WATER RESOURCES RESEARCH GRANT PROPOSAL

Title: Modeling the fate of reclaimed water constituents after application to tree crops.

Focus Categories: WQL, NU, MOD,

Keywords: Wastewater irrigation, Water reuse, Water quality modeling, Phytoremediation, Nutrients, Groundwater recharge, Solute transport, Irrigation scheduling.

Duration: 03/2000 to 02/2001.

Federal: $16,830.00

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Principal investigators:

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Congressional district: 5

Statement of critical regional water problems

Recent increased eutrophication of Florida's surface water resources has resulted from the discharge of nutrients mainly from sewage effluent into rivers and lakes. This has lead to the active promotion in methods other than river discharges, such as reuse of reclaimed water for agricultural irrigation and use of land application systems such as rapid infiltration beds (RIBS) by the Florida legislature (Florida Statutes, 1999). However if application of reclaimed water to land is not carefully managed, it has the potential to impact groundwater resources, increasing nitrate and salt contents of water which may be extracted for potable use. Nitrates in drinking water have been linked to metheamaglobinemia in infants and stomach cancer in adults (Moss, 1988). The primary source of drinking water in much of Florida is the upper Floridian aquifer which lays beneath the surficial aquifer; however the upper Floridian aquifer is often poorly confined and prone to contamination from the surficial aquifer. In a recent study (USGS, 1998), surficial groundwater samples were taken from urban, forest and agricultural areas of the Georgia-Florida coastal plain. Twenty percent of the surficial aquifer samples taken from agricultural areas exceeded the USEPA nitrate standard for drinking water of 10 mg l^{-1} NO_3-N. The source of this nitrate was considered to be inorganic fertilizer and animal wastes which have been applied at high levels over several years. Nevertheless large scale irrigation of reclaimed water to agricultural crops in Florida has the same if not greater potential to impact groundwater resources. Continuously wet soil greatly increases the occurrence of rainfall induced leaching from the soil, even if the irrigation supply is matched to crop water demand.

Estimating the concentrations of nitrate and salt in groundwater recharge from reclaimed water is a complex problem. It is dependant on the hydraulic loading, amount of rainfall, evaporation and transpiration of the crop and on an intricate series of processes which transform nitrogen (N) species in the unsaturated and saturated zones. Reclaimed water often contains ammonium as the dominant form of N, this can be adsorbed by soil particles but is also converted to nitrate, which is readily leached from the soil profile. Ammonium and nitrate are generated in the soil by mineralisation of soil organic matter. Increased availability of water can enhance this process, so application of reclaimed water will not only introduce N from the water, but also has the potential to increase N inputs from the soil. Removal of N from the system is accomplished by processes such as ammonia volatilization, which is dependent on the pH of the soil and reclaimed water and on weather conditions. Microbial denitrification coverts nitrate into nitrogen gas in anaerobic conditions and is dependant on temperature and the concentration of carbon present. Plant uptake is an important removal mechanism which can be relatively easily manipulated by selecting plants which have a high demand for both water and nutrients; however this demand is highly dependent on plant growth which is in turn related to weather, seasonal effects and a number of other factors. The complicated nature of the soil-plant-reclaimed water system outlined above necessitates the development of mathematical models to assist in understanding and managing the processes which control salt and nitrate leaching to groundwater. In summary, the application of reclaimed water to the land as an alternative to discharging to surface water is an increasing practice which has the potential to contaminate groundwater resources. Mathematical models can assist in understanding, predicting and controlling the effects of complex soil and plant processes on water quality as it passes through the unsaturated zone to the groundwater.

Statement of the results, benefits and information expected:

Intensive cultivation of fast growing tree species such as poplar (*Populus*), *Eucalyptus* and willow (*Salix*) is a viable and developing alternative to conventional agricultural management and offers diversification of land use into non-food commodity crops. Using a silvicultural technique known as short rotation intensive culture (SRIC), in which densely planted trees are harvested on a cycle of less than 10 years, these species can have a large water and nutrient demand, characteristics which can be utilized in the phytoremediation of reclaimed water. Another important environmental benefit associated with the production of woody crops is that wood chips can be co-fired with coal for energy production. Woody biomass is a carbon (C) neutral fuel, the quantity of C released to the atmosphere on its combustion is equal to the quantity removed from the atmosphere during the plants growth. Potentially 10% of Florida fossil fuel use may be displaced by the use of woody biomass, reducing CO_2 emissions to the atmosphere by up to 90,871 metric tons per year (Segrest, 1999).

Since 1998, an five year research study at Water ConservII has been conducted by the School of Forest Resources and Conservation in collaboration with Woodard & Curran, the City of Orlando and Orange County to assess the environmental and economic benefits of using fast growing tree species for phytoremediation of reclaimed water. Water ConservII near Winter Garden, Florida receives secondary treated effluent from the City of Orlando Water Reclamation Facility and Orange County South Regional Reclamation Facility. The water contains mean NO_3-N and Cl^- concentrations of 6.92 mg l^{-1} and 86 mg l^{-1} respectively and is currently supplied to approximately 70 agricultural customers free of charge irrigating 4,450 ha of citrus plantations. In March 1998 a 2.8 ha test plot was established with SRIC crops. Continuous monitoring of this reclaimed water irrigated plot generates considerable data useful for mathematical modelling of the soil-plant-effluent system. The main objective of the proposed project is to develop a simulation model to predict water, chloride and nitrate transport and fate after application of reclaimed water to the phytoremediation trial plot. The model will benefit water treatment facilities such as Water ConservII by assisting in scheduling water applications, minimizing the impact of nitrate and chloride leaching on the water quality of the surficial aquifer while still meeting the crop demands for water and nutrients. The final outcome of the project is anticipated to be an operational model which uses climate, soil, and tree growth data to predict the daily allowance of reclaimed water which may be applied to tree crops.

Nature, scope and objectives of the research

Water ConservII is located on sandhills at Winter Garden west of Orlando. The experimental area utilizes a split-split-block design with three replications to compare four silvicultural options (no compost or mulch; compost only; mulch only; and compost plus mulch) for enhancing the uptake of reclaimed water applied at the rate of 17 mm day^{-1}. Six species: castorbean (**CB**, *Ricinus communis*), cottonwood (**CW**, *Populus deltoides*), *Eucalyptus amplifolia* (**EA**), *E. camaldulensis* (**EC**), *E. grandis* (**EG**) and *Leucaena leucocephala* (**LL**) are planted at a density of 3,586 trees ha^{-1} within the 2.8 ha plot.

The research objectives to date have been to identify suitable tree species and silvicultural techniques for the treatment of reclaimed water. Height, survival and stem diameter results from the ongoing 5 year research project 'Phytoremediation of Water ConservII sites by Woody Biomass' have indicated that **EG**, **CW**, and **CB** produce the highest biomass of the six tree species studied. Nitrate concentration in soil solution samples taken from below the root zone (1.5 meter) have ranged from 0.01 to 13.8 mg l^{-1}. Total N is on average lowest (2.13 mg/l) in plots which received neither mulch or compost treatment and highest in plots with compost only (7.87 mg/l).

Currently, water is applied to the tree crops at a constant rate throughout the year supplying 1.19 kg N $ha^{-1}day^{-1}$ independent of climatic conditions or the demand of the crop. Plants use less water and nutrients during the cooler winter months when growth and transpiration are minimal. During the cooler periods, soil microbial processes, such as nitrification are slowed. Plant nutrient and water demand also vary between years, depending on plant growth. Clearly, to maximize the efficacy of phytoremediation of reclaimed water, the quantity of water applied should be controlled to balance crop and soil microbial demands.

The objective of the research is to develop a model which will predict the fate and transport of nitrogen, water and chloride in reclaimed water after application to SRIC crops. Crop demand will be used to drive irrigation scheduling which may be utilized by growers and reclaimed water facilities to both minimize the risk associated with nitrate leaching to groundwater and to maximize crop production.

Methods, procedures and facilities

Existing model assessment

Models which simulate nitrogen, water and chloride dynamics in soil-plant systems (see Section 12) will be critically assessed for their suitability for modeling at Water Conserv II. A number of criteria will be used for assessment purposes, including;

- agreement between measured and simulated results provided by the model authors,
- number of input parameters required by the model,
- level of difficulty associated with parameter collection and
- level of difficulty associated with operator use.

Data collection

Much of the data already collected from the trial plot will be useful for modeling purposes, including:

- Non-destructive biomass measurements; height, stem diameter and survival measured twice yearly,
- Soil chemical analyses at the start of the trial,
- Soil solution chemical analysis taken every 2 months since May 1999,
- Transpiration measurements recorded hourly since May 1999,
- Climatic data recorded at a local weather station continuously throughout the trial, including; rainfall, temperature, windspeed, solar radiation and humidity.

The type and quantity of additional data collection for modeling purposes will depend on model selection, but is likely to include; soil hydraulic conductivity and porosity, leaf area index, leaf N concentration and leaf stomatal and canopy conductance. Many of these variables require specialized field equipment.

Model development

The assessment of existing models (described above) will determine whether a model must be specifically developed or an existing model may be adapted for the conditions at

Water ConservII. If an existing model is selected, full parameterization using Water Conserv II data will be conducted prior to validation of the model.

Development of a new model would be achieved by conducting a series of controlled laboratory and greenhouse trials to identify and quantify the processes which control water, nitrogen and chloride dynamics in plant-soil-reclaimed water systems. Plant nitrogen uptake will be examined in a lysimeter trial where reclaimed water is applied at different rates to soil columns planted with a single tree. Water leaching from the soil columns would be collected and analyzed for nitrate and chloride content. The quantity of water, and nitrate removed from solution can then be related to a function of growth and/or transpiration.

Soil microbial activity will be studied in a soil incubation trial. Soil and wastewater mixtures will be incubated at different levels of temperature and time to determine mineralisation and nitrification rates in relation to temperature and time. Soil water flow will be assessed using a soil column tracer experiment which will determine breakthrough times of a fluorescent tracer dye in Water ConservII soil given different application rates.

Implementation of irrigation schedule and model validation

The model will be validated in the field by implementing the irrigation schedule output of the model. Soil solution analysis, tree growth and transpiration data will be compared to simulated data to assess the success of the modeling effort. Formal statistical analysis techniques will be used to comparing predicted and simulated data to assess the adequacy of the model.

Related Research

A comprehensive literature review has identified a number of existing models which are capable of simulating some or all of the significant processes governing water, nutrient and chloride fate and transport in SRIC reclaimed water systems. A model has been developed in Australia which simulates nutrient and water dynamics in a sewage treatment works effluent irrigated plantation of pine and eucalyptus (Snow *et al.* 1997). Models also exists which describe the different components of the treatment process. For example, there are some 20 published models with the capability of simulating nitrogen transformations in soils. Only one of these (SOILN) has a component for forest soil simulations. The others are used to simulate agricultural behavior which differs from SRIC treatment systems, primarily because the harvest rotation of SRIC is 3 to 4 year cycles, whilst arable system are harvested annually.

Models which simulate the water dynamics of SRIC also exist, (for example SPAC and SOIL), but are used primarily for simulating conventionally managed stands without wastewater input. Short rotation intensive culture growth models are also designed for untreated stands, to assist with management strategies for maximal biomass production, whilst minimizing the use of inorganic fertilizer or irrigation. Eckersten & Slapokas

(1990) describe a model to simulate the nitrogen turnover and productivity in irrigated willow plantations. This model can also account for variable soil nutrient status, and was constructed by combining sub-models of biomass production and nitrogen turnover.

The following review identifies, compares and contrasts a selection of models. The models included are currently available for simulating all or part of the plant-soil-effluent treatment system, and represent relevant examples which may be employed to simulate effluent treatment processes using SRIC.

Soil water dynamics models for SRIC

S.P.A.C.

The soil plant atmosphere continuum model or SPAC (Kowalik and Eckersten, 1989 and Eckersten, 1994) simulates the transpiration, heat and water balances of a stand. The model was originally developed for cereal crops but has also been adapted for SRIC plantations, where it considers the atmosphere, plant and soil in terms of different layers. SPAC simulates the flow of water from the soil, through the plant to the atmosphere. Atmospheric driving forces are: solar radiation, air temperature, relative humidity of the air, wind speed and precipitation. The soil driving force is soil water potential. The model also provides the option of simulating minute values of the meteorological driving variables and soil water potential.

SPAC requires some 55 parameters relating to: plant water availability, aerodynamic resistance, stomatal resistance and plant resistance. This large number of parameters increases the complexity of the model and requires the collection of large amounts of data for model calibration (Rauch, 1996).

S.O.I.L.

SOIL (Jansson & Haldin 1980; and Johnsson & Jansson 1991) simulates water and energy dynamics in a one-dimensional soil covered with vegetation in a similar way to SPAC and was also developed originally for use on arable crops such as wheat. However in the SOIL model the soil is separated into distinct layers. The depth of the layers and the boundary conditions can be defined for different situations, such as saturated soil and groundwater flow. Compartments can also be included for snow, surface ponding, and intercepted water. This allows for more realistic simulation of field conditions where soil horizons exist with differing thickness and hydraulic properties

The SOIL model has frequently been used to simulate the heat and water driving variables for models which simulate nitrogen dynamics (for example, Johnsson et al., 1987; Eckersten & Jansson, 1991 and Blombäck et al, 1995). SOIL is used in this manner to simulate the nitrate dynamics of runoff, vertical fluxes and soilwater flow between the modeled soil layers. The nitrogen models can then utilize this information to simulate microbial and plant uptake processes.

SOIL requires in excess of 120 parameters making this model highly complex, difficult to calibrate and onerous to use. In a four year simulation of 3 different crop covers (barley with and without N fertilization and grass), in central Sweden, the simulated soil water content showed good agreement with measured values at depths of 15 and 60 cm (Johnsson and Jansson, 1991). However the values chosen for a number of the parameters (for example the reduction function for root water uptake) were assumed to be the same as those used by previous SOIL simulations. As a consequence, a lack of confidence in the accuracy of simulations lead the authors to conclude that more accurate model calibration was required. Models with a large number of parameters often impose the need for compromises to be made between accurate parameterization and accurate simulations. If the parameters used are inappropriate, there is no confidence in the findings.

Models describing soil N dynamics.

S.O.I.L.N.

The SOILN model (Jansson et al. 1991, Bergström & Jarvis 1991) uses outputs from SOIL such as surface runoff, infiltration, water flow between soil layers and soil temperature as the driving variables to simulate the biological activity of the plant soil atmosphere system. Biological activity is given in terms of nitrogen and carbon fluxes. The model can be separated into three sub-models; the soil, crop and forest. The soil sub-model is at the core of the model and was described in detail by Johnsson et al. (1987). It considers plant uptake, mineralisation, immobilization, nitrification leaching and denitrification processes in a layered agricultural soil. In addition to the physical descriptions of the plant and soil characteristics required by SOIL, SOILN uses biological variables such as the rates of denitrification, mineralisation and immobilization. Each soil layer is allocated an organic and an inorganic pool of N. Inorganic pools of N include NH_4-N and NO_3-N, organic pools include humus, leaf litter, and manure derived faeces. Carbon pools for litter and manure are included to determine immobilization and mineralisation rates. Nitrogen can be transported between layers or to drainage tiles as soluble nitrate, and can be lost from all layers by denitrification. The crop and forest sub-models describe the uptake of nitrogen into the plant and the plant growth, for cereal or SRIC crops, respectively. The driving variables for these sub-models are meteorological data. The forest sub-model was derived from the WIGO model (see below), which simulates the uptake of N into plant parts and the loss of N from the stand at senescence.

Like SPAC and SOIL, SOILN requires a large number of parameters for calibration (>140). For the reasons discussed above, this can cause the model to be difficult to calibrate and manage.

L.E.A.CH.N

LEACHN is the nitrogen version of the series of models known as Leaching Estimation And Chemistry Models (L.E.A.CH.M). It is a deterministic model, which simulates the chemical physical and biological processes that influence the fate of nitrogen in field soils. Many of the process sub-models, such as those describing mineralisation, nitrification and denitrification, are identical to those used by SOILN (Johnsson *et al.* 1987) and like SOILN, this model considers soil as a multi-layered system and each layer is assumed to be homogeneous. The main difference between SOILN and LEACHN is the way in which the water and chemical kinetics are calculated, making field application of LEACHN less arduous. In addition to a smaller parameter set, three of the critical soil parameters may be estimated rather than measured using established relationships. Chemical transport is relatively insensitive to these soil hydraulic properties, and soil water content distributions usually depend upon the balance between rainfall, evapotranspiration and runoff, none of which are controlled primarily by soil hydraulic properties. The authors maintain that estimation of these values will result in little loss of accuracy. However hydraulic conductivity is highly significant when considering the flow of water, especially at low soil water contents. LEACHN would therefore appear to have potential for application to field sites where little characterizable data is available, however little work on the use of LEACHN for SRIC plantations currently exists in the literature.

Dynamic thermal-time nitrate model

Nitrate accumulation in urban wastewater biosolids treated soils can be described as a simple exponential function of thermal-time (Smith, Evans & Woods, 1998 and Smith and Hall, 1997). Thermal-time is defined as cumulative effective average diurnal temperature above a specified base temperature. The base temperature is the temperature at which NO_3^- production ceases. Thermal-time nitrate models realistically consider nitrification as an enzyme mediated microbial activity which is dependant on temperature. On the other hand, models such as SOILN and LEACHN, simulate nitrification by assuming a nitrate to ammonium ratio which is characteristic of a particular soil, the transformation rate is constant for that soil. This therefore overlooks the fact that nitrification is temperature dependent. SOILN and LEACHN have been designed for agricultural systems in which the ammonium concentration is low and therefore nitrification is also small. In systems where ammonium has been added, for example sludge amended and wastewater irrigated soils, the process of nitrification becomes more significant, justifying the need for a thermal-time approach.

Multiple process models for forest systems

Growth and Nitrogen turnover model

The Growth and Nitrogen turnover model (Eckersten and Slapokas, 1990) simulates the biomass production and quantity of N in an irrigated established SRIC plantation. The model uses an adaptation of the willow growth model (Eckersten *et al.* 1989), and a nitrogen turnover sub-model, which describes the mineralization of humus and leaf litter. The model also takes account of any fertilization added to the stand. The growth and nitrogen turnover model applies to a horizontally uniform stand, but assumes that the growth is not limited by water and nutrient availability other than nitrogen. Inputs to the model are: leaf weight, the same climatic factors that are used in the willow growth model, and fertilization rate.

The advantage of using models combining more than one process is that feedback mechanisms may be employed between the sub-models. Feedback loops allow complex biological feedback mechanisms to be simulated to provide closer agreement between field observations and modeled data, without increasing the complexity of application. The growth and nitrogen turnover model combines biomass production and N turnover processes, but requires approximately the same number of parameters as the willow growth model, which only simulates biomass production.

APSIM for effluent

This is a physically-based model which simulates the water, nitrogen and sodium chloride (NaCl) in effluent irrigated pine and eucalyptus plantations (Myers et al., 1994; Snow et al, 1997 & Snow, 1999). The simulation of soil NaCl provides two advantages for modeling SRIC effluent treatment systems:

1. NaCl is a major component contributing to soil osmotic potential in wastewater irrigated soils. Elevated soil NaCl concentrations can be phytotoxic to SRIC due to Na^+ and Cl^- toxicity and osmoregulatory disfunction.
2. Cl^- behaves conservatively in soil (Sanks & Asano, 1976). Its flow dynamics may therefore represent the flow dynamics of other conservative components of the applied wastewater such as NO_3-N.

The model is composed of a number of sub-models to describe different processes such as plant growth, tree water usage, nitrogen transformations and litter decomposition. All of the sub-models have been developed from existing models except for the plant biomass production sub-model. Plant growth is simulated using empirical geometric functions which do not account for climatic factors such as temperature and light level, however a submodel is in the development stage which can mechanistically calculate plant growth based on climate.

APSIM for effluent requires a small amount of site-specific information based on the soil characteristics and meteorological data. The other parameters are taken from published literature, but were not presented by Snow *et al.* (1997). Snow *et al.* 1997 argued that, despite a better agreement between the measured and modeled data after calibration, in order to apply the model to sites where no calibration data is available, it is preferable to consistently use the parameter values provided by the literature whether calibration data are available or not.

Initial results obtained from the simulation indicated a close agreement between simulated and observed water use (Figure 1). The largest difference between modeled and measured cumulative transpiration was 8% of the annual tree water use. The model was also able to simulate a rapid increased in soil Cl concentration from 0.25 to 1.5 t ha^{-1}, which resulted from low winter rainfall and high effluent concentration. Simulated and observed soil solution mineral N concentrations at 1 m depth are shown in Figure 2. Snow *et al.* (1997) reported a good comparison between simulated and observed mineral N data, however goodness-of-fit statistics were not provided as evidence for these claims. Figure 2 shows a large amount of scatter in the observed data which was not accounted for by the simulation.

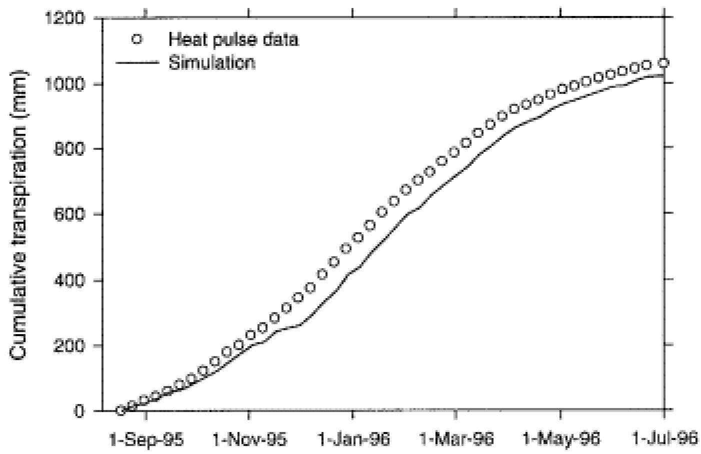

Figure 1. Measured and simulated transpiration (Snow *et al.* 1997).

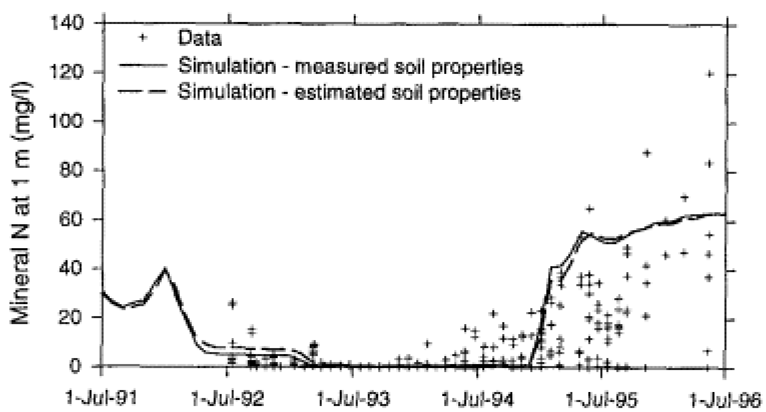

Figure 2. Measured and observed mineral N concentration in soil at 1m depth (Snow *et al.* 1997)

APSIM for effluent incorporates a number of significant assumptions:

- effluent application is by spray irrigation only
- wastewater application rate is lower than the saturated hydraulic conductivity of the soil,
- application rate and soil properties are assumed not to vary spatially,
- only conductive soils are considered by the model and
- denitrification is assumed to be zero.

These assumptions hold at Water ConservII because the soil is highly conductive and is relatively homogenous and the reclaimed water is applied using a sprinkler system.

APSIM for effluent shows considerable potential for application to SRIC treatment systems such as Water ConservII. However current publications (Snow *et al.* 1997; Myers *et al.* 1994 & Snow, 1999) do not include detailed descriptions of the model.

Recent personal communication with the authors has led to the suggestion that APSIM for effluent may be provided by them for field testing at Water ConservII with a monetary contribution plus full training by the authors of the model.

In summary, the dominant processes controlling N dynamics in SRIC effluent treatment systems are:

1. plant uptake as a function of biomass production and tissue N concentration,
2. leaching losses, which are controlled by water dynamics and
3. soil processes such as denitrification and nitrification, which increases the risk of leaching losses by converting labile NH_4-N to mobile NO_3-N and
4. NH_3 volatilization

Therefore a combination of models or sub-models which describe: growth, evapotranspiration, advection and dispersion in soils, and soil processes could potentially simulate water, nitrogen and chloride dynamics at the Water ConservII site. APSIM for effluent shows the greatest potential to meet this objective.

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