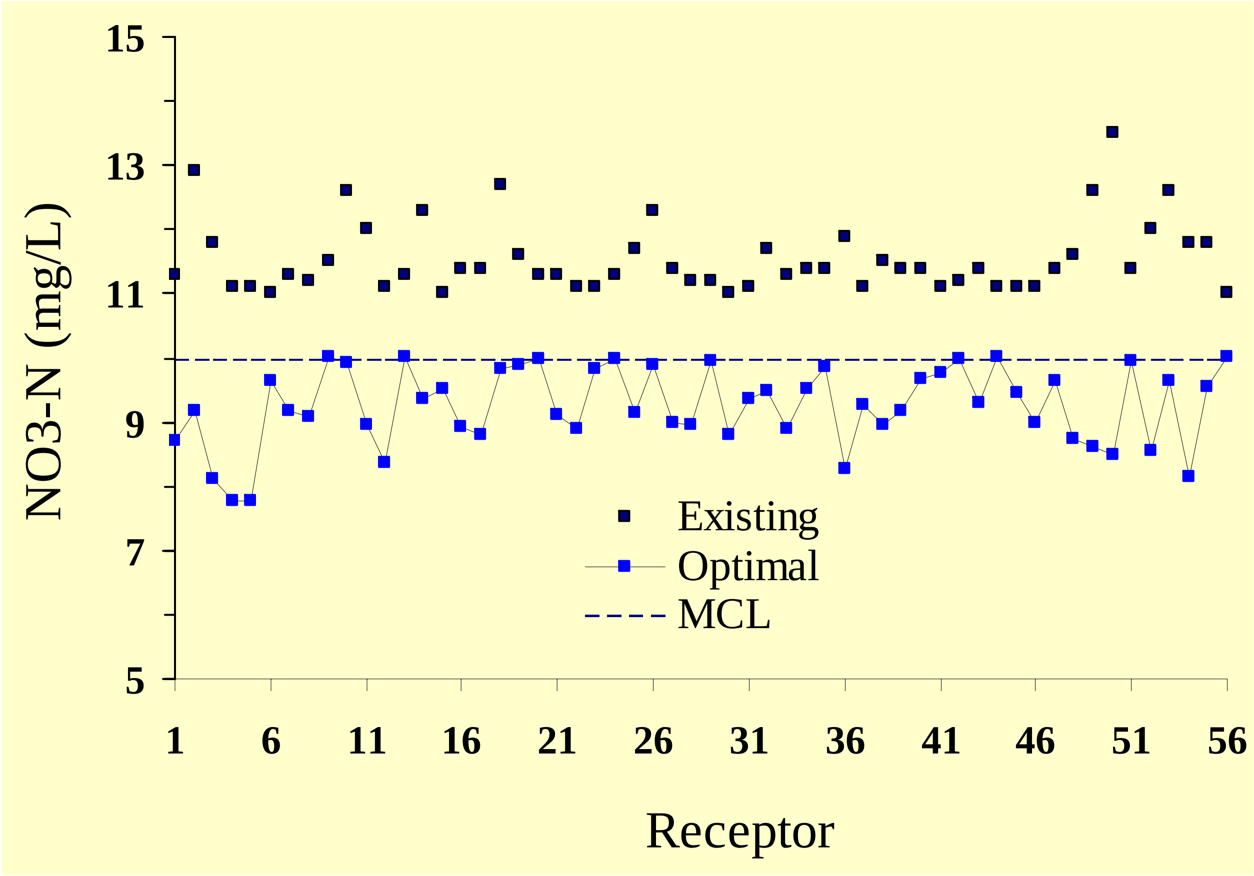
Total Nitrogen Loading

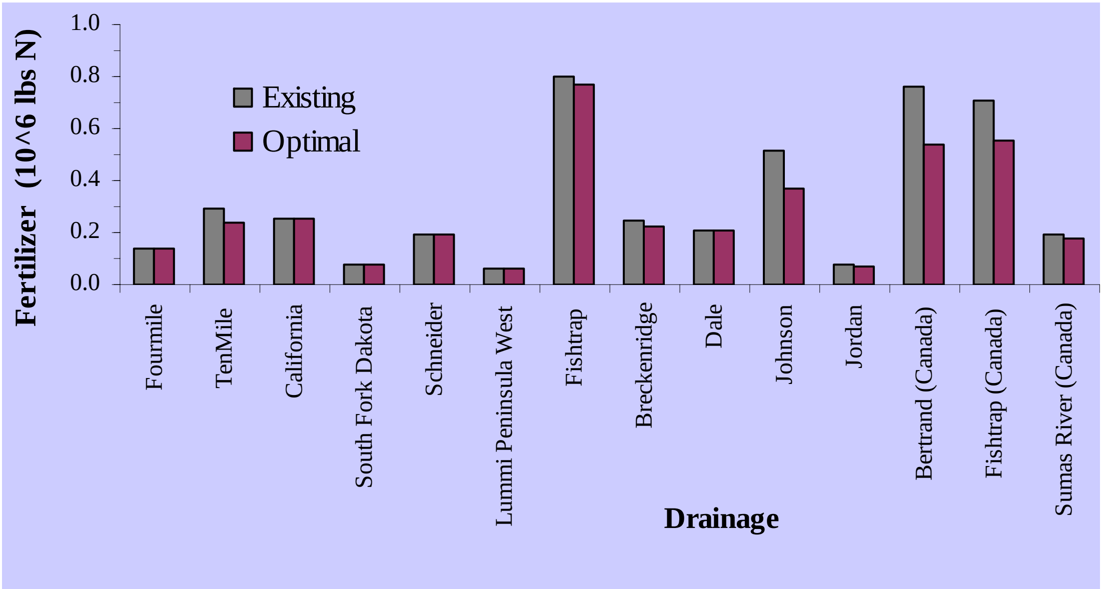


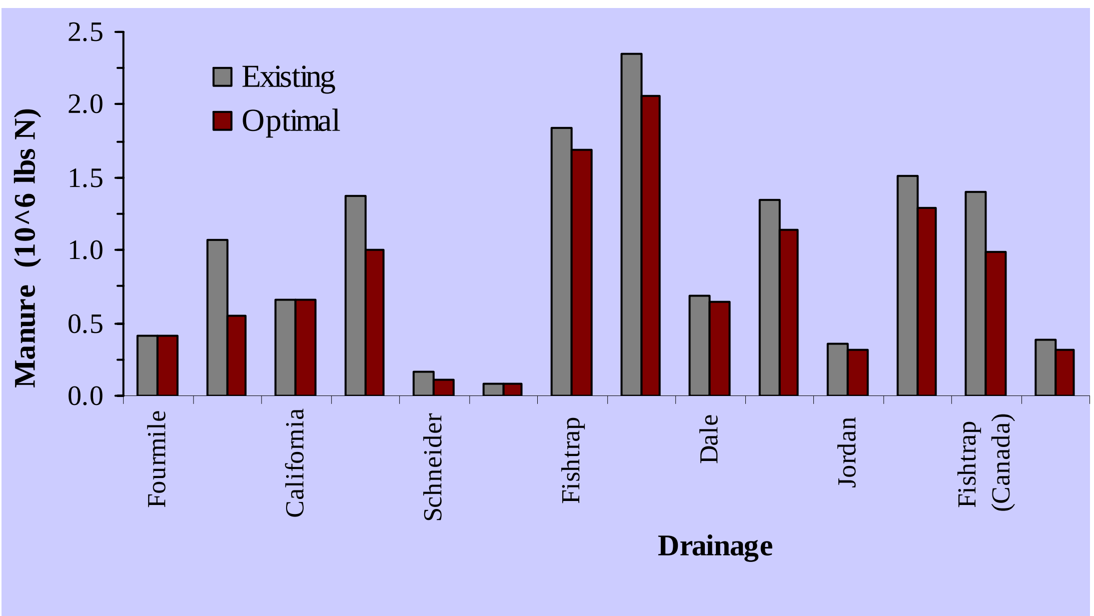
Transient soil nitrogen balance



Health Risks for different N-Loadings







Existing and optimal N-loadings from fertilizer and manure

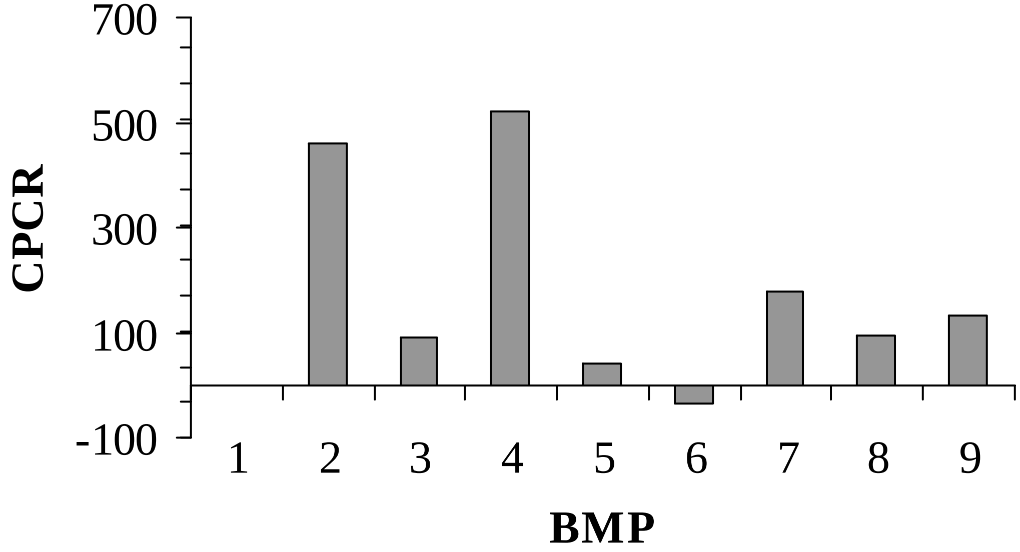
Drainage	Manure Loading (x10^6 lbs.yr)			Fertilizer Loading (x10^6 lbs.yr)		
	Existing	Sustainable	Reduction (%)	Existing	Sustainable	Reduction (%)
Fourmile	0.410	0.319	22	0.060	0.060	0
Tenmile	1.070	0.619	42	0.124	0.103	17
California	0.653	0.523	20	0.110	0.110	0
S. Fork Dakota	1.376	1.040	24	0.032	0.032	0
Schneider	0.159	0.115	28	0.083	0.083	0
Lummi Peninsula	0.085	0.069	18	0.028	0.028	0
Fishtrap	1.838	1.345	27	0.346	0.332	4
Breckenridge	2.347	1.750	25	0.107	0.095	11
Dale	0.694	0.567	18	0.090	0.090	0
Johnson	1.344	1.105	18	0.160	0.160	28
Jordan	0.359	0.311	13	0.030	0.030	4
Bertrand (Canada)	1.516	1.125	26	0.231	0.231	29
Fishtrap (Canada)	1.406	1.093	22	0.240	0.240	21
Johnson (Canada)	0.391	0.296	24	0.075	0.075	11

BMP	Description	Mean Cost (x10^6 $)
1	Do-nothing	0
2	Dairy cattle head reduction	43.8
3	Manure composting/exporting	8.7
4	Fertilizer application reduction	12.3
5	Adopt a feeding strategy for dairy cattle	-1.7
6	Adopt a feeding strategy for dairy cattle + fertilizer application reduction	10.6
7	Manure composting/exporting + fertilizer application reduction	21.0
8	Manure composting/exporting + adopt a feeding strategy for dairy cattle	2.1
9	Manure composting/exporting + fertilizer application reduction + adopt a feeding strategy for dairy cattle	14.4

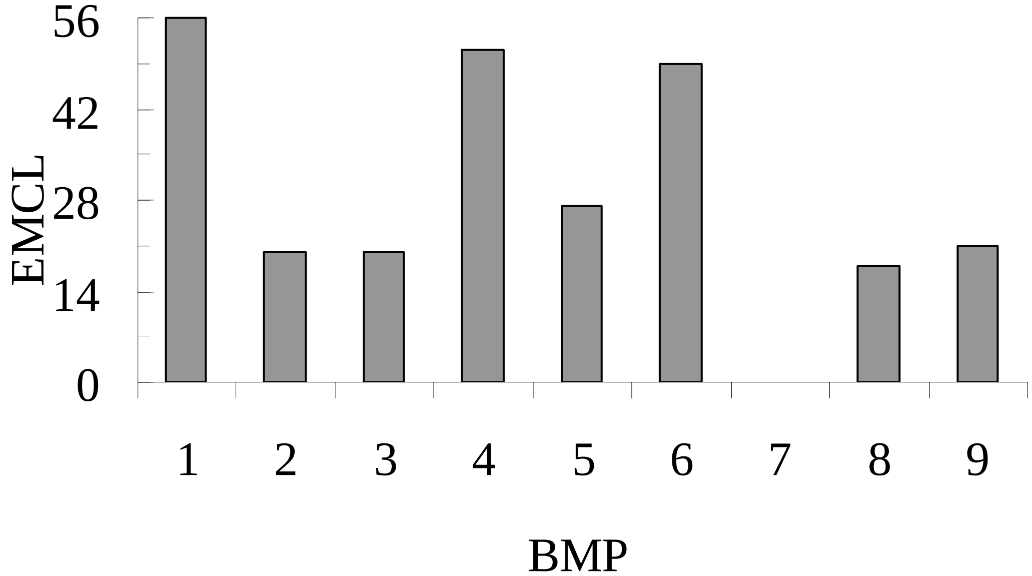
Multi-criteria decision analysis

<u>Criteria</u>

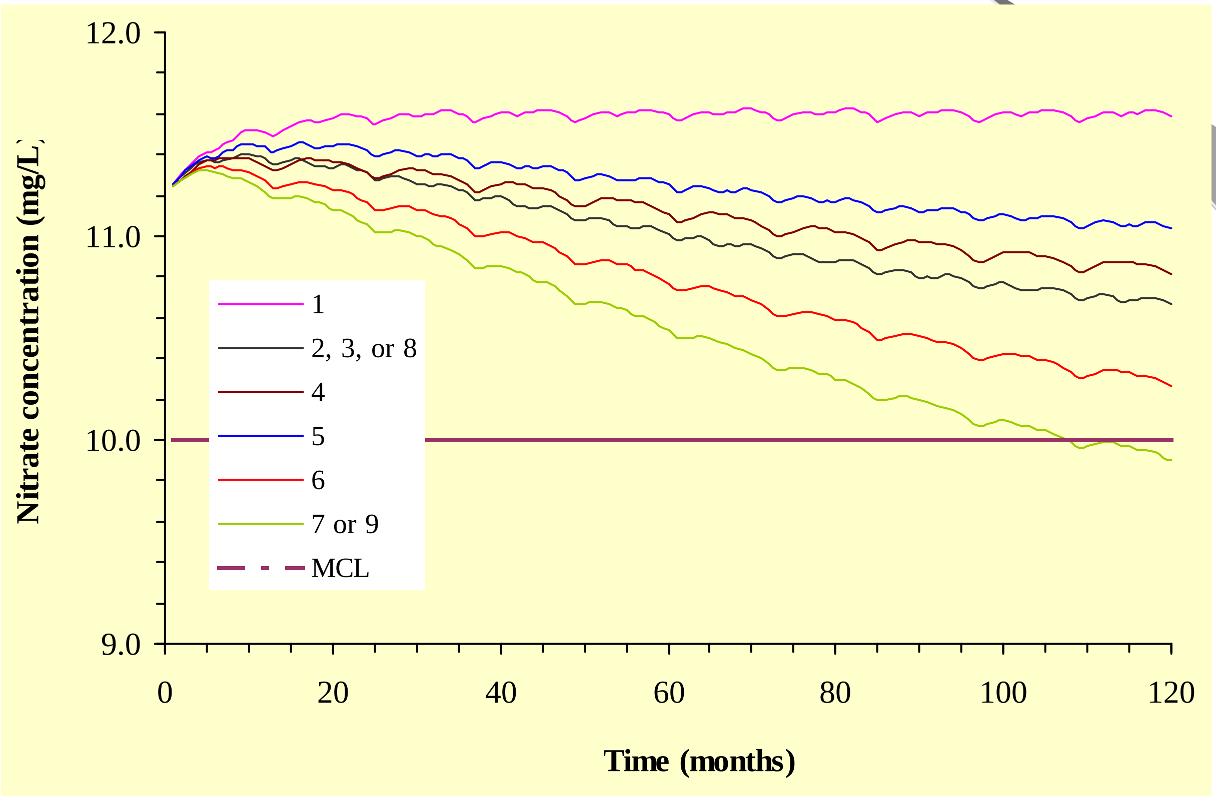
- Summation of concentration deviations above MCL
- Number of receptors exceeding MCL
- Net cost
- Cost per unit concentration reduction
- Nitrate buildup in the ground water
- Nitrogen buildup in the soil
- Cumulative nitrate flux to the surface water
- Nitrate leaching
- Total on-ground nitrogen loading
- On-ground nitrogen runoff losses
- On-ground nitrogen volatilization losses



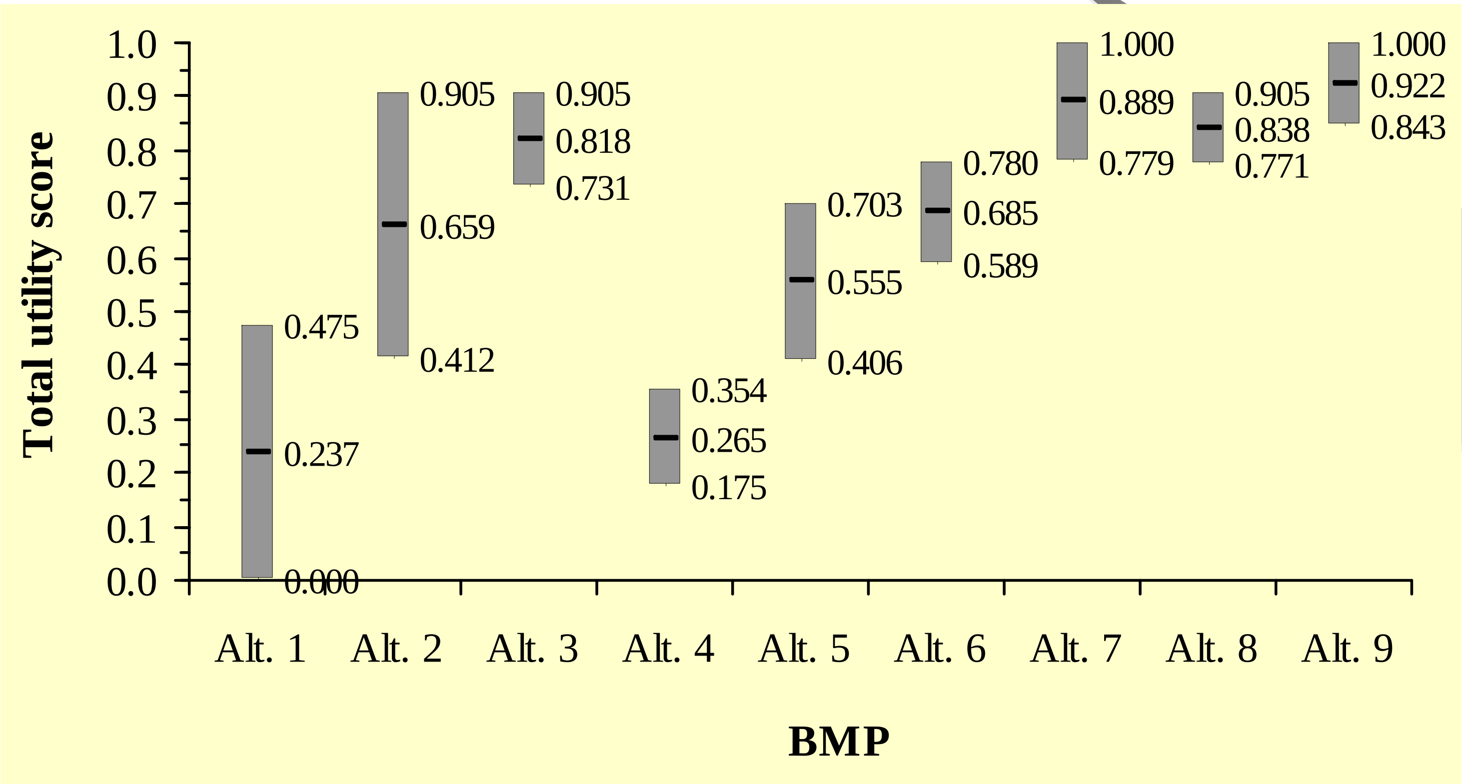
Values of Decision Criteria



Efficiency of BMPs



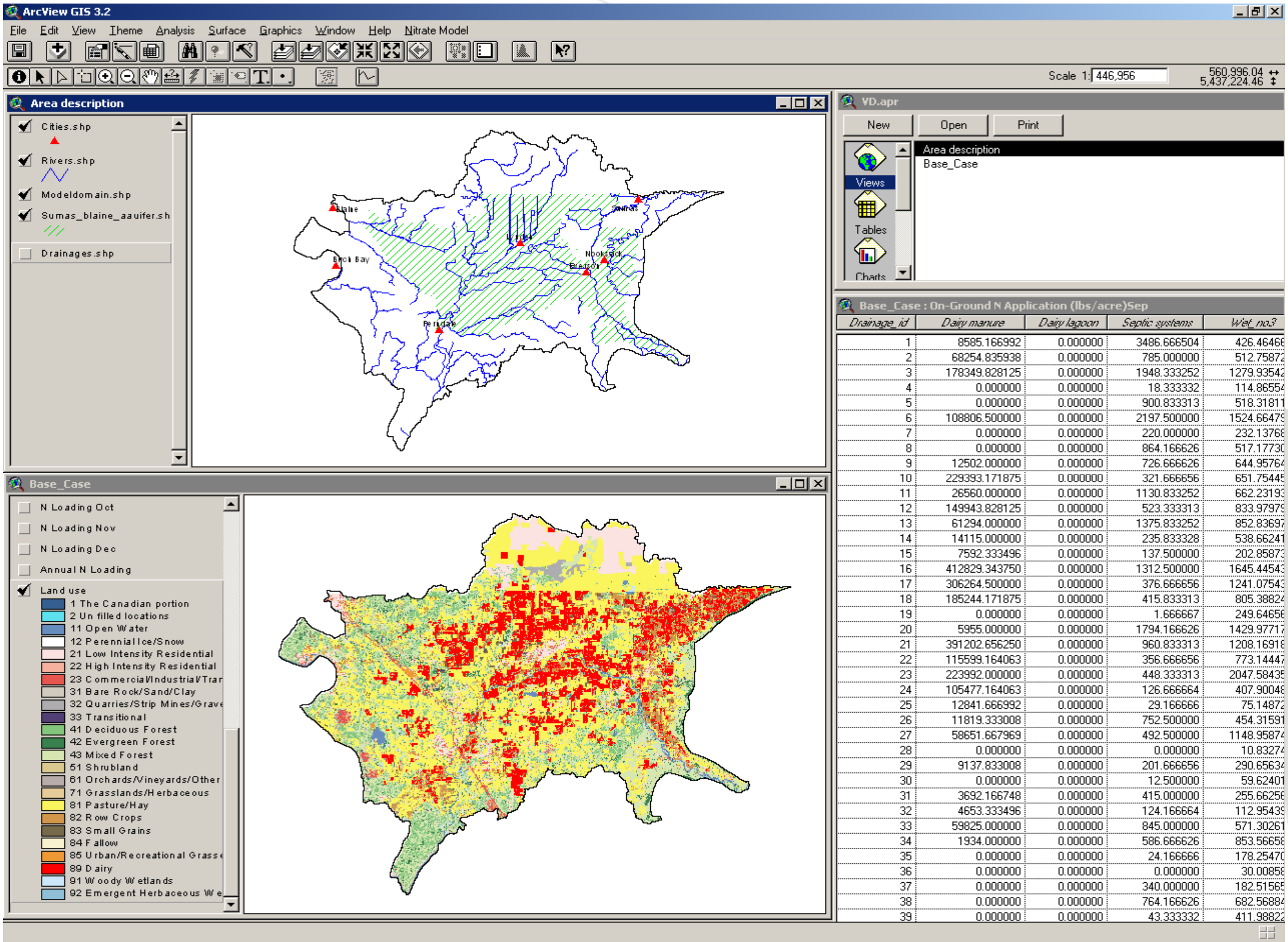
Importance Order of Criteria Method

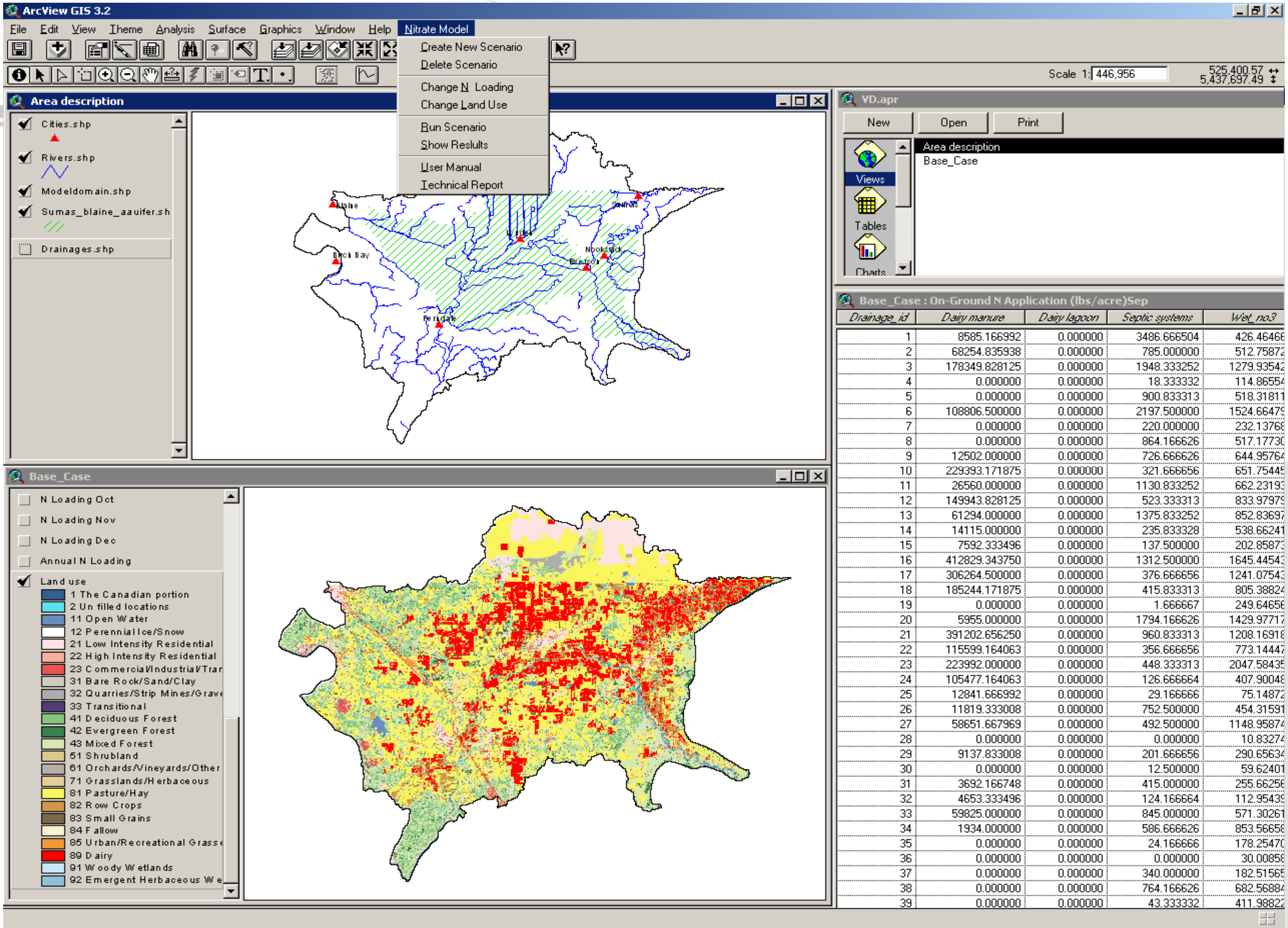


Ranking of BMPs

Ranking	Utility Score of BMP		
	Maximum	Average	Minimum
1	9	9	9
2	7	7	7
3	8	8	8
4	3	3	3
5	6	2	6
6	2	6	5
7	5	5	2
8	4	1	4
9	1	4	1

Decision-Support System




ArcView GIS 3.2
File Edit View Theme Analysis Surface Graphics Window Help Nitrate Model
Create New Scenario
Delete Scenario
Change N Loading
Change Land Use
Run Scenario
Show Results
User Manual
Technical Report
Scale 1: 446,956
525,400.57
5,437,697.49
Area description
Cities.shp
Rivers.shp
Modeldomain.shp
Sumas_blaine_aquifer.sh
Drainages.shp
VD.apr
New Open Print
Views
Tables
Charts
Area description
Base_Case
Base_Case : On-Ground N Application (lbs/acre)Sep
Drainage_id Dairy manure Dairy lagoon Septic systems Wet_no3
1 8585.166992 0.000000 3486.666504 426.46466
2 68254.835938 0.000000 785.000000 512.75872
3 178349.828125 0.000000 1948.333252 1279.93542
4 0.000000 0.000000 18.333332 114.86554
5 0.000000 0.000000 900.833313 518.31811
6 108806.500000 0.000000 2197.500000 1524.66479
7 0.000000 0.000000 220.000000 232.13768
8 0.000000 0.000000 864.166626 517.17730
9 12502.000000 0.000000 726.666626 644.95764
10 229393.171875 0.000000 321.666656 651.75445
11 26560.000000 0.000000 1130.833252 662.23193
12 149943.828125 0.000000 523.333313 833.97979
13 61294.000000 0.000000 1375.833252 852.83697
14 14115.000000 0.000000 235.833328 538.66241
15 7592.333496 0.000000 137.500000 202.85873
16 412829.343750 0.000000 1312.500000 1645.44543
17 306264.500000 0.000000 376.666656 1241.07543
18 185244.171875 0.000000 415.833313 805.38824
19 0.000000 0.000000 1.666667 249.64656
20 5955.000000 0.000000 1794.166626 1429.97717
21 391202.656250 0.000000 960.833313 1208.16918
22 115599.164063 0.000000 356.666656 773.14447
23 223992.000000 0.000000 448.333313 2047.58435
24 105477.164063 0.000000 126.666664 407.90048
25 12841.666992 0.000000 29.166666 75.14872
26 11819.333008 0.000000 752.500000 454.31591
27 58651.667969 0.000000 492.500000 1148.95874
28 0.000000 0.000000 0.000000 10.83274
29 9137.833008 0.000000 201.666656 290.65634
30 0.000000 0.000000 12.500000 59.62401
31 3692.166748 0.000000 415.000000 255.66256
32 4653.333496 0.000000 124.166664 112.95439
33 59825.000000 0.000000 845.000000 571.30261
34 1934.000000 0.000000 586.666626 853.56658
35 0.000000 0.000000 24.166666 178.25470
36 0.000000 0.000000 0.000000 30.00858
37 0.000000 0.000000 340.000000 182.51565
38 0.000000 0.000000 764.166626 682.56884
39 0.000000 0.000000 43.333332 411.98822
Base_Case
N Loading Oct
N Loading Nov
N Loading Dec
Annual N Loading
Land use
1 The Canadian portion
2 Un filled locations
11 Open Water
12 Perennial Ice/Snow
21 Low Intensity Residential
22 High Intensity Residential
23 Commercial/Industrial/Trar
31 Bare Rock/Sand/Clay
32 Quarries/Strip Mines/Grave
33 Transitional
41 Deciduous Forest
42 Evergreen Forest
43 Mixed Forest
51 Shrubland
61 Orchards/Vineyards/Other
71 Grasslands/Herbaceous
81 Pasture/Hay
82 Row Crops
83 Small Grains
84 Fallow
85 Urban/Recreational Grass
89 Dairy
91 Woody Wetlands
92 Emergent Herbaceous We

Benefits

- Site-independent soil nitrogen dynamics model provides spatial and temporal distribution of nitrate leaching to ground water.
- The decision model predicts the sustainable on-ground nitrogen loading that satisfies the health risk constraints.
- The decision model can be used in predicting aquifer vulnerability to nitrates under a variety of land use classes and practices.
- Evaluate and prioritize management options under a variety of economic and environmental decision criteria.

Conclusions

- In agriculture-dominated watersheds, high nitrate leaching is due mainly to agricultural practices. The difference between the nitrate leaching and on-ground nitrogen loading is usually substantial and signifies a soil buildup of nitrogen.
- Accounting for the spatial distribution of on-ground nitrogen loadings and nitrate leaching is essential for reliable modeling of nitrate fate and transport in ground water.
- The proposed integrated modeling framework allows for the accurate simulation of the outcome of the current land use practices and the proposed BMPs.